# Shift in Rayleigh matches after adaptation to monochromatic light of various intensities

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## Abstract

The action spectrum for inducing a long-lasting protan shift in colour matches was investigated. Rayleigh matches were measured before and after 30 min adaptation to monochromatic light of 520, 550, 580 or 620 nm. For each wavelength, seven retinal illuminances, ranging from 3.0 to 5.0 log td, were chosen in random order. Results for one colour-normal observer show that the shift in Rayleigh match after adaptation increases monotonically as a function of the luminance of the adapting light. The dynamic response range is from 3.3 to 4.7 log td. The wavelength of the adapting light had no systematic influence on the form of the response function. The results imply that the effect is triggered by light absorbed in the photopigments themselves. © 1998 Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

We have recently reported that an hour spent reading in natural sunlight will cause a long-lasting shift in colour matches [1,2]. Our finding contradicts the common view that the processes of light and dark adaptation in photopic vision are complete within minutes. Wright [3] and Brindley [4] have demonstrated that colour matches are shifted in a protan direction after brief bleaching exposures, owing to a reduction in the optical density of the photopigment and thus a change in self-screening; but even after nearly all the cone photopigment has been bleached by exposure to intense light, both the density of pigment and the observer's sensitivity are said to fully recover in only 7 min [5]. Our own effect, in contrast, may last for as long as 5 h.

Fig. 1 illustrates the phenomenon for one colour-normal, female observer. Rayleigh matches were measured using a 3-channel colorimeter before and after a 1-h exposure period, during which the subject read scientific papers in English sunlight giving an illumination of 80 000 lux at the reading surface. In these experiments matches were measured with a temporal substitution

paradigm and a double-staircase method. The field size was 2°. Each data point is the mean ± S.E.M. of 20 trials. The ordinate shows the amount of red in the red/green (R/G) mixture needed to match the standard as a function of time. Zero on the abscissa indicates the beginning of the exposure period. The dotted line is the mean of all matches before exposure. After exposure to light the matches are shifted in the protan direction, i.e. more red is needed in the R/G mixture to match the standard. The shift is maintained for at least 5 h before matches return to the pre-adapted level. Since our adapting conditions are ones often encountered in the natural world and because matches always return to pre-adapted levels, we assume that the protan shift represents a normal mechanism of adaptation rather than some subclinical pathology.

The mechanism of the effect is at present unknown, although we have considered several possibilities [2]. It may be related to long-lasting changes observed by reflection densitometric methods [6,7].

In the present study we ask what is the action spectrum for inducing the effect. We already know that it can be produced by an artificial light source (575 W Sirio daylight fresnel) giving an illumination of about 40 000 lux at the reading surface and it survives when the UV and shortwave components of the light source

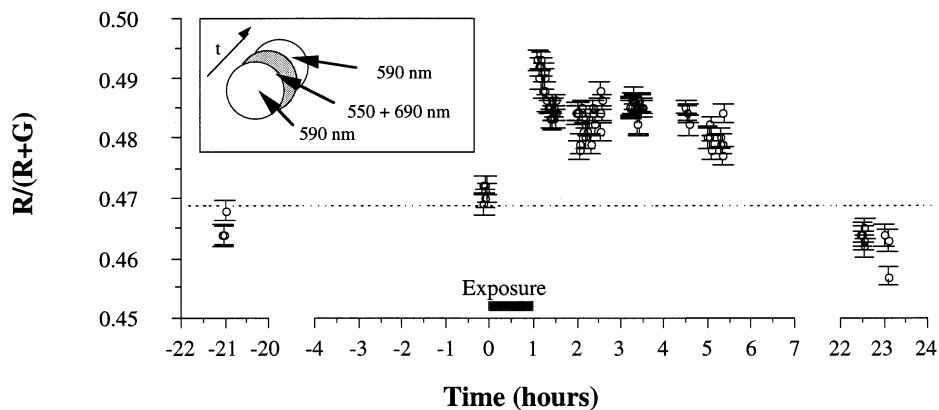* Corresponding author. Fax: +44 1223 333581; e-mail: jm123@cam.ac.uk.

Fig. 1. Long-lasting protan shift in Rayleigh matches after 1-h adaptation to natural sunlight. From Jordan and Mollon [2]. For explanation see text.

are removed. We now ask: can the effect be induced with a range of monochromatic lights? What is the form of the dose-response curve? And is it the same for different wavelengths? Only if the dose-response function does have a constant shape can we derive a true action spectrum, i.e. establish what radiances at different wavelengths are equivalent in their effects [8].

The question addressed in the present study is distinct from the question of how spectral sensitivity is altered after adaptation. Some preliminary results on that issue have been reported elsewhere [9].

## 2. Methods

The subject was GJ, who is female and colour-normal and has extensive practice at making Rayleigh matches. A circular, 7.6° field presented in Maxwellian-view served as adapting stimulus. Measurements were made for four different adapting wavelengths and seven different adapting intensities. Each of these 28 conditions was tested on a different day and at least one working day was allowed between test days in order to eliminate transfer effects. The adapting illuminances ranged from 3.0 to 5.0 log td in steps of $\approx 0.3$ log units. For any one wavelength, the different troland values were tested in randomised order. Four adapting wavelengths were tested in the order 580, 620, 550 and 520 nm.

Rayleigh matches were measured on a Schmidt and Haensch Nagel anomaloscope, run from a voltage stabiliser and giving a field size of 2.3°. Matches were measured in blocks of five for alternate eyes for 1 h before and 1 h after the adaptation period. Only the right eye was exposed to the adapting wavelengths and the other served as a control. The exposure period was 30 min. Before and after exposure there was a break of 15 min. The total session lasted $\approx 3$ h. To guarantee maximum precision in the Nagel matches the room

temperature was kept constant at 22°C [10]. Furthermore, the time of day at which the test runs were carried out was kept constant throughout the experiment.

## 3. Results and discussion

Fig. 2 illustrates the outcome of a single experiment. Nagel matches are plotted as a function of time. Each data point is the mean of five matches. Filled symbols represent the left, control eye and open symbols the right, test eye. The black bar coincides with the 30-min adaptation period. Lines drawn through the data are the means for the control (dotted line) and test eye (solid line) before and after adaptation. In this case the subject adapted to a 550 nm light of fairly high retinal illuminance (5.0 log td). There is a shift of 1.13 Nagel units in the Rayleigh match for the test eye and no significant shift in the non-exposed eye after adaptation. Note the difference between the two eyes at the baseline level[1]. Fig. 3 shows another example of an individual experiment. In this case the subject adapted to a 620 nm light of lower retinal illuminance (3.33 log td). There is a small shift of 0.4 Nagel units in the test eye and no shift in the comparison eye after adaptation.

To derive a dose-response function for each adapting wavelength, we first calculated the difference in the test and control eyes before adaptation and the equivalent difference after adaptation. We took the change in this difference as the magnitude of the effect. By referring the changes to the control eye in this way, we minimised the effects of any possible variations in the instrument or any systemic variations in the subject. If

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[1] Interocular differences in Rayleigh matches appear to be relatively common [11,12]. Shevell and He suggest that these differences are often due to differences in effective optical density of the photopigments in the two eyes.
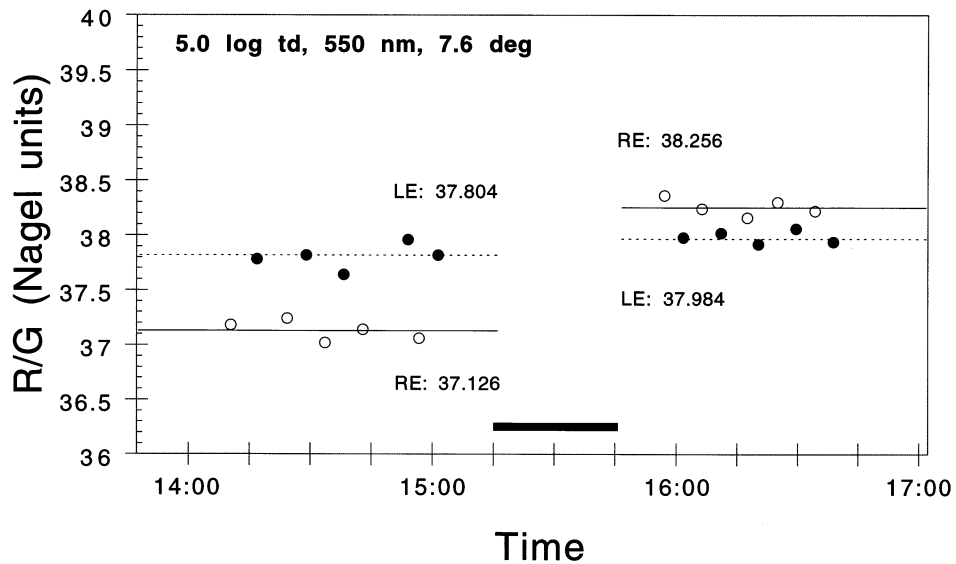
Fig. 2. Protan shift of 1.13 Nagel units in the test eye after 30 min adaptation to a 550 nm light of 5.0 log td retinal illumination. Open symbols represent the test eye, filled symbols the comparison eye. Lines drawn through the data are the means for the left (dotted line) and right eye (solid line) before and after adaptation.

we take just the absolute shift in the Rayleigh match in the test eye, then we obtain very similar, but slightly noisier, results.

Results for four adapting wavelengths are shown in Fig. 4(a). The shift in Rayleigh matches after exposure to light is plotted as a function of the troland value of the adapting light. Different symbols represent different wavelengths of the adapting light, as shown in the legend. It is clear from the figure that the protan shift after light-exposure increases monotonically as a function of the troland value of the adapting light. The dynamic response range is from about 3.3–4.7 log td. The four dose-response curves have a similar form and are well described by a sigmoidal function with a centre value at $\approx 3.7$ log td. In so far as the individual sets of data are superposed when plotted on a luminance scale, we can conclude that the action spectrum for inducing the protan shift resembles the photopic luminosity function $V(\lambda)$.

To derive a formal action spectrum we must strictly assume that the dose-response functions are identical in form for different adapting wavelengths, as would be the case if the initiating signal originated in a single class of cones obeying the Principle of Univariance [8]. In so far as the initiating signal derives from both the long- and the middle-wave cones, this assumption may
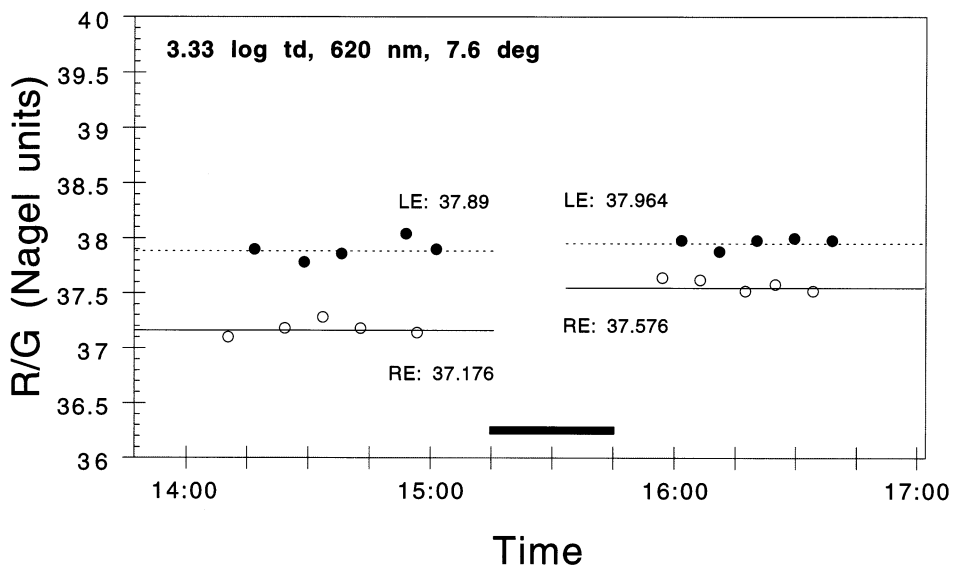
Fig. 3. Small protan shift of 0.4 Nagel units in the test eye after 30 min adaptation to a 620 nm light of 3.33 log td retinal illumination. Symbols are as in Fig. 2.
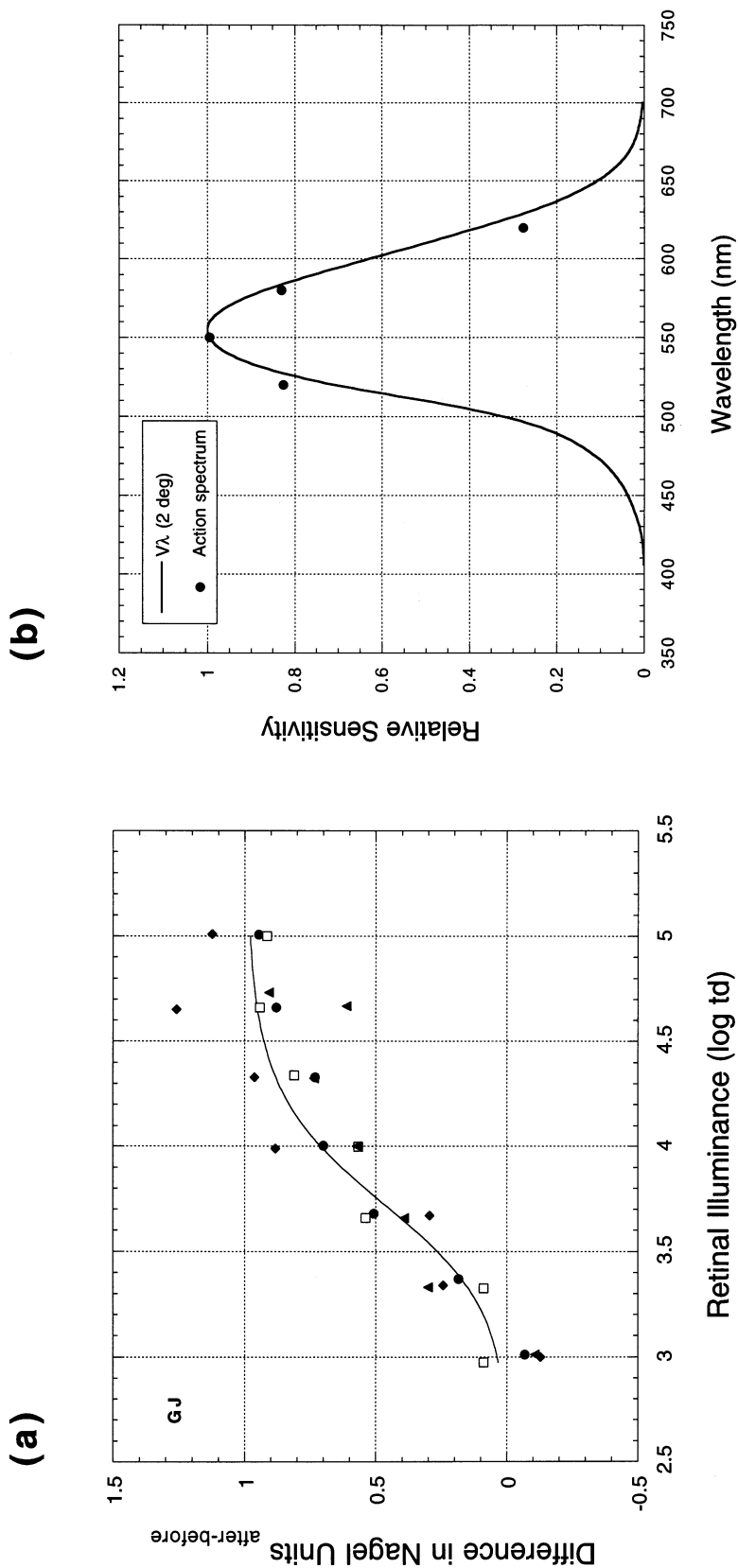
Fig. 4. (a) Size of shift versus retinal illuminance for four different wavelengths of the adapting light. Diamonds represent the 520 nm adapting condition; circles: 550 nm; open squares: 580 nm; triangles: 620 nm. The triangle plotted at 4.74 log td corresponds to the highest retinal illuminance available for the 620 nm adaptation stimulus. The solid line is the sigmoidal function that best fits all the data points. (b) Action spectrum for producing the protan shift (filled circles) compared with the photopic luminosity function $V(\lambda)$.

only be an approximation. To obtain the best estimate of the dose-response curve, we first fitted to each data set separately a sigmoidal function with the equation

$$y = (A_1 - A_2)/(1 + (x/x_0)^p) + A_2,$$

where $A_1$ and $A_2$ denote the initial and final value of $y$ respectively, $x_0$ describes the centre value and $p$ the power of the function. We constrained $A_1$ to be zero and $A_2$ to be the average of the values obtained at 5.0 log td. The power values of these four functions were then averaged and the centre values were re-estimated using the average function. The four resulting centre values were expressed in radiance units and, transformed to relative sensitivites, are plotted as filled circles in Fig. 4b. For comparison $V(\lambda)$ is also plotted as a solid line in the same figure.

Since the action spectrum for our effect closely resembles $V(\lambda)$, we can infer that the effect is probably triggered by light absorbed in the cone photopigments themselves. This hypothesis is independent of the question of whether colour matches change because the cone pigments themselves are changed in spectral sensitivity or because some other ocular pigment has migrated or changed its absorption.

## Acknowledgements

## References

[1] Jordan G, Mollon JD. A long-lasting effect of light adaptation on colour vision. Invest Ophthalmol Vis Sci Suppl 1995;36:392.

[2] Jordan G, Mollon JD. Adaptation of colour vision to sunlight. Nature 1997;386:135–6.

[3] Wright WD. The breakdown of a colour match with high intensities of adaptation. J Physiol 1936;87:23–33.

[4] Brindley GS. The effects on colour vision of adaptation to very bright lights. J Physiol 1953;122:332–50.

[5] Rushton WAH, Fulton AB, Baker HD. Dark adaptation and the rate of pigment regeneration. Vis Res 1969;9:1473–9.

[6] Baker H, Kuyk Th K. In vivo density of cone pigments after repeated complete bleaches. In: Williams TP, Baker BN, editors. The Effects of Constant Light on Visual Processes. New York: Plenum Press, 1979:347–53.

[7] De Lint PJ, Berendschot TJM, Van de Kraats J, Van Norren D. Slow optical changes in human photoreceptors induced by light. In: De Lint PJ, editor. Fundus Reflectometry in a Clinical Setting. PhD thesis, University of Utrecht, 1997:81–98.

[8] Naka KI, Rushton WAH. S-potentials from colour units in the retina of fish (Cyprinidae). J Physiol 1966;185:536–55.

[9] Jordan G, Mollon JD. Long-term changes in colour matching functions after exposure to artificial sunlight. Perception Suppl 1996;25:14.

[10] Jordan G, Mollon JD. The Nagel anomaloscope and seasonal variation of colour vision. Nature 1993;363:546–9.

[11] Palacz O, Glinski J, Kuprianowicz W. The problem of the practical value of Ishihara's test and anomaloscopic examination on the basis of the results of examinations of right and left eye in normal subjects. Klinika Oczna. Acta Ophthalmol Polonica 1972;42:81–5.

[12] Shevell SK, He JC. Interocular difference in Rayleigh matches of color normals. In: Drum B, editor. Colour Vision Deficiencies XII. Dordrecht: Kluwer Academic, 1995:185–91.