

More evidence for sensorimotor adaptation in color perception

Aline Bompas

Laboratoire de Psychologie Expérimentale, CNRS,
Université René Descartes, France



J. Kevin O'Regan

Laboratoire de Psychologie Expérimentale, CNRS,
Université René Descartes, France



Sensorimotor adaptation can be defined as a perceptual adaptation whose effects depend on the occurrence and nature of the performed motor actions. Examples of sensorimotor adaptation can be found in the literature on prisms concerning several space-related attributes like orientation, curvature, and size. In this article, we show that sensorimotor adaptation can be obtained for color, as a consequence of the introduction of a new sensorimotor contingency between eye movements and color changes. In an adaptation phase, trials involved the successive presentation of two patches, first on the left, and then on the right or the opposite. The left patch being always red and the right patch green, a correlation is introduced between left–right (respectively right–left) eye saccades and red–green (respectively green–red) color change. After 40 min of adaptation, when two yellow patches are successively presented on each side of the screen, the chromaticity of the left and right patches need respectively to be shifted toward the chromaticity of the red and green adaptation patches for subjective equality to be obtained. When the eyes are kept fixed during the adaptation stage, creating a strong nonhomogeneity in retinal adaptation, no effect is found. This ensures that, if present, adaptation at a given retinal location cannot explain the present effect. A third experiment shows a dependency of the effect on the eyes' saccadic movements and not on the position on the screen, that is, on the position of the eyes in the orbits. These results argue for the involvement of sensorimotor mechanisms in color perception. The relation of these experimental findings toward a sensorimotor theory of color perception is discussed.

Keywords: color, eye movements, sensorimotor, adaptation

Introduction

Adaptation to the spatial distortions introduced by prisms is a well-known phenomenon (Gibson, 1966; Harris, 1965; Held & Freedman, 1963; Rock, 1966; Welch, 1974). In particular, a subject wearing wedge prisms experiences compressions, extensions, and distortions of the visual scene that depend on his eye and head movements. With time, subjects partially adapt to these unusual correlations between movements and sensory changes. As a consequence, when the prisms are removed, aftereffects are obtained that can be measured by the strength of prisms, oriented in the opposite direction, necessary to cancel the perceptual distortion experienced when eye or head movements are performed.

Literature on prism adaptation has contributed to establish the role of action in the perception of space-related attributes like orientation, curvature, size, or depth and it is now common to think that space perception involves adaptable sensorimotor mechanisms. On the other hand, the influence of action on color perception has never been successfully addressed experimentally. Classical attempts were made to modify the perceived color as a function of gaze direction, that is, not properly on action but on proprioception. To this purpose, Kohler (1962) had one subjects wear left-field yellow/right-field blue goggles for several weeks and

obtained the desired shift: white adjustments differed depending on gaze direction (left versus right). However, his results failed to be replicated by better-controlled attempts (McCullough, 1965), even with longer exposure (Harrington, 1965). However, the consequences of an involvement of action—essentially eye movements—in color perception have been discussed at several occasions in philosophical work (Broackes, 1992; Hurley, 1998; Myin, 2001) and artificial vision (Clark & O'Regan, 2000; Skaff, Arbel, & Clark 2002), in particular as a way to achieve color constancy using the nonuniformity of retinal sampling.

In a recent series of experiments, Bompas and O'Regan (2006) also had subjects wear left-field yellow/right-field blue spectacles but for a different purpose. Half-split colored spectacles introduce a correlation between gaze direction and color, but as McCullough (1965) showed, no contingent adaptation linking these two kinds of sensory inputs can be obtained. However, the change introduced by the spectacles can be described in a slightly different way: they create a contingency between eye saccades—from one visual hemifield to the other—and color changes. Contrary to the first-mentioned contingency, absolute and static, this second one, relative and dynamic, proved to be easily subject to adaptation (Bompas & O'Regan, 2006). The test stage of these recent experiments involved the successive presentation, on each side of a computer screen, of two patches whose color the subjects had to compare

using an eye saccade. Forty minutes of exposure with the spectacles proved to be enough to measure consistent shifts in subjective equality. The shifts were in opposite directions for left/right and right/left eye saccades. A control experiment confirmed, with the same 40-min exposure stage with the spectacles, the failure to measure shifts in absolute color judgments, that is, on single patches presented on the left or on the right. These results showed that Kohler (1962) was wrong considering that adaptation to the split-field spectacles could be adequately described according to the “situational conditioning” hypothesis, as a form of color adaptation contingent on gaze direction or position in external space. Instead, the effect of the spectacles seems to be better described as a sensorimotor adaptation. This suggests that, in this particular example, the visual system is more sensitive to sensorimotor contingencies than to sensory correlations.

In Bompas and O'Regan (2006), as in Kohler's (1962), a large part of the visual field was tinted yellow when the subject gazed leftward and tinted blue when the gaze was directed rightward. A problem could have come from the fact that whereas the spectacles allowed the central retina to be equally adapted to blue and yellow, this was not the case for periphery: for example, when the eyes gazed leftward, a small part of the blue glass was still visible on the right side of the visual field and could not be removed. This had the consequence that the right periphery was more adapted to blue, and the left periphery to yellow, causing an asymmetry that may have been at the root of some part of the observed effects. In the present experiment, we avoided the problem of nonhomogeneity of adaptation of the peripheral retina by using a computer-controlled adaptation method. In this, we presented only a single colored patch at a time: one colored patch when the eyes gazed leftward and another one when the eyes gazed rightward. This procedure permits more precise control of retinal stimulation. The method used is also simpler, can be easily replicated, and allows more flexibility in further study of the effect.

Experiment 1 is a computer-controlled replication—with red and green—of our earlier spectacle experiment. The adaptation stage involves repeated eye movements between red patches on the left and green patches on the right. The test trials involve the same time sequence and positions on the screen as in adaptation trials. **Experiment 2** is a control experiment where (a) in the adaptation stage, the eyes are kept fixed in the center of the screen during the appearance of the colored patches in periphery. The test trials are identical to those in **Experiment 1**. The experiment is intended to show that nonhomogeneities in retinal adaptation cannot explain the effect found in **Experiment 1**. Indeed, such uncontrolled nonhomogeneities could have occurred in **Experiment 1** as a consequence of performing the eye saccades slightly before the disappearance of the first patch or slightly after the appearance of the second patch. **Experiment 3** is another control experiment where the adaptation stage is identical to that in **Experiment 1** and test trials are made from the center to the periphery. The pur-

pose of this experiment is to show that the effect depends on movement and not on position. It involves testing the effect with a different pair of departure and arrival positions of the eye saccade than used during adaptation. The experiment aims to show that the effect cannot be understood as the learning of a regularity between colors and sides of the screen (conditioning) or as the adaptation to the correlation between color and position in space or even between colors and position of the eyes in the orbits (sensori-sensorial adaptation).

Methods

Observers

Thirty-four subjects participated in the three experiments, including 10 subjects in **Experiment 1**, 11 subjects in **Experiment 2**, and 13 subjects in **Experiment 3**. All the subjects were Psychology students, naive to the purpose of the experiments, and were not paid for their participation. One subject in **Experiment 2** and three subjects in **Experiment 3** were excluded because their psychometric function slopes were too small, indicating they had difficulties in doing the color discriminations necessary to determine the point of subjective equality (PSE). All the subjects spent 15 min in the dark room before the beginning of the experiment during which the task was explained to them.

General procedure

The experiments fell into three parts: a 40-min adaptation stage was preceded and followed by a 5-min test phase. The comparison between pretest (t_0) and posttest (t_1) permitted us to measure the effect of adaptation on perceptive judgments. During adaptation and test stages, eye movements were not measured by an eye-tracker but, when required, were imposed by the task, which was designed not to be feasible without proper eye movements.

Stimuli

The stimuli were generated using Matlab with the psychophysics toolbox extension (Brainard, 1997; Pelli, 1997) on a PC. They were coded with 24-bit precision and were presented on a CRT display (NVidia Vanta, 80 Hz refresh). The subject's head was stabilized by a chin rest. The viewing distance was 30 cm. Luminance (Y) and chromaticity coordinates (x , y) were measured with a Minolta CS-100 photometer with close-up lens N°110. The experiments were conducted in a dark room. All the stimuli were 10 deg wide, round, isoluminant ($Y = 2.6 \text{ cd.m}^{-2}$) patches and were presented for 400 ms on a black background ($Y = 0.03 \text{ cd.m}^{-2}$). The patches varied in hue and were presented with varying eccentricities.

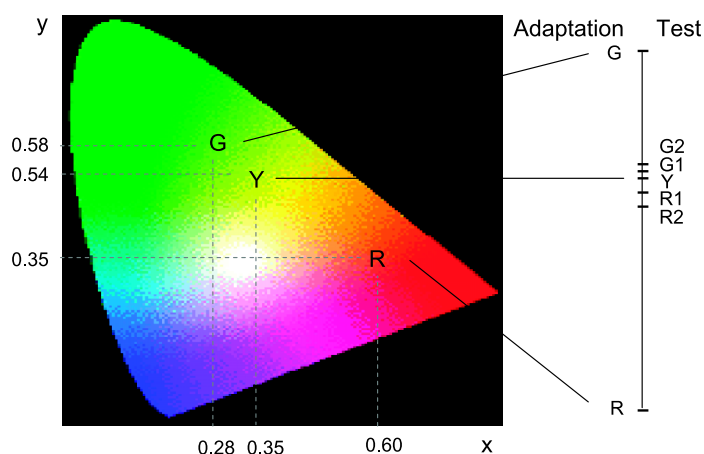


Figure 1. Chromaticity coordinates of stimuli in adaptation and test stages (CIE 1931).

Adaptation stage

The adaptation stage involved red or green patches (R: $x = 0.60$, $y = 0.35$; G: $x = 0.28$, $y = 0.58$) relative to the chromaticity coordinates in the CIE 1931 system, see Figure 1. The patches were presented centered at 12 deg eccentricity, on the left side for the red patches and on the right side for the green patches. The patches could be either perfectly round or slightly oval.

Test stage

The colors used in the test stage involved five unsaturated colors that were mixtures of the two equiluminant lights R and G used during adaptation (Figure 1). Y ($x = 0.35$, $y = 0.54$) was a neutral yellow. R1 and R2 were two different hues chosen between Y and R, whose distance from Y represented 5% and 10% of YR, that is, of the distance between Y and R in the CIE 1931 space. G1 and G2 were two different hues of yellows at 5% and 10% of YG. (Percentage values along these axes were taken as an arbitrary metric, which we did not assume to reflect a perceived color-difference metric. Such a metric was not required in the present experiments.) All the patches were round. In Experiments 1 and 2, the patches were presented at 12 deg eccentricity, on the left side or on the right side of the screen. In Experiment 3, the patches were presented first in the center of the screen and then at 24 deg eccentricity, on the left or on the right side of the screen.

Procedure

Adaptation stage

Each adaptation trial involved the successive presentation of two patches, either first on the left and then on the right

side of the screen, or the opposite. The patches presented on the left were always red whereas the patches presented on the right were green (Figure 2).

In Experiments 1 and 3, the subjects were given a task involving repeated eye movements from the red patch to the green one or reciprocally, namely, a form comparison task between the two patches. The purpose of the adaptation stage in both Experiments 1 and 3 was to introduce a correlation between left-to-right (respectively right-to-left) saccades and red–green (respectively green–red) color changes. The subjects' task was to report if, for each trial, the forms of the two patches (round or oval) were the same or different. The subjects received feedback. The difference between the circular and the oval patches was small and both patches appeared for only 400 ms, so that the task was not feasible without gazing directly at the patches and making the eye movement explicitly required by the task. The subjects were asked to move the eyes so as to “always look directly at each patch when it appeared.” They were explicitly asked to anticipate the appearance of the patches, using the arrows at the beginning of each trial to make a saccade before the first patch appeared and then to move the eyes back again before the second patch appeared on the opposite side of the screen.

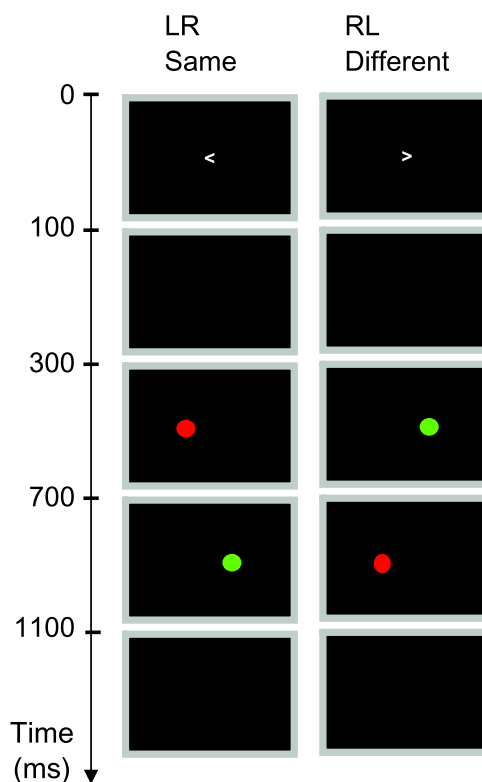


Figure 2. The time sequence of adaptation trials in Experiments 1 and 3. Left/red and right/green patches are presented successively, either in the left–right order (LR) or the right–left order (RL). Left: left–right trial with two round patches. Right: right–left trial with a round patch on the right and an oval patch on the left. Subject's task is a form comparison.

The time sequence of adaptation trials is illustrated in [Figure 2](#): A small arrow (0.36 deg) indicated the side of the first patch, whose appearance was immediately followed by the second patch. The subjects responded by pressing the upper (same form) and lower keys (different forms).

In [Experiment 2](#), subjects were given a different task that involved no eye movement, namely, the detection of a small “+” (0.36 deg) that appeared randomly at the location of the arrow for 100 ms ([Figure 3](#)). The subjects responded by pressing the upper (target present) and lower keys (target absent).

Test stage

To measure the effect of the adaptation stage, direction of eye saccade, color changes, and positions on the screen were manipulated. The subjects received the same instructions concerning eye movements and anticipation as they did in the adaptation stage.

In [Experiments 1](#) and [2](#), each test trial involved the successive presentation of two patches, either first on the left and then on the right side of the screen (LR), or in the right-to-left order (RL). The five color changes used in the test stages were G2R2, G1R1, YY, R1G1, and R2G2, corresponding respectively to -10% , -5% , 0% , $+5\%$, and $+10\%$ of the color change RG used during adaptation.

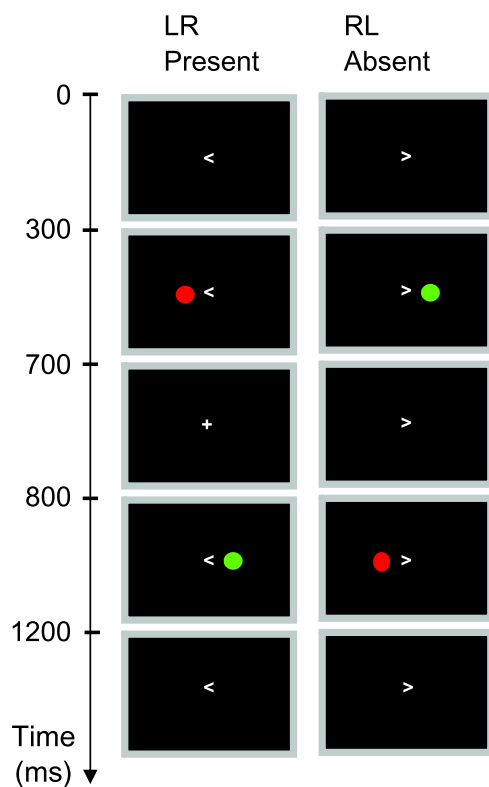


Figure 3. The time sequence of adaptation trials in [Experiment 2](#). Subjects were required to detect the presence of a target in the center of the screen. Left: left–right trial with target present. Right: right–left trial with target absent.

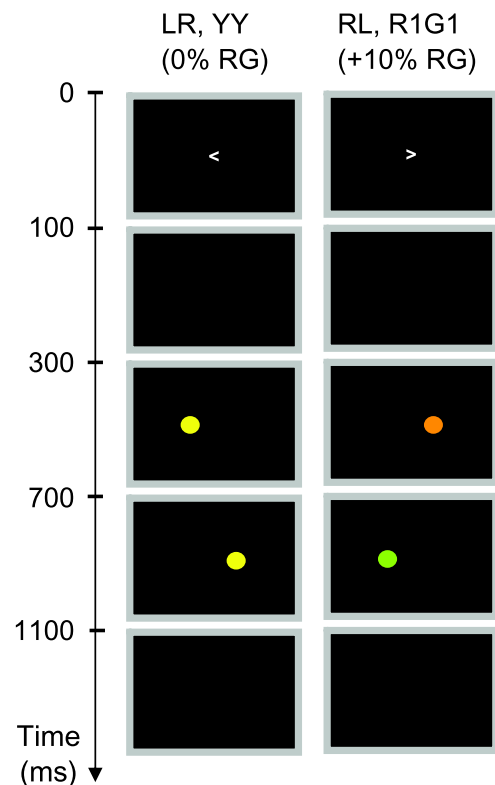


Figure 4. The time sequence of test trials in [Experiments 1](#) and [2](#). Left: left–right trial without color change (the two patches are neutral yellow). Right: right–left trial with the large color change from reddish to greenish yellow, color change corresponding to $+10\%$ of RG.

The time sequence of test trials in [Experiments 1](#) and [2](#) is illustrated in [Figure 4](#): An arrow indicated the side of the first patch, whose appearance was immediately followed by the second patch. The subjects’ task was to determine if the second patch was redder or greener than the first patch. The subjects responded by pressing the upper (greener) and lower keys (redder). Each color change was presented 18 times in each of the left–right (LR) and the right–left (RL) orders.

In [Experiment 3](#), the time sequence of test trials was identical but the first patch always appeared in the center of the screen whereas the second patch could appear on the right (CR’ trials) or on the left (CL’), at the position indicated by the arrow preceding each trial. The position of the second patch was chosen so that the saccadic vector between the two patches remained the same as in the adaptation stage and the previous test stages (CR’ = LR, CL’ = RL, see [Figure 5](#)).

Predictions

In the pretest, no difference is expected between LR and RL conditions and the proportion of “greener” answers is expected to be 50% in both directions. During the adaptation

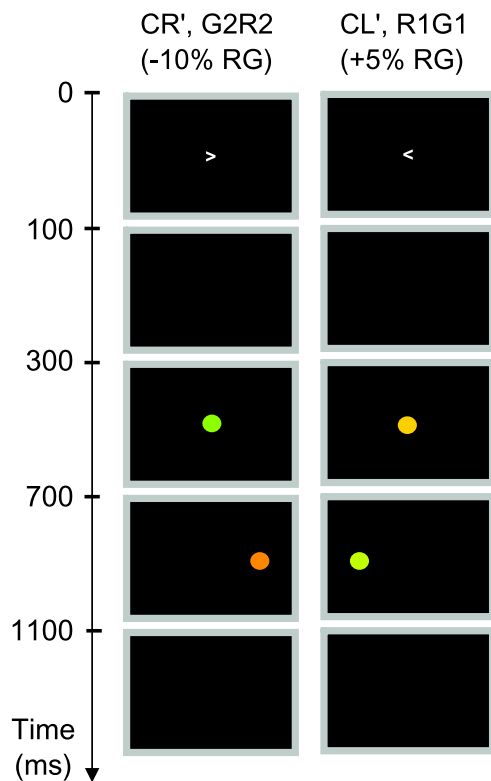


Figure 5. The time sequence of test trials in Experiment 3. Left: center-right trials with the large color change from greenish to reddish yellow. Right: center-left trial with the small color change from reddish to greenish yellow.

stage, left–right (respectively right–left) eye saccades are correlated with a color change from red to green (respectively from green to red). If the visual system adapts to this correlation, the effects of an LR and RL eye movements are expected to be opposite. In particular, on a given trial, when both patches are neutral yellow (YY trials), the colored illusion should result in responding “redder” in LR and “greener” in RL, among the four possible patterns of answers. If perceptual adaptation occurs between the pretest and the posttest, the proportion of “greener” answers is expected to increase in RL trials and to decrease in LR trials. Adaptation is established if (1) differences between test stages before and after adaptation are obtained and if (2) these differences are opposite for LR and RL trials, pointing in the same direction as our predictions.

Results

Experiment 1: With eye movements

Nine of 10 subjects gave the predicted pattern of answers (“redder” in LR and “greener” in RL) for the two first YY trials of the posttest, just after adaptation. On the other hand,

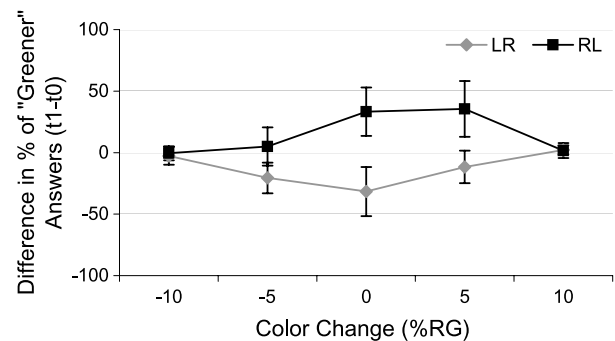


Figure 6. Experiment 1: Effect of adaptation is measured by the difference in the percentage of “greener” answers between pretest (t_0) and posttest (t_1). Mean effect of a 40-min adaptation with eye movements is presented as a function of color change for left–right (LR) and right–left (RL) eye movements. Error bars indicate one standard deviation on either side of the mean calculated across the 10 subjects.

on the last YY trials of the pretest, only one subject answered this way.

As a first analysis, differences in the proportion of “greener” answers between pretest (t_0) and posttest (t_1) were calculated for each subject, color change, and direction of eye movement. The mean differences introduced by the adaptation stage are presented as a function of the color change in Figure 6. Color judgments were modified by the adaptation stage in accordance with our predictions and opposite effects were observed for LR and RL directions. Large color changes (-10 and $+10\%$ RG) were less affected, indicating that they remained correctly perceived even after adaptation.

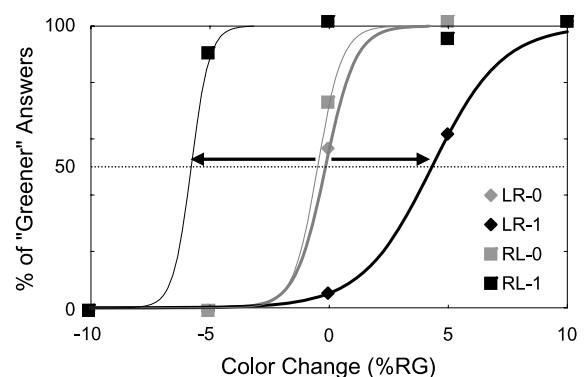


Figure 7. Illustration of the PSE shift determination on one subject. Data points represent the percentage of “greener” responses for the five color changes used corresponding to -10% , -5% , 0% , $+5\%$, and $+10\%$ of YgBg. Data (symbols) are fitted with sigmoids (lines) for left–right (LR, thick) and right–left (RL, thin), before (0, grey) and after (1, black) adaptation. The PSE is the color change corresponding to 50% “greener” answers. The PSE shift is the difference in PSE between t_0 and t_1 , represented by the arrows.

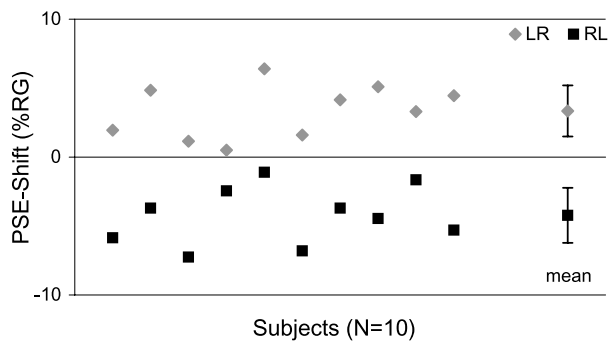


Figure 8. **Experiment 1:** PSE shifts for left-right (LR) and right-left (RL) eye movements induced by 40-min adaptation with eye movements, for each of the 10 subjects, and mean PSE shifts with error bars indicating one standard deviation on either side of the mean calculated across the 10 subjects.

To statistically quantify the effect, we fitted the percentage of “greener” responses as a function of the color change with a sigmoid and obtained the PSE, as illustrated for a single subject in [Figure 7](#). The PSE is interpreted as the physical color change that would be perceived as nonchanging by the subject. The PSE shift is the difference between pretest and posttest and quantifies the effect of the adaptation stage.

The mean PSE shift was compared for LR and RL ([Figure 8](#)), showing significant differences, $F(1,9) = 131$, $p < 0.001$. For LR eye movements, the mean PSE shift is significantly positive, mean = 3.4%, $F(1,9) = 29.2$, $p < 0.001$, indicating that subjective equality is obtained for chromaticity changes that were perceived before exposure as “reddish yellow to greenish yellow changes” (positive percentage of RG), that is, for the type of changes imposed during adaptation when moving the eyes from left to right. Conversely, the mean PSE shift for RL is negative, mean = -4.2%, $F(1,9) = 40.4$, $p < 0.001$. This confirms that adaptation has occurred, the color change encountered during the adaptation stage being partly compensated.

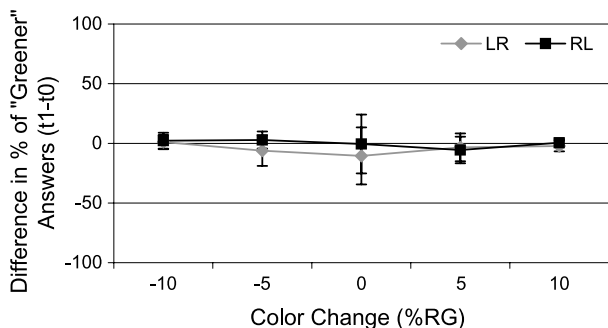


Figure 9. **Experiment 2:** Mean effect of a 40-min adaptation without eye movements as a function of color change for left-right (LR) and right-left (RL) eye movements. Error bars indicate one standard deviation on either side of the mean calculated across the 10 subjects.

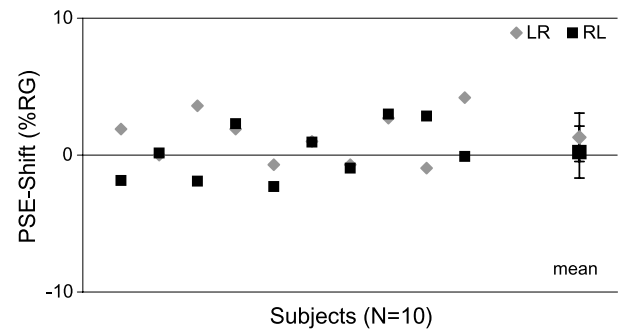


Figure 10. **Experiment 2:** PSE shifts for left-right (LR) and right-left (RL) eye movements induced by 40-min adaptation without eye movements, for each of the 10 subjects and mean PSE shifts with error bars indicating one standard deviation on either side of the mean calculated across the 10 subjects.

Experiment 2: Control without eye movement

When the eyes are kept fixed in the center of the screen during the appearance of the red and green patches, a strong nonhomogeneity in retinal adaptation is created. However, no effect on color judgment is obtained. In this experiment, only 3 of 10 subjects answered both “redder” in LR and “greener” in RL on the first YY trials of the posttest.

This absence of significant effect can also be seen in [Figure 9](#), showing the effect of the adaptation stage for each color difference in the test stage. The PSE shifts confirm this absence of effect. In the LR condition, a small, not quite significant PSE shift is obtained, mean = 1.3%, $F(1,9) = 4.83$, $p < 0.06$, whose presence is not confirmed in the RL condition, mean = 0.22%, $F(1,9) = 0.12$, $p > 0.5$, as illustrated in [Figure 10](#). Moreover, no significant difference is observed between LR and RL, $F(1,9) = 1.53$, $p > 0.2$. Also, the effect of adaptation without ([Experiment 2](#)) and with ([Experiment 1](#)) eye movements differed significantly for both LR, $F(1,18) = 5.76$, $p < 0.05$, and RL conditions, $F(1,18) = 23.39$, $p < 0.001$.

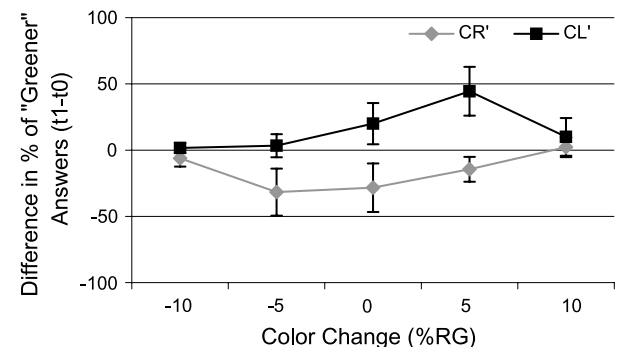


Figure 11. **Experiment 3:** Mean effect of a 40-min adaptation with eye movements as a function of color change for center-right (CR') and center-left (CL') eye movements. Error bars indicate one standard deviation on either side of the mean calculated across the 10 subjects.

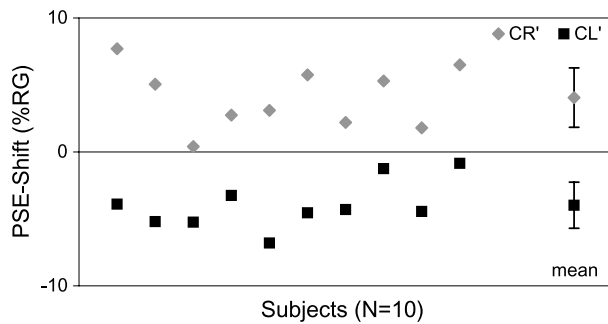


Figure 12. **Experiment 3:** PSE shifts for center-right (CR') and center-left (CL') eye movements induced by 40-min adaptation with eye movements, for each of the 10 subjects and mean PSE shifts with error bars indicating one standard deviation on either side of the mean calculated across the 10 subjects.

Experiment 3: With eye movements from center to periphery

In this experiment, we adapted the subjects with the left–right adaptation stage but the effect was measured in the test stage with center-to-periphery (center-to-right, CR' and center-to-left, CL') eye movements. Here again, 8 of 10 subjects gave the predicted answer on the two first YY trials of the posttest.

As can be seen in [Figure 11](#), the effect of the adaptation stage in [Experiment 3](#) is the same as in [Experiment 1](#) (the two experiments do not differ significantly), where positions were identical in test and adaptation stages. Here also a positive PSE shift is obtained in the CR' condition, mean = 4.1%, $F(1,9) = 30.09$, $p < 0.001$, whereas PSE shift is negative in the CL' condition, mean = -4.0%, $F(1,9) = 48.34$, $p < 0.001$, the difference between CR' and CL' also being significant, $F(1,9) = 131$, $p < 0.001$, as shown in [Figure 12](#).

Discussion

Interpretation of the results in terms of sensorimotor adaptation

The effect, obtained as a consequence of the adaptation stage, consists of significant changes in color judgments that exhibit a strong dependency on the principal manipulated factor, that is, the direction of eye movements. Before we consider the question of its perceptual amplitude, let us discuss the possible interpretations of this effect. Because we obtained a perceptual adaptation contingent on motor properties, our effect can be considered eligible for “sensorimotor adaptation.” Before this can be established, two alternative interpretations must be excluded, which was the purpose of [Experiments 2](#) and [3](#). The first interpretation would attribute the origin of the effect to a purely

sensory, low-level adaptation (retinal adaptation for example). The other interpretation would involve the contingent adaptation of color perception to position: position of the patches in the external space or position of the eyes in the orbits.

Excluding the retinal interpretation

The best way to exclude the sensorial interpretation would have been to provide to the retina the same stimulation as in the active adaptation trials but without eye movements. However, in our case, this hard task was not necessary because we can presume that the central retina was equally adapted to red and green and that nonhomogeneities in adaptation only concerned the left and right retinal peripheries. We therefore chose to induce local, strong non-homogeneities in periphery to show that they could not produce the effect found in [Experiment 1](#). These non-homogeneities were not designed to mimic those produced in [Experiment 1](#). It is reasonable to presume that they were locally stronger and spatially less distributed because the eyes were fixed during the appearance of the patches. However, failure to obtain an effect in this condition makes a retinal interpretation implausible.

Moreover, two aspects of the present experiment appear incompatible with the retinal interpretation: the time required for the adaptation stage and the duration of the effect. First, the effect cannot be obtained with a short adaptation stage. This was shown by a replication we did of [Experiment 1](#) on five subjects with the entire pretest, an exposure stage of 1 min (16 trials) and just a few posttest trials. We found that only one of five subjects responded in a way that was characteristic of the occurrence of adaptation. We saw no point in trying to obtain, with a 10-min test stage, PSE shifts potentially induced by a 1-min adaptation stage. Secondly, the duration of the effect proves to be longer than what would be expected from a retinal interpretation: if one considers now the two last YY trials of the posttest, 10 min after the end of the adaptation stage, 10 of 20 subjects in [Experiments 1](#) and [3](#) still give the expected response.

Movement versus position

In [Experiment 3](#), we modified the position of the patches in the test stage to confirm that the effect was not linked to absolute, static information but involved relative, dynamic motor information. [Experiments 1](#) and [3](#) differed in the arrival and departure positions of the eye saccade performed to go from the first patch to the second patch in the test stage. In [Experiment 1](#), the pairs of positions were identical in the adaptation and test stages, whereas they differed in [Experiment 3](#). The obtained results were similar, which shows that the effect does not depend on this factor. Further experiments may now show that the effect depends instead on the properties of the eye saccades, that is, orientation and size.

To confirm this involvement of a motor component in adaptation, [Experiment 1](#) might be replicated with the insertion of a time delay between the disappearance of the first patch and the appearance of the second patch in the exposure stage. This would allow the same association between color and side to be kept but would weaken the sensorimotor contingency between eye saccades and color change.

Amplitude of the effect

As a first approximation, we can assume that the pair of yellows that look similar across the eye saccade are given by the PSE. Here the mean PSE shifts are 4% of the red–green distance introduced during adaptation, ranging from 1% to 6% depending on the subjects. Before we comment on these percentages, several precautions must be taken. First, the limited number (five) of color changes used in the test trials may have constrained the subjects' responses so that the effect stayed within the limits of the proposed changes. Secondly, distance in CIE space is not a color-difference metric and therefore does not ensure a linear progression of the perceived color difference from 0% to 5% and 10%. For these reasons, the amplitude of the colored illusion cannot be directly derived from the mean PSE shifts. However, to evaluate the “visibility” of the effect, it is interesting to notice that a 4% change, if presented before adaptation, would have been correctly identified at 84% by the mean observer. This figure is the mean percentage of correct answers given by the sigmoids obtained when fitting the pretest data of each of the thirty subjects. It indicates that the color change perceived as nonchanging after the adaptation stage was clearly identifiable by the mean subject before adaptation.

General discussion

Relation to previous experiments

The results observed in the present study confirmed the conclusion of our previous spectacle experiment (Bompas & O'Regan, 2006): The method we used produced a perceptual change that can neither be interpreted as a purely physiological adaptation of cone sensitivity nor as a conditioning between color and position in space (or between retinal and proprioceptive information). The present results also permit three new conclusions.

First, sensorimotor adaptation can be obtained with a very simple artificial stimulus without any relation to the real world and without the subject being engaged in active color-oriented exploration.

Secondly, adaptation requires neither the presentation of a large color set, nor the stimulation of the whole visual field. Whereas we do not know the effect of these two parameters, we can already conclude that a single color pair stimulating a

small part of the visual field is enough to obtain a measurable effect. It can be added that the use of a single color pair does not prevent the effect to generalize to the “in-between” colors, as obtained by mixing the two colored lights used, as is the case here for yellow.

Thirdly, the effect works at least for both red/green and blue/yellow. This conclusion seems trivial at this point. However, Kohler (1962) justified his choice for blue and yellow by assuming that adaptation to the half-split colored goggles involved the same mechanisms as those responsible for adaptation to the blue and yellow fringes produced by prisms—and the optics of normal eyes—on vertical contrasts. Moreover, the color differences induced by the macular pigment between central and peripheral vision also involve the blue/yellow dimension. Furthermore, blue/yellow and red/green perceptive dimensions are believed to concern different channels, which are different functionally and from an evolutionary point of view, and which could therefore behave differently toward eye movements. The possibility that similar sensorimotor adaptation might be induced for any arbitrarily chosen color pair(s) remains to be tested.

Theoretical developments

These experiments were essentially motivated by the hypothesis that the induced sensorimotor adaptation mimics a generally occurring natural process of learning the sensorimotor contingencies between eye movements and changes in the retinal input (O'Regan & Noë, 2001). What could be the purpose of such learning? Consider holding a uniformly colored piece of paper in a room illuminated both by the natural light of a sunny day and the artificial lighting of the room. When moving the eyes along the nonhomogeneously illuminated surface, the reflected spectrum received by the observer varies in a way that is defined by the physical laws obeyed by light reflection from this surface—laws that are specific to the reflectance of the paper. Whereas the reflected light spectrum, at any given moment, does not unambiguously specify the reflectance of the surface, specification of the surface could be improved by moving the eyes along it, thereby effectively increasing the number of light sources illuminating the surface. We thus propose that eye movements provide a good way to improve the determination of the reflectance properties of environmental surfaces. Eye movements could allow the visual system to take advantage of the nonuniformities in both the illuminant and the eye (Roorda & Williams, 1999) to achieve color constancy, as proposed by Skaff et al. (2002). According to this, our effect is interpreted as the adaptation of mechanisms continuously tuned to sensorimotor dependencies and at work in normal color vision.

The next step in the development of a sensorimotor theory of color vision will be to determine the possible involvement of these mechanisms in the active constitution of perceptual color space. According to this, future work will address the hypothesis that a perceptual organization, defining the

relations of similarity and distance between the surfaces, can emerge from the statistics in the reflection properties experienced by an observer throughout his life. Related ideas have been successfully applied to provide an explanation of unique hues from singularities in the reflection properties of surfaces, as can be found in Philipona and O'Regan ([in press](#)).

Acknowledgment

We thank David Philipona for comments and suggestions.

Commercial relationships: none.

Corresponding author: Aline Bompas.

Email: aline.bompas@tuebingen.mpg.de.

Address: MPI for Biological Cybernetics, Department of Bülthoff, Spemannstraße 38, 72076 Tübingen, Germany.

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