The Nagel anomaloscope and seasonal variation of colour vision

G. Jordan & J. D. Mollon

Department of Experimental Psychology, University of Cambridge,
Downing Street, Cambridge CB2 3EB, UK

In 1948 the German physicist, Manfred Richter, reported that colour vision has a seasonal variation[1,2]. For four colour-normal subjects, he found a sinusoidal variation in the proportion of red and green required to match a monochromatic yellow, the equation known as the 'Rayleigh match'[3]. In summer, subjects required more red in their mixture. The measurements were made with the Nagel anomaloscope, an instrument introduced in 1907[4,5] and which today, essentially unchanged, remains the definitive clinical instrument for classifying the many phenotypic variations in colour vision. The variation that Richter recorded in the red–green ratio was large (three Nagel units), and it now takes on fresh interest because it is comparable in size to the difference in Nagel settings later reported between normal observers of different genetic types[6,7]. We have been able to replicate Richter's result, but report here that it is almost certainly instrumental: the Nagel anomaloscope proves to be very sensitive to ambient temperature.

One of us (G.J.) made almost daily Rayleigh matches for over one year using a conventional modern Nagel anomaloscope run from a stabilized power supply. Five settings were made at about the same time each day. G.J.'s matches (Fig. 1*c*) show seasonal variation with similar phase to Richter's data: a greater proportion of long-wave light is required in the match during the summer months. The amplitude of the variation in our data, if expressed in terms of anomalous quotients[8] (to allow comparison of the different instruments), is close to that of Richter's.

In the December of this study, we noticed that Nagel matches dropped suddenly at weekends and at the beginning of the Christmas holiday, when the heating of our laboratory was turned off. We suspected that Richter's effect might be mediated by variation in ambient temperature. We do not know the indoor temperatures in his laboratory in 1946–1947, but it is likely, particularly in summer, that they reflected in part the variation in outdoor temperature, and in Fig. 1*b* we plot the monthly outdoor temperatures for Berlin for that period (supplied by the Berlin meterological office). In Fig. 1*d* we show analogous data recorded at the National Institute of Agricultural Botany, Cambridge, during the period of our own study. The four functions of Fig. 1 are similar: sine waves fitted to the data agree in phase to within a few degrees. But these are only correlational data, and season has many correlates; so we manipulated experimentally room temperature and then the local temperature of the Nagel anomaloscope.

The Nagel anomaloscope is essentially a spectroscope, consisting of an ocular, a compound direct-vision prism, and three entrance slits that define the primaries (Fig. 2). Its modern form, the Model I manufactured by Schmidt and Haensch, is optically similar to the two versions of the instrument described by Nagel. We have examined three instruments: two in Cambridge, a Model I supplied in 1988 and a Model II from early this century, and a 1974 Model I in Dortmund.

Figure 3*a* shows, for two colour-normal observers, how settings on a Model I vary with room temperature. There is a correlation of >0.9 between Rayleigh match and ambient temperature: the higher the temperature, the more protan the setting, that is, the greater the proportion of red light required in the mixture. The slope amounts to 0.175 Nagel units per degree Celsius. A very similar dependency is seen for the older, Model II, instrument, and for the Dortmund instrument (Fig. 3*b*, *c*).

How does ambient temperature affect Nagel settings? There are six possibilities. (1) The change might be in the observer. For example, there might be a change in body temperature, which in turn altered the slopes of the long-wave limbs of the photopigments[9]. Or there might be a change in the ionic environment of the photoreceptors that changed their spectral sensitivities[10]. (2) A variation in the power supply could lead to a variation in lamp current and thus in the colour temperature of the output. (3) Ambient temperature might directly influence the lamp's operating temperature. (4) Temperature might affect the position or width of the entrance slits of the anomaloscope, and thus the effective primaries. The entrance slits that define the red and green primaries are 8.5 mm apart and the relative proportions of the two primaries are controlled by a movable tongue (Fig. 2*b*). The maximum width of either slit is less than 0.5 mm. Because a distance of only 8.5 mm corresponds to a wavelength difference of over 100 nm and because the Rayleigh match is made at a red-green balance where the normal eye is very sensitive, a very small change in the position or relative widths of the slits could be expected to be visible[11]. (5) Thermomechanical stress may change the angle that the ocular or the objective makes to the prism and thus change the effective primaries. (6) Temperature may change the refractive index of the prism and thus the effective wavelengths of the primaries. The temperature coefficient for the refractive index of typical optical glass is 5×10^{-6} °C^{-1}. Because the refractive index typically varies with wavelength by 9×10^{-5} nm^{-1}, the shift in wavelength would be 0.05 nm °C^{-1} (ref. 12). As there is a large variation in temperature coefficients and the prism in the Nagel is likely to be a compound of flint and crown glass, it is difficult to estimate the exact effect, but the change is large enough to be visually apparent.

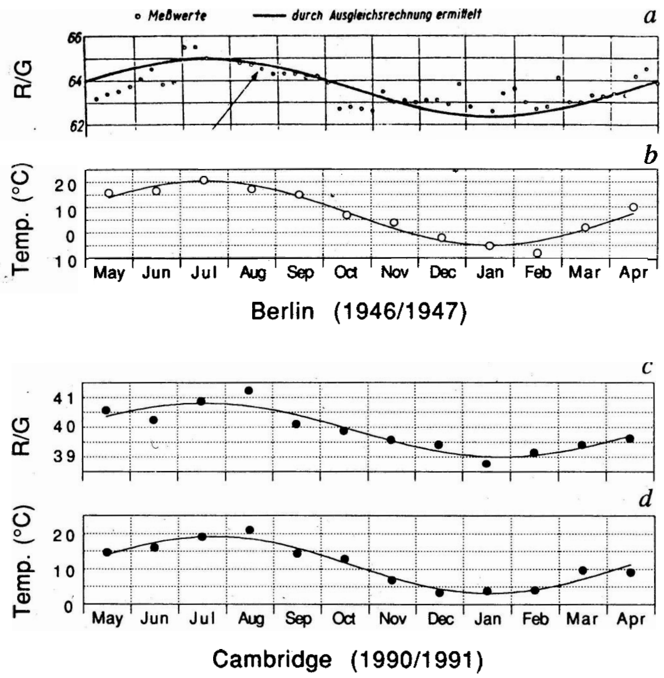


FIG. 1 Seasonal variations in Rayleigh matches. *a*, Rayleigh matches of four normal male observers obtained in Berlin, May 1946 to April 1947[1]; *c*, mean Rayleigh matches of one female observer recorded in Cambridge, May 1990, to April 1991[15]. The Rayleigh match represents the relative proportions of red and green light required in a mixture to match monochromatic yellow light, and is expressed in the scale units of the anomaloscopes used in the two experiments. *b*, *d*, Outdoor temperatures recorded in Berlin and Cambridge during the corresponding periods. The solid curves shown in panels *b*–*d* are best-fitting sine waves, with period and phase free to vary.

The following experiments were designed to distinguish between these possibilities. We set up our Model I and our Model II anomaloscopes side by side and operated them from the same power supply, voltage-stabilized to within a variation of less than 1%. The laboratory was air-conditioned, and room temperature was constant within a range of 1 °C. The two observers made measurements alternately on the two instruments while we locally heated or cooled the prism housing of one of the two. Figure 4*a* shows the Rayleigh settings for the case where the Model I was varied and the Model II served as control; Fig. 4*b* shows the complementary experiment. In both cases, a variation in Rayleigh match is seen only for the manipulated instrument.

These experiments allow us to rule out three of the possibilities listed. The variation cannot be in the observers, who remained in a constant environment and made settings alternately on the two instruments. Nor can it lie in the power supply, common to the two instruments. And the variation is unlikely to be in the lamps, which were turned on only long enough to do each set of five matches, and we measured little thermal coupling between the prism housing and the lamp housing.

Direct heating of the slits had less effect than heating of the prism housing, but it is not possible fully to uncouple the temperature of these two parts of the instrument (and of the ocular and objective tubes). So we removed from our Model II instrument both the ocular and the objective, isolating the prism in its mount. We passed a He–Ne laser beam through the prism from the ocular face to the objective face, and monitored its displacement on a distant wall as room temperaure was manipulated. Part of the beam was reflected at the first (ocular) face of the prism, allowing us to monitor mechanical movement of the prism and mount. The laser source was in a stable environment. An increase of 15 °C in the ambient temperature at the prism had no effect on the reflected beam, but the refracted beam was displaced by 0.53 mrad away from the red entrance slit, implying that the primaries vary with temperature.

We are satisfied that Rayleigh matches on the Nagel anomaloscope exhibit a thermal dependence. The effect is instrumental and probably arises from change in refractive index at the air–prism interfaces or at interfaces within the compound prism. In the absence of any evidence that Richter controlled the ambient temperature of his instrument, we must conclude that his seasonal variation is largely or wholly artefactual. Doubt must similarly fall on the correlation reported by Waaler for Nagel settings of parents and children[6], because family members

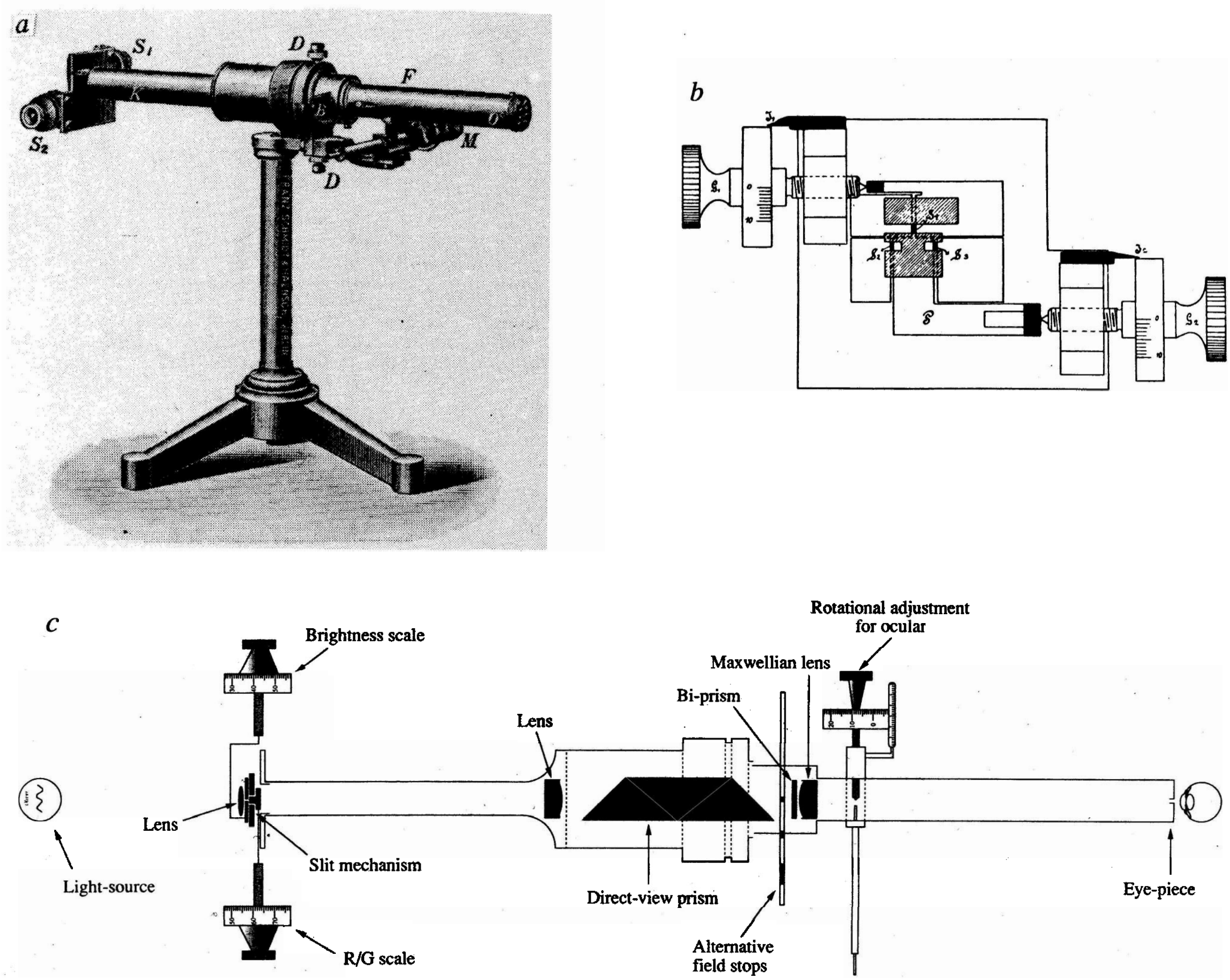
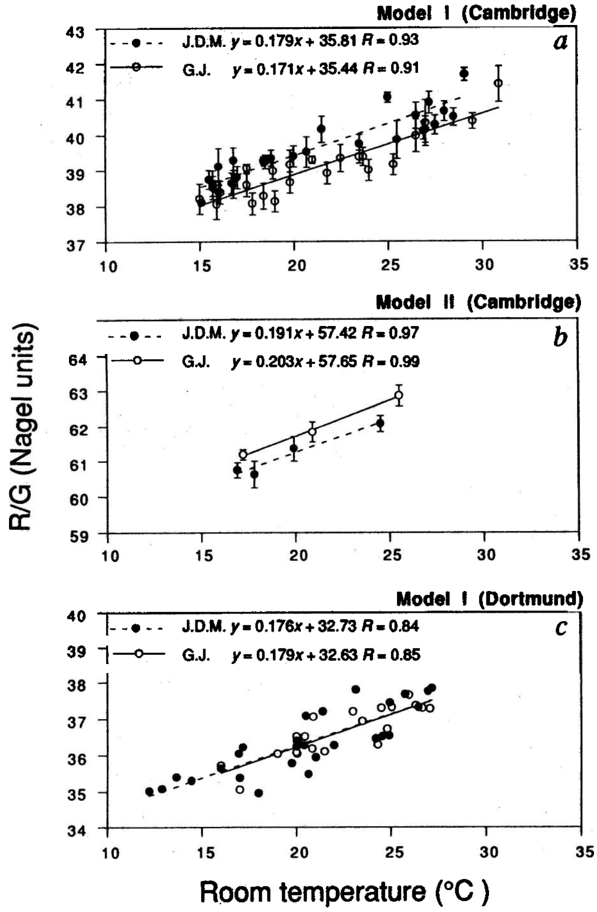


FIG. 2 *a*, Nagel anomaloscope Model II in its original form[4]. The eyepiece is on the right of the instrument and the slit mechanism on the left. The difference between Models I and II is that Model II has a facility to change the angle of the ocular, and thus the three primaries selected for the equation. *b*, Detail of the slit mechanism. Movement of the tongue (P) between the two sides of the slit increases either the red or the green primary while reducing the other. The upper slit controls the radiance of the yellow primary. *c*, Plan view of the Nagel anomaloscope, Model II. The direct-vision prism is housed in the centre part of the instrument, and a biprism and lens provide a horizontally divided field seen in maxwellian view. The optics of the modern Model I anomaloscope are very similar[16].



◀ FIG. 3 Variation of Rayleigh matches as a function of room temperature. R/G Nagel settings are shown for two normal observers on three different instruments. The two Cambridge instruments were run from a stabilized power supply. *a*, *c*, Measurements for the two different Model I instruments: the slope of the function is ~0.17 Nagel units per degree C. *b*, Settings on an antique Model II instrument manufactured by Spindler and Hoyer: the slope of the function is about 0.19 Nagel units per degree C. For all three instruments the rate of change in anomalous quotient is about 0.01 per degree C.

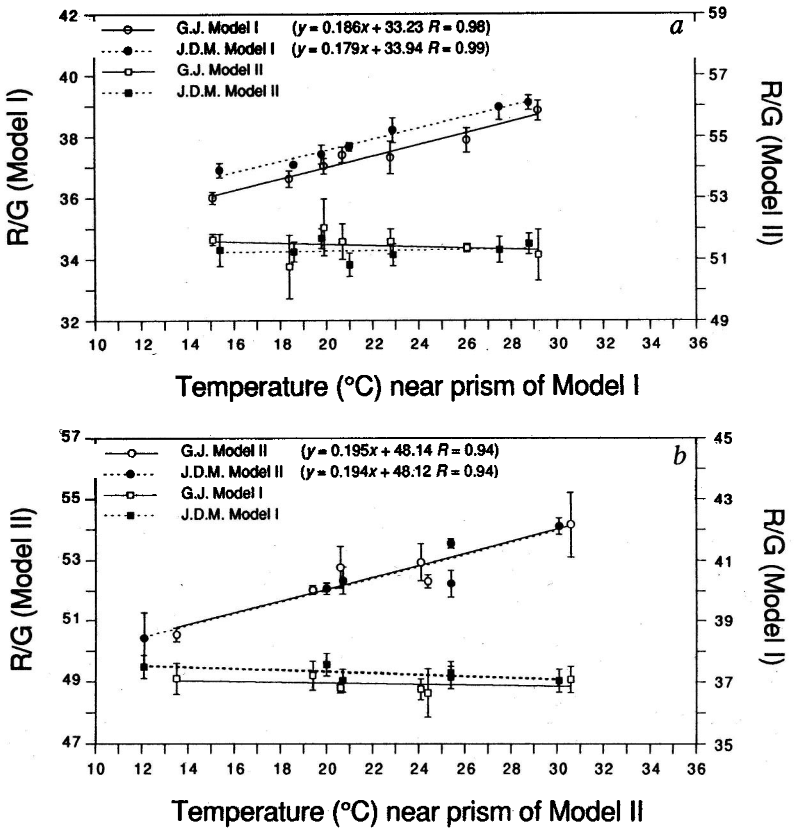


FIG. 4 Experiment in which the prism housing of one anomaloscope was gently heated or cooled, while the second instrument was held at a constant temperature. Settings were made alternately on the test and on the control instrument. In each panel the left-hand ordinate, and the upper two sets of data points, represent the R/G settings of the manipulated anomaloscope, whereas the right-hand ordinate and the lower two sets of data points represent the corresponding settings on the control instrument. In each case, the abscissa represents the temperature measured (with a K-type thermocouple) at the surface of the prism housing of the manipulated instrument. The data points for the manipulated instrument show slopes of ~0.17–0.19 Nagel units per degree C, but no systematic changes are seen for the control instrument.

are likely to have been tested at similar times; and although later molecular studies have confirmed a genetic source of variation in normal Rayleigh matches[13], temperature must have been a significant source of variance in all population studies that have used the Nagel anomaloscope.

It may seem unlikely that the Nagel anomaloscope has been used for so long without anyone noticing its thermal dependence, but we end by citing a passing caution made in 1915: "A further influence on the investigation, and one that is sometimes detectable and uncontrollable, may not be generally known, namely the temperature of the apparatus [Nagel anomaloscope] or of the experimental room. With it the dispersion-power of the prisms of the apparatus changes noticeably, and therewith the wavelengths of the monochromatic light that is used"[14]. ☐

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1. Richter, M. *Z. wiss. Photogr. Photophy. Photoch.* **43,** 209–237 (1948).
2. Richter, M. *Klin. Mon. Augenheilkunde* **119,** 561–575 (1951).
3. Rayleigh, L. *Nature* **25,** 64–66 (1881).
4. Nagel, W. A. *Z Augenheilkunde* **18,** 201–222 (1907).
5. Nagel, W. in *Handbuch der Physiologischen Methodik* (ed. Tigerstedt, R.) (Hirzel, Leipzig, 1909).
6. Waaler, G. H. M. *Nature* **215,** 406 (1967).
7. Waaler, G. H. M. *Avhandl. Det Norske Videnskaps-Akad. Oslo I Mat.-Naturv. Klasse.* Ny Serie, No. 9, 1–25 (1967).
8. Pokorny, J., Smith, V. C., Verriest, G. & Pinckers, A. J. L. G. *Congenital and Acquired Color Vision Defects* (Grune & Stratton, New York, 1979).
9. De Vries, H. *Experientia* **4,** 357 (1948).
10. Knowles, A. *Vision Res.* **20,** 475–485 (1980).
11. Moreland, J. D. in *Colour Vision Deficiencies II* (ed. Verriest, G.) 14–18 (Karger, Basel, 1974).
12. Merton, T. R. *Proc. R. Soc.* **113,** 704–708 (1927).
13. Winderickx, J. *et al. Nature Genet.* **1,** 251–255 (1992).
14. Köllner, H. *Arch. Augenheilkunde* **78,** 302–335 (1915).
15. Jordan, G. *Polymorphism of Normal Colour Vision in Humans* (University of Cambridge, Cambridge, 1992).
16. Heinsius, E. *Farbsinnstörungen und ihre Prüfung in der Praxis* (Ferdinand Enke, Stuttgart, 1973).

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