
HOW TO FIND A TRITAN LINE

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Introduction

Modern experiments on colour vision often seek to isolate one of the cardinal directions of colour space. These were identified psychophysically by Krauskopf *et al.* (1982), and correspond to two physiologically distinct channels in the retina and lateral geniculate nucleus (Derrington *et al.* 1984; Dacey 2000). One channel compares long-wave-sensitive (L) cone signals with middle-wave-sensitive (M) cone signals, and the other compares short-wave-sensitive (S) cone signals with some combination of L- and M-cone signals. The physical lights required to isolate one of the cardinal directions depend not only on the spectral sensitivity of the photoreceptors, but also on spectrally selective prereceptoral filtering. Spectral transmission properties of the lens vary with age (Pokorny *et al.* 1987) and there are large variations in the normal population in the amount and distribution of macular pigment (Moreland and Bhatt 1984; Hammond *et al.* 1997). Existing psychophysical procedures to determine an individual's tritan confusion line (i.e. the axis of colour space that modulates only the excitation of the short-wave cones) are the Webster method (Webster *et al.* 1990; Webster and Mollon 1994), and the minimally distinct border method (Tansley and Boynton 1976; Boynton and Kaiser 1978). We present here a new psychophysical method designed to locate—for an individual observer and for a specific position in the visual field—the tritan line.

We exploit the phenomenon of “transient tritanopia” (Mollon and Polden 1975). In the classical experimental arrangement, the threshold is measured for a violet probe stimulus first on a steady yellow field and then against a dark background shortly after the yellow field has been turned off. Paradoxically the threshold is higher against the dark field and may remain so for several seconds after the yellow field has been extinguished. To explain transient tritanopia, Pugh and Mollon (1979) have proposed that the S-opponent channel is optimally sensitive in the middle of its operating range, but has a compressive response function, so that it becomes less sensitive when driven to one or other extreme of its response range. After the offset of the yellow field, the S-opponent channel is polarized, perhaps because a restoring force that opposes the yellow field continues to act for a short time. In the present experiment we measure, not the absolute threshold for detection, but the threshold for detecting a chromatic difference along a particular direction in colour space, that is, the threshold for distinguishing between a neutral background and a coloured target defined by a particular hue angle (see Fig. 29.1). We

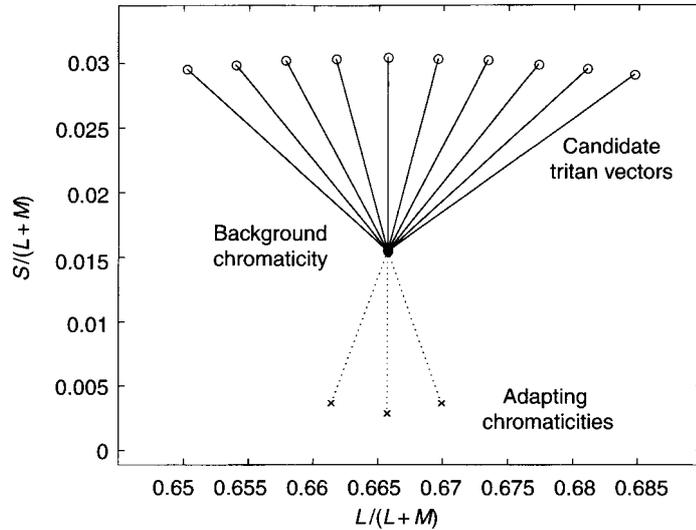


Figure 29.1 A plot showing the MacLeod–Boynton chromaticity co-ordinates of our stimuli. The filled circle represents the background chromaticity (approximately equal energy white). The array of ten vectors, plotted as solid lines, represent the ten candidate tritan directions. They were chosen to span a range including the tritan confusion line for the Judd (1951) 2° observer, that is, a vertical line in this plot. In our experiments, chromatic contrast between test and background was modified with a staircase until a threshold was found. Starting chromaticities are indicated with open circles. We suggest that the vector exhibiting the maximum transient tritanopia effect corresponds to an individual's tritan line. In Experiment 1, we compared the effects of three different adapting field chromaticities, shown on the plot as (×) symbols.

measure such thresholds shortly after extinction of a long-wave field and we repeat these measurements for different hue angles of the target. We predict that the threshold for detecting a chromatic change will be maximally elevated for the axis of colour space that offers no modulation of the L/M-opponent mechanism. For in this direction—the tritan line that we are seeking—detection must depend only on the S-opponent mechanism.

In an alternative tradition, one might expect that adaptation would produce maximal loss in sensitivity for test stimuli that were complementary to the adaptation, whatever axis was chosen for the chromaticity of the adapting field. This would be fatal for a method of finding a tritan line, since the result would depend on the choice of adapting field chromaticity and the method becomes circular. If, however, conditions of transient tritanopia tap the opponent stage of colour processing and selectively desensitise the S-opponent mechanism while leaving the L/M-opponent mechanism little changed, moderate changes in adapting chromaticity should not rotate the vector exhibiting maximal loss of sensitivity.

In Experiment 1 we test this prediction. In Experiment 2 we increase the viewing distance, thereby moving the stimulus to a retinal area with higher macular pigment density, and we test whether our method is able to reveal the associated change in tritan line.

Methods

Experiment 1

All stimuli were presented on a calibrated CRT. The chromaticities used in these experiments are conveniently described as vectors from the background chromaticity (equal energy white) and in each case we specify the clockwise angular rotation from the theoretical tritan axis ($+S/(L + M)$) in MacLeod–Boynton space. The aim is to identify the chromaticity vector that exhibits the largest loss of sensitivity under conditions of transient tritanopia. Ten test vectors were chosen spanning a range that covered both sides of the theoretical tritan axis, from 312° to 54° in MacLeod–Boynton space. Three different adaptation vectors were used: 160° , 180° , and 200° . The length of the adaptation vector was constrained by the available monitor gamut: a distance of 0.0126 units in MacLeod–Boynton space was the maximum possible with our arrangement (see Fig. 29.1).

Observers were first required to view a spatially uniform (60 cd/m^2) adapting field for two minutes, and then the trial sequence began. After each top-up adaptation period the display changed abruptly to equal energy white (22.5 cd/m^2), and after 400 ms a chromatic probe stimulus was presented. In order to maintain the subject's adaptive state, the duty cycle was fixed, with 7.25-s adaptation every 8 s. The sequence of events in a trial is depicted schematically in Fig. 29.2. Baseline thresholds were also measured for each of the probe stimuli. For the latter measurements, there was an initial two minute adaptation to equal energy white, but trial timings were under the subject's control.

The test stimuli resembled Ishihara plates in that spatial luminance noise ($\pm 7 \text{ cd/m}^2$) was used to ensure that neither luminance differences nor edge artefacts could be used as a cue for discriminating the chromatic target against the field (Regan *et al.* 1994). The chromatic target formed a 90° segment of a ring. At the viewing distance of 1 m, the thickness of the chromatic arc was 1.55 degrees of visual angle and the separation between fixation and test loci was a minimum of 3 degrees. We chose this arrangement in order to use an area of retina that is relatively homogeneous for short-wave cones and for macular pigment. By presenting the chromatic test in one of four possible locations, chosen at random and at equal eccentricities, we discouraged the observer from moving fixation and forcing the stimuli to a retinal region where the macular pigment density, and thus the tritan line, were different.

A spatial 4AFC task was used: the observer was required to locate the position of the coloured patch, and the chromatic distance between this test patch and the background was modified with a staircase until a threshold was found. In each block of measurements a single candidate chromaticity vector was tested and two randomly interleaved staircases tracked the threshold for 75 per cent discrimination. Conditions were blocked in order that subjects could derive the optimal strategy for detecting each candidate chromaticity. Five blocks with the same adapting chromaticity were presented in a single experimental session. The order of blocks was counterbalanced for test chromaticity, and sessions were counterbalanced for adapting chromaticity, including the no-adaptation, baseline

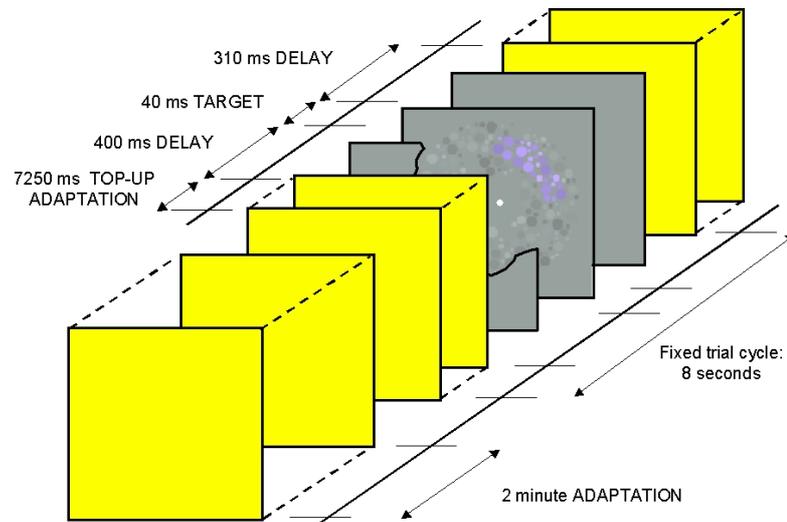


Figure 29.2 See also colour plate section. A schematic diagram showing the sequence of events in a trial. The initial two minute adaptation is followed by a repeated trial-cycle comprising a period of top-up adaptation followed, after 400 ms, by a 40-ms test array. The test arrays resemble Ishihara plates in that spatial luminance noise is used to mask luminance artefacts. The chromatic target formed a 90° arc that was presented in any one of 4 quadrants chosen at random. Ten different probe chromaticity vectors were tested as candidates for the tritan line. In Experiment 1 we compared three different adapting chromaticities. In Experiment 2 we increased the viewing distance, from 1 to 4 m, to determine whether the tritan axis rotated when the eccentricity of the target was reduced from 3 to 0.75 degrees of visual angle.

condition. To allow after-effects to dissipate there was a minimum interval of 30 minutes between sessions.

Experiment 2

We repeated the measurements for an adapting field with a hue angle of 180° , but increased the viewing distance from 1 to 4 m. The separation between the fixation point and the test loci was thus reduced from 3.00 degrees to 0.75 degrees of visual angle, and the width of the chromatic arc was reduced from 1.55 degrees to 0.39 degrees of visual angle.

Results

Observers R. E. S. and J. D. M. have normal colour vision, and are experienced psychophysical observers. R. E. S. was naïve to the purposes of the study; J. D. M. is one of the authors. Baseline thresholds for both observers plot as ellipses in MacLeod–Boynton space, with the major axis oriented along the L/M -opponent direction. Since the scaling of the S -opponent axis of MacLeod–Boynton space is arbitrary, we describe the data in a scaled version of MacLeod–Boynton space ($S/(L + M) \times 4.0$), chosen such that baseline

thresholds plot as a circle, and baseline sensitivity, considered in the scaled space, is approximately equal across all vectors.

Data from Experiment 1 are plotted in Fig. 29.3. Values along the abscissa are probe chromaticities, defined as clockwise angular rotation from the theoretical tritan line in

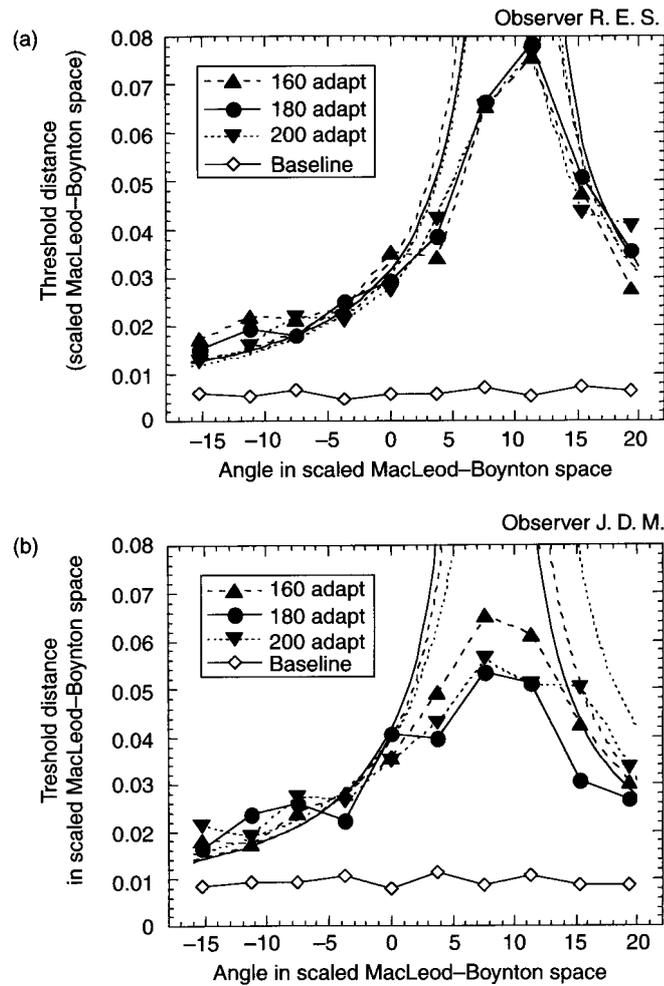


Figure 29.3 Data from Experiment 1, (a) for observer R. E. S., (b) for observer J. D. M.. Thresholds are expressed in a scaled version of MacLeod-Boynton space ($S/(L+M) \times 4.0$) such that baseline performance, considered in the scaled space, is approximately equal over all test angles. Values along the abscissa are probe chromaticities, defined as clockwise angular rotation from the theoretical tritan line in scaled MacLeod-Boynton space. Values on the ordinate are thresholds for the baseline condition (open diamonds), or following offset of the adapting field (solid up-triangles 160°, solid circles 180°, solid down-triangles 200°). Smooth curves describe theoretical performance determined only by the available L/M-opponent signal. Line-style for the three conditions matches that used for the data.

scaled MacLeod–Boynton space (expansion of the $S/(L + M)$ axis has transformed the range of test vectors from 102° to 34°). Thresholds for the baseline condition (open diamonds) plot as a horizontal line after scaling, and thresholds following offset of the adapting field (solid up-triangles, down-triangles, circles) show elevations from baseline, indicating a transient tritanopia effect. We suggest that the maximum elevation locates the tritan line.

In order formally to locate the position of the tritan line, we have developed the simple template represented by the smooth curves of Fig. 29.3. The template is intended to describe the thresholds that would be obtained if the S-opponent channel were completely desensitised and thresholds depended only on the L/M signal. For the Judd observer, whose fovea is represented by the standard MacLeod–Boynton chromaticity diagram, we can directly estimate the sensitivity of the L/M channel to each test vector, that is, we can estimate the length of the vector that is needed to give some specified threshold contrast in the L/M channel. The resulting threshold function must be symmetrical around the tritan line, asymptoting to infinity where contrast in the L/M channel falls to zero. We use a least-squares procedure to fit this template to the empirical data with just two free parameters, a vertical scaling factor to allow for individual differences in the sensitivity of the L/M channel and a horizontal scaling factor to accommodate the shifts in the tritan line that we are interested in. Since the phosphors of the monitor are fixed, the effect of variation in pre-receptoral filters such as macular pigment is to displace the set of test chromaticities by a nearly constant factor, and so our symmetrical template is a useful first approximation for locating the tritan line.

Despite the large differences in adapting field chromaticity, the three curves give comparable estimates for the tritan vector for each observer. For R. E. S. the curve for the 160° adapting field shows a peak at 33.7° in MacLeod–Boynton space (9.48° in the scaled space), and curves for 180° and 200° fields show a peak at 33.9° (9.53° in the scaled space). For J. D. M., critical vectors are 31° , 29° , and 35° (8.5° , 7.8° , 10.1° in the scaled space) for adapting fields of 160° , 180° , and 200° respectively. There is no evidence, from either observer, that the estimate of the tritan line is systematically biased by the L/M component of adaptation. The variation we observe in the estimate of the tritan line is small: a range of 6° in MacLeod–Boynton space for one observer, and a range of 0.2° for the other observer. The transient tritanopia method is robust to changes in adapting field chromaticity of $\pm 20^\circ$ rotation from the theoretical tritan axis in MacLeod–Boynton space, a range of 40° .

The data for Experiment 2 are plotted in Fig. 29.4. Again, smooth curves describe theoretical performance determined only by the available L/M-opponent signal. For observer R. E. S. the peak effect occurs for a vector of 8° in MacLeod–Boynton space (2.1° in the scaled space) and for J. D. M. the peak occurs at 12° in MacLeod–Boynton space (3.1° in the scaled space). Thus when the viewing distance was increased from 1 to 4 m, the tritan vector in MacLeod–Boynton space for our observers shifted from 34° to 8° (R. E. S.) and from 29° to 12° (J. D. M.).

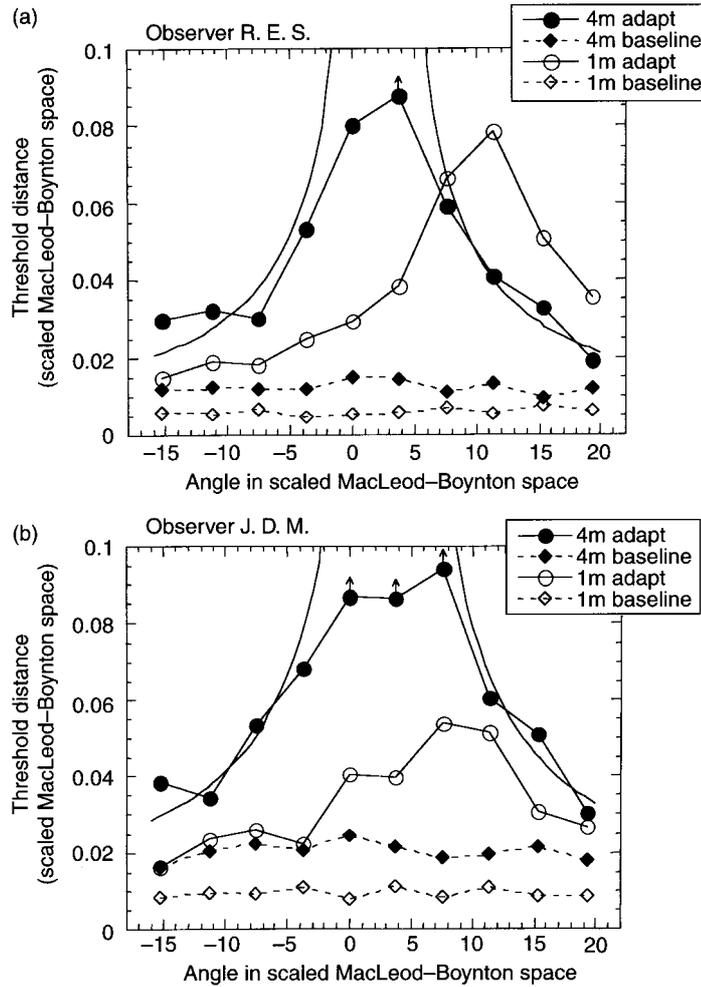


Figure 29.4 Data from Experiment 2, (a) for observer R. E. S., (b) for observer J. D. M.. The axes are the same as for Fig. 29.2. Filled symbols represent data obtained at a viewing distance of 4 m (circles adapt 180°, diamonds baseline). Upward pointing arrows, on the maximum point for R. E. S. and on the three central points for J. D. M., show conditions in which an out-of-range stimulus was requested, at least once, during the progression of the staircase. When this occurred the closest possible chromaticity was presented and the trials continued—the points are however an underestimate of the 75 per cent detection threshold. Smooth curves describe theoretical performance determined only by the available L/M-opponent signal. Open symbols represent data obtained in Experiment 1 with a 1-m viewing distance, and are plotted for comparison.

The results from Experiment 2 are consistent with an increase in macular pigment density towards the foveola. The primary difference between the Judd (1951) 2° observer and the CIE (1964) 10° observer is in macular pigment density. The MacLeod–Boynton chromaticity diagram assumes an observer with the spectral sensitivity of the Judd (1951) 2° observer. We could however construct a chromaticity diagram that was analogous to the MacLeod–Boynton chromaticity diagram, but based on the CIE (1964) 10° Observer. Suppose that in the latter space, we establish the loci of physical lights, produced from our monitor primaries, that lie on a vertical line passing through the chromaticity of the background, that is, the tritan line of the 10° Observer. If now we represent these physical lights in the standard MacLeod–Boynton space, then it turns out that they fall on a straight line oriented at 30° clockwise from the vertical. It is consistent that our observers resemble more closely the 1964 Observer when detecting stimuli at >3° eccentricity, and the Judd observer when detecting stimuli presented around 1°.

The effect of filtering by macular pigment can be seen intuitively if we consider, not just the chromaticity of each stimulus, but its spectral composition, that is, for stimuli produced on a CRT, the relative contribution of each phosphor. Light from the blue phosphor is an effective stimulus for S- and M-cones and filtering by macular pigment will disproportionately reduce the energy available from this phosphor. Compared to the neutral background, our test stimuli contain a high proportion of light from the blue phosphor and they are therefore shifted to relatively lower L : M ratios when filtered by macular pigment. The test vector that is matched to the L : M ratio in the background must be further to the right in the array of candidates when the stimuli are filtered by macular pigment, than when they are not.

Conclusion

We propose transient tritanopia as an effective method for locating an individual's tritan line. The method has several practical advantages. Firstly, the procedure can be carried out using a CRT, without the need to construct a uniform auxiliary field (as is required for the method described by Webster *et al.* 1990). Secondly, it allows almost free choice of the spatial properties of the stimulus so that the experimenter can determine the tritan line for the exact retinal region to be used in a subsequent experiment. In preliminary experiments we have found that judgements of minimally distinct borders are extremely difficult to make non-foveally. We have also tested two further potential psychophysical methods, employing "small-field tritanopia" and reaction time, but neither produced precise and reliable results non-foveally (Sumner 2000). Further advantages over the minimally distinct border method are that the transient tritanopia method uses the observer's performance rather than subjective judgements, and that luminance noise may be employed so stimuli need not be precisely equiluminant.

The transient tritanopia method is a reliable means of locating an individual's tritan confusion line. In particular, the data we present here, confirm that this method is robust to moderate changes in the L/M component of adapting field chromaticity. We also show

that the transient tritanopia method allows the experimenter to track successfully the rotation of the tritan line arising from changes in retinal location of the stimuli.

Acknowledgments

H. E. Smithson was supported by a BBSRC studentship and P. Sumner was supported by an MRC studentship. The work was additionally supported by MRC G9807068 to J. D. Mollon. We are grateful to Dr R. Sorensen for acting as an observer and to Prof J. Pokorny and Prof V. C. Smith for discussion.

References

- Boynton, R. M. & Kaiser, P. K.** (1978). Temporal analog of the minimally distinct border. *Vision Research*, *18*(1), 111–3.
- Dacey, D. M.** (2000). Parallel pathways for spectral coding in primate retina. *Annual Reviews in Neuroscience*, *23*, 743–75.
- Derrington, A. M., Krauskopf, J., & Lennie, P.** (1984). Chromatic mechanisms in lateral geniculate nucleus of macaque. *Journal of Physiology*, *357*, 241–65.
- Hammond, B. R., Jr., Wooten, B. R., & Snodderly, D. M.** (1997). Individual variations in the spatial profile of human macular pigment. *Journal of the Optical Society of America A*, *14*(6), 1187–96.
- Krauskopf, J., Williams, D. R., & Heeley, D. W.** (1982). Cardinal directions of color space. *Vision Research*, *22*, 1123–31.
- Mollon, J. D. & Polden, P. G.** (1975). Colour illusion and evidence for interaction between cone mechanisms. *Nature*, *258*, 421–2.
- Moreland, J. D. & Bhatt, P.** (1984). Retinal distribution of macular pigment. In G. Verriest (Ed.), *Colour Vision Deficiencies*, Vol. VII: Dr W Junk Publishers.
- Pokorny, J., Smith, V. C., & Lutze, M.** (1987). Aging of the human lens. *Applied Optics*, *26*(8), 1437–40.
- Pugh, E. N. & Mollon, J. D.** (1979). A theory of the Pi 1 and Pi 3 colour mechanisms of Stiles. *Vision Research*, *19*, 293–312.
- Regan, B. C., Reffin, J. P., & Mollon J. D.** (1994). Luminance noise and the rapid determination of discrimination ellipses in colour deficiency. *Vision Research*, *34*, 1279–99.
- Sumner, G. P. H.** (2000). *The salience of colour: Studies in visual ecology and psychophysics*. Ph.D. thesis, University of Cambridge, UK.
- Tansley, B. W. & Boynton, R. M.** (1976). A line, not a space, represents visual distinctness of borders formed by different colors. *Science*, *191*(4230), 954–7.
- Webster, M. A., De Valois, K. K., & Switkes, E.** (1990). Orientation and spatial-frequency discrimination for luminance and chromatic gratings. *Journal of the Optical Society of America A*, *7*(6), 1034–49.
- Webster, M. A. & Mollon, J. D.** (1994). The influence of contrast adaptation on colour appearance. *Vision Research*, *34*(15), 1993–2020.