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Dependence of Perceived Purity of a Chromatic Stimulus on Saturation Adaptation

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Summary. *Background and Objective.* The purpose of sensory adaptation of the visual system is to adjust sensitivity of the photoreceptors to optimize the dynamic range of response of the visual system. It has been shown in numerous research papers that chromatic adaptation influences both color appearance and color discrimination. However, there are almost no studies in which the influence of chromatic adaptation on perceived purity has been investigated. Therefore, the aim of this study was to investigate how chromatic adaptation to stimuli with certain saturation influences perceived purity of test stimuli with the same hue but different saturation.

Material and Methods. As the stimuli were modulated in saturation only, we refer to the type of chromatic adaptation used in our study as saturation adaptation. Two types of psychophysical methods – the method of adjustment and the method of constant stimuli – were used.

Results. The results obtained with the method of constant stimuli reveal that saturation adaptation seems to be nonlinear much the same way as the Bezold-Brücke and the Abney effect. In addition, hysteresis of saturation adaptation can be observed in the method of adjustment.

Conclusions. Pronounced hysteresis of perceived color purity was observed when approaching to the point of subjective equality from the side of low saturation of the matching stimulus compared with the side of high saturation of the matching stimulus. There was a time course of mechanisms of saturation adaptation similar to those of chromatic adaptation previously quoted in literature.

Introduction

Adaptation is a feature characteristic to all living bodies. Sensory adaptation is a common feature of all sensory systems including the visual system. Sensory adaptation adjusts the threshold of sensitivity of receptors (1–4). The resultant relationship between the response of the sensory system and the input signal may be complex and depends on the response of each subsystem. What regards to vision, sensory adaptation may be divided into several classes: luminance adaptation, chromatic adaptation, contrast adaptation, etc. The consequence of luminance adaptation is difficulties to see objects in a darkened room after adaptation to a bright light, and eye pain when looking into a bright light after dark adaptation. In much the same way, chromatic adaptation is responsible for a number of effects on color appearance (5). The basis of chromatic adaptation is regulation of sensitivity of each class of photoreceptors independently according to the intensity of the surrounding light. Regulation of sensitivity is accomplished by controlling the gain of the response of photoreceptors. The gain control is modeled by the Michaelis-Menten equation and the Von Kries

model and is nonlinear (6–8). At the first moment, the visual system may seem to be linear. However, this is generally true for a limited range of values of a stimulus, and when entering into extreme regions where the stimulus values are very large or very small, the nonlinearities of the visual system are observable. For example, two well-known color vision effects – the Bezold-Brücke and the Abney effect – result from nonlinear characteristics of the human visual system and are described in more details by Siminoff (9) and Knottenberg and Scheibner (10). Shortly, the Bezold-Brücke effect is related to the change of a hue along with light intensity, while the Abney effect is a change of a hue due to changes of saturation. We wanted to know if nonlinearities of visual processes, which are the basis of these nonlinear effects, also cause nonlinear perception of purity of chromatic stimuli.

Chromatic adaptation has been shown to influence the attributes of chromatic stimuli such as color appearance (11–14) and color discrimination (15, 16). Loomis and Berger investigated whether there is analogy between luminance adaptation and chromatic adaptation (15). They found not only that color discrimination is the best around the adapting chromaticity, but also is worsened when moving away from it. Hita et al. (17) investigated capabilities

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of the observer to discriminate successive stimuli after adaptation to a variety of stimuli. They found that adapting to red background diminished the overall capacity to discriminate between successive colors, whereas adapting to stimuli with other color, produced the changes of capability to discriminate colors depending on chromaticity of the adapting stimulus.

Among all studies related to the effects of chromatic adaptation on color appearance, there are almost no studies investigating the effect of chromatic adaptation on perceived color purity. Since there are so few papers related to perception of purity, we were interested in the dependence of perceived purity on chromatic adaptation. In our study, perceived purity of 2 stimuli (a referent and a matching stimulus) under different states of chromatic adaptation was compared. Under all states of chromatic adaptation, we looked for the point of subjective equality (PSE) defined as a condition when the subject perceives both stimuli equally pure. We also define a difference $D = S_R - S_M$ at the PSE (we here denote saturation of the referent stimulus by S_R whereas that of the matching stimulus by S_M). As a measure of saturation, we chose the length of vector joining the white point and location of the stimulus in CIE diagram expressed as percentage of the length of the vector joining the white point and the red phosphor.

In order to avoid possible confusion of purity and hue, we chose the adapting and test stimuli lying on the same axis joining the white point and the location of the red phosphor. Such a type of chromatic adaptation when both the adapting and test stimuli have one and the same hue but different saturation we called saturation adaptation. In our study, we hypothesize that saturation adaptation is nonlinear in

the same way as the Bezold-Brücke and Abney effects are. The aim of this study was to determine the time course of saturation adaptation and to make hypothesis about its possible location in the human visual system.

Material and Methods

Subjects. Altogether 4 subjects – 3 women and 1 man (V.K., G.K., I.Z., and M.K.) – took part in the experiments. All of them had the best-corrected visual acuity of 20/20 or higher. The subjects were aged between 21 and 48 years. A critical precondition for subject's suitability for the experiment was normal trichromasy. All subjects were tested for any possible color deficiency with the Farnsworth color vision test, and no one showed any color vision anomalies.

The Method of Adjustment. During the whole experiment, the subject fixated at the small white dot. The experiment started with a blank screen lasting for 10 seconds, which was followed by a demonstration of the referent and the matching stimulus. Saturation of the referent stimulus S_R was kept constant all the time. As the time progressed, saturation of the matching stimulus S_M either decreased from 1 to 0.5 or increased from 0.5 to 1 linearly at a rate of 0.05 per second (Fig. 1). At the time moment $t = t_0$ when the subject had reached the PSE, the difference D was saved in an ASCII file. The difference D was negative if saturation of the referent stimulus was lower than that of the matching stimulus and positive in the opposite case. The experiment with the method of adjustment was performed for S_R values ranging from 0.7 to 0.95 in steps of 0.05. For each value of S_R , the adjustment procedure was repeated for 10 times.

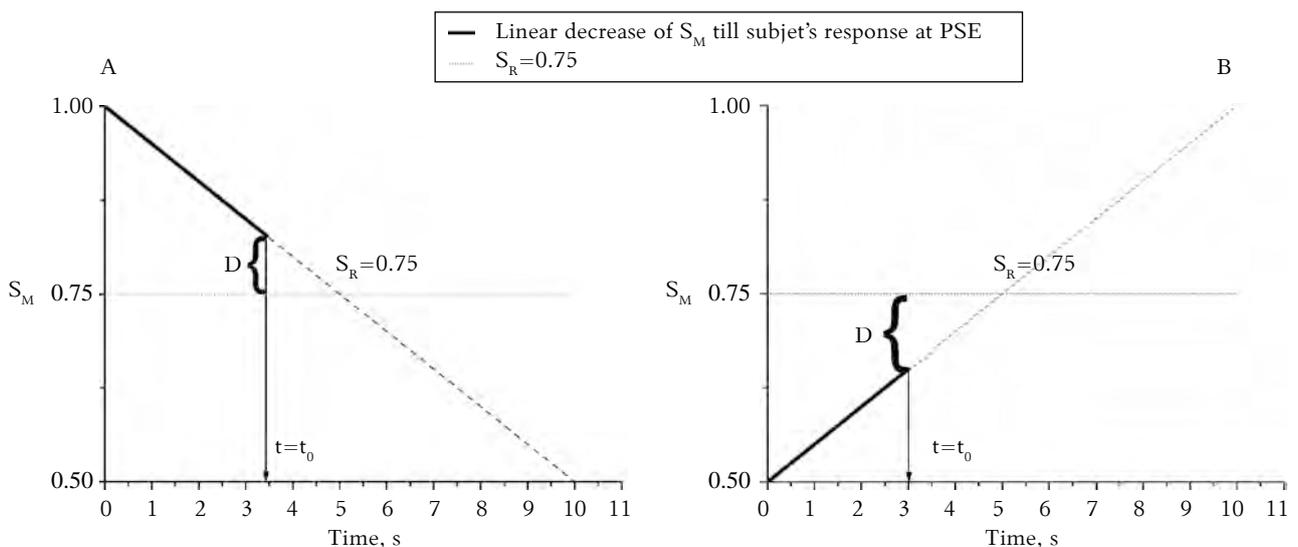


Fig. 1. Procedure in the experiment with the method of adjustment

At time moment $t=0$, saturation of the matching stimulus S_M started either to decrease (A) or increase (B). Saturation of the referent stimulus S_R was always kept constant.

The Method of Constant Stimuli. To determine the characteristics of the time course of saturation adaptation, the method of constant stimuli was used. As in the previous experiment, the subject fixated the small white dot during the whole experiment. The experiment consisted of 3 separate phases as shown in Fig. 2: blank screen, adapting phase t_a , and test phase t_t . The blank screen lasted for a period $t_b = 10$ s. During the adapting phase, the subject saw the referent stimulus with $S_R = 0.75$ and the adapting stimulus with $S_M = 0.5$. Duration of the adapting phase varied from 0.25 to 1.25 seconds in steps of 0.25 second. The adapting phase was followed by the test phase. The start moment of the test phase was marked by a loud beep. During the test phase, the subject saw the referent stimulus with $S_R = 0.75$ and the matching stimulus. Saturation of the matching stimulus S_M varied stepwise from 0.5 to 1 in steps of $1/36$. As the test phase started, the subject had to give an answer to a question whether the matching stimulus looked more pure than the referent stimulus, or not. The subject was instructed to give the answer as soon as possible to minimize adaptation effects during the test phase. The answer was given by pressing the appropriate key on a keyboard. As a new test phase started, saturation of the matching stimulus was randomly chosen by software. By using the collected data, psychometric functions were measured, and the difference D was found at the PSE.

Stimuli. Software for generating and presenting the stimuli was written in Microsoft Visual Basic v6.0 DirectDraw. Stimuli were presented on an IBM ThinkPad (model R50e) LCD monitor driven by an

Intel 82852/82855 GM/GME Graphics Controller.

In both psychophysical methods of our studies, a referent and a matching stimulus was used. Both stimuli were uniformly colored with an angular size of each stimulus 8° as viewed from a distance of 40 cm. The centers of both stimuli were 40° apart from each other. The stimuli were viewed against a black background, and the subject had to fixate a small white dot at the center of the referent stimulus. The subject was adapted under different conditions, i.e., the referent stimulus was more saturated than the matching stimulus or vice versa. In one of the experiments, the referent stimulus had constant saturation while saturation of the matching stimulus changed linearly. In the second experiment, both stimuli had constant saturation during the adapting phase, but the duration of the adapting phase could be varied. During the experiments, chromatic coordinates of both stimuli were modulated along the axis joining the white point and the red phosphor. Luminance of both the referent and the matching stimulus was kept constant $Y = 40$ cd/m². The room was darkened, and illumination was 20 lx so that peripheral stimuli did not sidetrack attention from the stimuli. The walls of the room were neutral gray.

Calibration. Chromatic coordinates of the stimuli monitor were measured by a chromometer Minolta (model CS-100A) providing information about CIE xyY chromatic coordinates of the stimulus. Chromatic coordinates were as follow: white $[x, y] = [0.327, 0.348]$; red $[x, y] = [0.590, 0.350]$; green $[x, y] = [0.324, 0.542]$; and blue $[x, y] = [0.159, 0.143]$. Luminance of the stimuli was always kept constant $Y = 40$ cd/m².

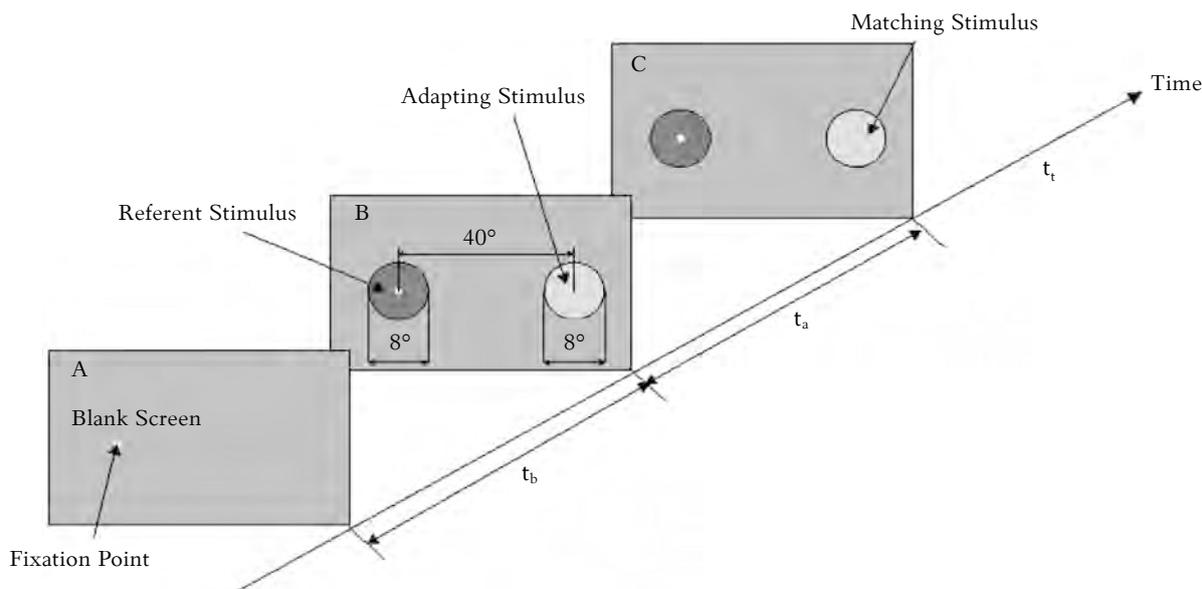


Fig. 2. The sequence of phases in the experiment with the method of constant stimuli
A, blank screen lasting for $t_b = 10$ seconds; B, adapting phase t_a ; C, test phase t_t .

Experimental Conditions. The head was supported on a chin to rest so that the same retinal regions were always adapted and tested. However, small movements of the head and the eyes were still present and could have an influence on the data obtained. The experiment was carried out binocularly.

Results

The Method of Adjustment. The dependence of the difference D on saturation of the referent stimulus S_R for both directions of adjustment is shown in Fig. 3. The black circles show the results when saturation of the matching stimulus increased from 0.5 to 1, while the black squares show results for the opposite direction of adjustment. On the x-axis, saturation of the referent stimulus S_R is given. For all S_R values, there was a gap between S_M values obtained when performing adjustment procedure from both sides of S_R . Error bars shown in Fig. 3 correspond to the standard deviation of the mean value.

The Method of Constant Stimuli. The data obtained was fitted with the Boltzmann sigmoid. The sigmoid is shown as the solid lines in Fig. 4. On the y-axis, the value of a fraction F is given showing how many times (out of 10) the subject responded the matching stimulus to look more pure than the referent stimulus. On the x-axis, the difference between S_M and S_R is given. At the PSE, a psychometric function has a value of 0.5, and the D value at the PSE can be read from the x-axis.

The shift of psychometric functions caused by the increasing duration of the adapting phase is clearly visible. At the upper diagram (Fig. 4A), the

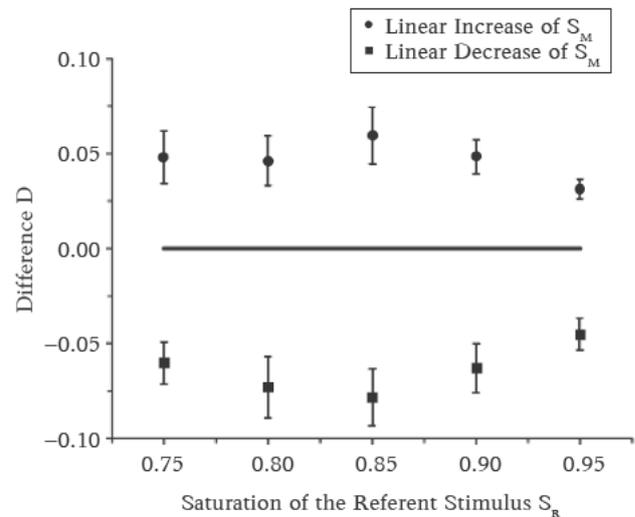


Fig. 3. Relationship between the difference D and saturation of the referent stimulus S_R at PSE in the experiment with the method of adjustment

Circles are the data for a case when the saturation of the matching stimulus S_M varies from 0.5 to 1. Squares are the data for a case when saturation of the matching stimulus S_M varies from 1 to 0.5.

mean shift averaged across all subjects is shown, whereas at the lower diagram of (Fig. 4B), the shift of psychometric functions is shown for the subject V.K. For all subjects, the data were obtained only for durations of the adapting phase of 0.25 and 1 second. The subject V.K. was investigated under conditions when duration of the adapting phase increased from 0.25 to 1.25 seconds in steps of 0.25 second. In Fig. 5, the value of the difference D at the PSE versus the duration of adapting phase is shown. Relationship between the difference D and the duration

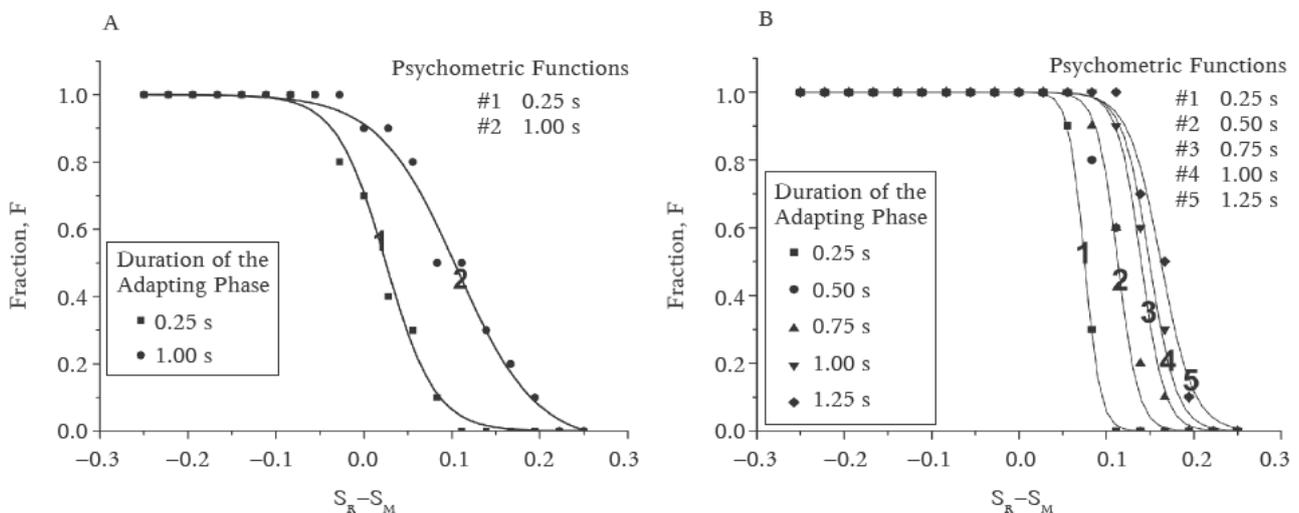


Fig. 4. Psychometric curves of saturation adaptation obtained in the experiment with the method of constant stimuli. The subjects were adapted for different time lengths: the averaged data of 4 subjects for a time period of 0.25 and 1 second (A), and time resolved data of one subject V.K. (B).

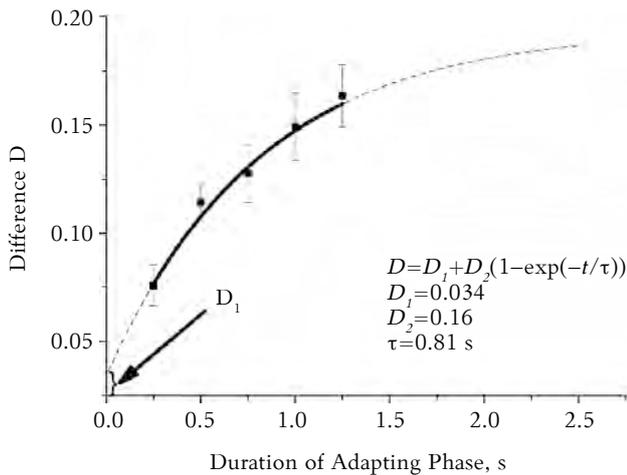


Fig. 5. Difference between saturation of matching stimulus and reference stimulus $D = S_R - S_M = 0.75 - S_M$ plotted against duration of adapting phase

The solid line is the exponential fit of data points allying within the interval of the duration of the adapting phase. Dashed lines are extrapolation of the same exponential fit beyond the limits of the adapting phase.

of the adapting phase was expected to be nonlinear and was fitted with an exponential growth function of type:

$$D = D_1 + D_2 \cdot (1 - e^{-\frac{t}{\tau}}) \quad (1)$$

Where D_1 and D_2 are constants, and τ is half-life of the time course of saturation adaptation. Half-life τ is a time period after which the value of $D_2 \exp(-t/\tau)$ has decreased e times compared to the value at time moment $t=0$. The obtained half-life value of saturation adaptation was $\tau=0.81$ second.

Discussion

Color perception under the influence of chromatic adaptation is studied usually in the central part of the visual field (14, 18, 19). Apart from these authors, the referent and the matching stimulus in our study were located in the central and the peripheral visual field, respectively. Therefore, we must discuss a possible impact of peripheral vision on the results obtained. There are a large number of studies confirming bleaching out of small chromatic stimuli when presented in the peripheral visual field. Gordon and Abramov (20) were the first to introduce the concept of the perceptive field; it is defined as an angular size of the peripheral stimulus at which the color vision experienced in the peripheral visual field is similar to that experienced foveally. Pitts et al. (21) measured the dependence of the size of the perceptive field for hue and saturation on retinal illuminance and found that the size for red stimuli never exceeded few tenths of degree at all luminance values. Sakurai et al. (22) measured the changes of perceived purity along different merid-

ians of the visual field and at different eccentricities. They used stimuli as small as 2° . The authors reported that when moving along the horizontal meridian as in our case, even small red stimuli desaturated only 1.3 times, i.e., to a smaller extent than stimuli with another color. We used as large peripheral stimulus as 8° strongly exceeding the size of perceptive field. In our experiment with the method of constant stimuli, the difference $D = S_R - S_M$ was only some hundredths for the shortest duration of the adapting phase of 0.25 second. This value of the difference D is very small, and therefore, it cannot be assumed that the peripheral stimulus was significantly bleached out due to demonstration in the peripheral field of view. Thus, we suppose that the results of our study would not differ significantly if a bipartite stimulus were shown in the central part of the visual field one of the part being the referent part while the other one – adapting/matching part.

We have observed hysteresis of the difference D in the experiment with the method of adjustment. Obviously, hysteresis is due to different conditions of chromatic adaptation when performing the adjustment from both sides of saturation of the referent stimulus. As can be seen from Fig. 3, the amount of hysteresis cannot be described by any function, but is steady observable across the range of S_R values. The stronger the effects of chromatic adaptation, the larger the value of the difference D should be. The effect of saturation adaptation increases with duration of the adapting phase. We therefore suggest that the difference D is a function of rate at which saturation of the matching stimulus S_M changes.

We measured the time course of saturation adaptation by analyzing the dependence of the difference D on the duration of the adapting phase. The dependence could be well fitted with an exponential growth function similar to that suggested by Keller et al. (23) in their article regarding enzyme kinetics. The successful fit with the exponential function may be a consequence of enzymatic processes occurring in the photoreceptors. The chain of the phototransduction cascade is too complicated for specific reactions to be identified as possible sources of the exponential relationship. Other visual subsystems could also be involved in the exponential character of the relationship as well. Additional experiments must be done to find the key reactions responsible for this type of relationship. As the calcium is one of the most important chemical elements involved in adaptation processes, two most basic enzymatic processes controlling the opening and the closure of the Ca channels (cGMP channels) seem to be related to the exponential character of the relationship. One such a process is GTP hydrolysis by guanyl cyclase into cGMP. The second process is converting cGMP to GMP by phosphodiesterase (4, 24).

Several authors have already measured the time course of chromatic adaptation. Shevell (14) measured the time course of chromatic adaptation by the hue-cancellation method. Under different states of chromatic adaptation, Shevell looked for intensity of the green light so that the test stimulus appeared neither greenish nor reddish. By plotting the intensity of the green light at cancellation point versus time after stimulus onset, he concluded that chromatic adaptation reached a steady state after as long as 10 minutes. Rinner and Gegenfurtner (18) measured the impact of adaptation to a chromatic background on color appearance and color discrimination. The authors plotted adaptation state (expressed in %) versus time after stimulus onset. They resolved 3 distinct half-life components in the time course of chromatic adaptation for both color appearance and color discrimination. Different half-life values point to various locations of processes involved in the processes of the chromatic adaptation and to that the visual system cannot be considered as a single circuit and must be divided into "subsections" each of which has a different time course. They suggested that the mechanism of the slowest component (half-life value, 20 seconds) might be located in the retina, geniculate bodies, or early cortical level. The second component had a half-life of about 40 ms to 70 ms. The authors identified the photoreceptors as the most likely location where this fast component could be located. The third component with a half-life about 10 ms was supposed to be located in the visual cortex. The half-life value of $\tau=0.81$ second obtained in our study is obviously greater than the extremely short life-time (10 ms) of the Rinner's (18) study, but considerable smaller than the long half-life (50 seconds). We consider that the half-life value obtained in our study is the closest to the value of 40–70 ms, and we therefore suggest that the processes responsible for the exponential relationship are located in photoreceptors.

Similarly to Rinner and Gegenfurtner (18), the time course of chromatic adaptation was also determined by Fairchild and Reniff (11). Fairchild and Reniff adapted the subject to different illuminants: D65, A, D90, and GRN, which changed each other in a sequence after certain periods. Under each state of adaptation, the subject adjusted chromaticity of the test stimulus until it looked achromatic. The proportional movement of adjusted chromaticity was plotted against duration of the adapting phase. The data were successfully fitted with a sum of 2 exponential functions. The authors obtained the half-life values of about 1 second for the faster component and 40–50 seconds for the slower component. The authors concluded that the mechanism of both components might be located at retinal level. The half-life value obtained in our study ($\tau=0.81$ sec-

ond) is very close to that of the faster component in the study by Fairchild and Reniff (11) suggesting even more that the enzymatic processes may be located in photoreceptors.

The reaction time may play a role in interpreting the results. The reaction time related to a task in which the subject is asked to press a button is called a choice reaction time and is typically 100 ms to 200 ms. The exponential curve may be displaced upward because of the changes in the D values, which in their turn are caused by S_M changes within the reaction time. Thus, the true half-life value may actually be shorter than 0.81 second.

It is clear that a large population must be tested to obtain statistically worth data. However, the subject who was tested with 5 durations of the adapting phase was the only one who was experienced and trained. Other subjects enrolled in the study were naïve to the experiment and not trained before the experiments. As these subjects were not trained, they got tired during the experiment resulting in an uncontrolled progress of the experiment. The number of subjects may not be sufficient to assess the effect quantitatively. However, the effect of hysteresis and chromatic adaptation may be apparent also if the number of the subjects is limited.

Longer durations of the adapting phase are required to obtain a more precise estimate of the half-life value. Longer durations of the adapting phase would also let measure the slow phase of chromatic adaptation. However, we think that the data obtained are sufficient to consider that the relationship is nonlinear and exponential. The nonlinear and exponential relationship is even more supported by the data found in literature. We have obtained an exponential relationship like other authors (11, 18, 19).

A conclusion on the presence of a specific saturation adaptation mechanism requires many additional experiments and cannot be stated yet. Actually, the term *saturation adaptation* that we use is a special kind of chromatic adaptation that in its turn is a special kind of light adaptation. The processes responsible for the chromatic adaptation processes occur at different levels of the visual system (25), and the exponential character of the relationship is not sufficient basis to state that these processes occur at the retinal photoreceptors.

Based on the data obtained by Rinner and Gegenfurtner, Fairchild and Reniff (11), and Shevell et al. (14) measuring the time course of chromatic adaptation it must be borne in mind that the referent stimulus, which was fixated by the subject, also underwent the changes of chromatic appearance. This may have brought some inaccuracy in the data obtained resulting in an improper assessment of the half-life values of saturation adaptation.

What regards inequality by gender the photopigments found in photoreceptors have the same molecular structure and spectral sensitivity irrespective of gender, and hence their properties and processes related to the photopigments are the same in men and women. That is why it is concluded that inequality by gender could not have had any effect on the results.

Conclusions

Pronounced hysteresis of perceived color purity was observed when approaching to the point of subjective equality from the side of low saturation of the matching stimulus compared with the side of

high saturation of the matching stimulus. There was a time course of mechanisms of saturation adaptation similar to those of chromatic adaptation previously quoted in literature.

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Statement of Conflict of Interest

The authors state no conflict of interest.

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