J. Physiol. (1951) 114, 98–106

THE VARIATIONS OF HUE DISCRIMINATION WITH CHANGE OF LUMINANCE LEVEL

By L. C. THOMSON and P. W. TREZONA

From the Vision Research Unit, Imperial College of Science and Technology, London, and the Institute of Ophthalmology, London

(*Received* 28 *September* 1950)

Whilst measuring for another purpose the hue discrimination curve by the method used by Pitt & Wright (1934) the authors obtained values for the just noticeable difference of wave-length at each wave-length which were found to vary with luminance level. This effect has been investigated with two observers; one with normal and the other with protanomalous vision. The effects of variation with luminance were greater for the protanomalous than for the normal observer.

METHOD

The Wright colorimeter (1946) was used with a square field subtending 1° 20′ at the eye. The upper half could be set at any desired wave-length and luminance, whilst the lower could be adjusted for both by the observer. This method of measurement enabled the value of the just noticeable wave-length difference to be determined at any desired luminance level. The observation consisted of adjusting the wave-length of the lower half of the field until its colour was just noticeably different from that of the upper field, when the luminance of the two halves had been equated. This was done by alternate adjustments of wave-length and luminance by the observer until a satisfactory setting was obtained.

Observers. Of the two observers used, one, L.C.T., has normal colour vision and the other, P.W.T., protanomalous vision. P.W.T. requires a larger amount of the red stimulus in her yellow match but the difference between hers and the normal match is slight. Her luminosity curve, however, is similar in the orange and red region of the spectrum to that obtained for protanopic vision (Thomson, 1951)

Procedure. Measurements began as soon as the observers had arrived at the colorimeter, since it was found that an initial period of dark adaptation did not influence the results. A wave-length setting was chosen for the upper field and the observer asked to adjust the lower field in the way indicated above. One reading only was taken. This was repeated for various luminance values of the upper field, which were presented to him in random order. Then another wave-length setting was chosen at random from a series placed at 20 mμ. intervals throughout the spectrum, and stretching as far into the red and violet as the instrument would allow. Further observations at various luminance levels were then obtained. Between three and six wave-length settings were found to be sufficient for one observational period on any one day and the experiment was continued on subsequent days until three readings had been obtained at each setting.

It is possible to perform the measurements in two ways; the lower field may be made either more red or more blue than the upper. In these experiments the results for steps towards the red were all obtained in one series and those for steps towards the blue in another.

The method of viewing was different for each observer. Whilst P.W.T. continually scanned the field, L.C.T. made a series of glances, always fixating on the centre of the field and making his judgement with the eye in this position. The results obtained by L.C.T.'s method might be influenced, to some extent, by any non-uniformity of spectral sensitivity of the retina above and below the fixation point. This would not apply to the measurements made by observer P.W.T.

Spectral sensitivity measurements. By providing a minute red (650 mμ.) fixation point directly below the centre of the lower side of the upper field, it was possible to measure the spectral sensitivity of the eye of each observer at the threshold of vision. A glance technique was used by both observers and at each wave-length the energy of the upper field was at first increased until this field could just be seen and then decreased until the observer just failed to see the field. The mean of these two readings, which were repeated on three separate days, was taken as a measure of the threshold light energy.

Spectral sensitivity curves were also measured by a flicker method at higher luminance levels, and were found to be similar in shape to the threshold curve.

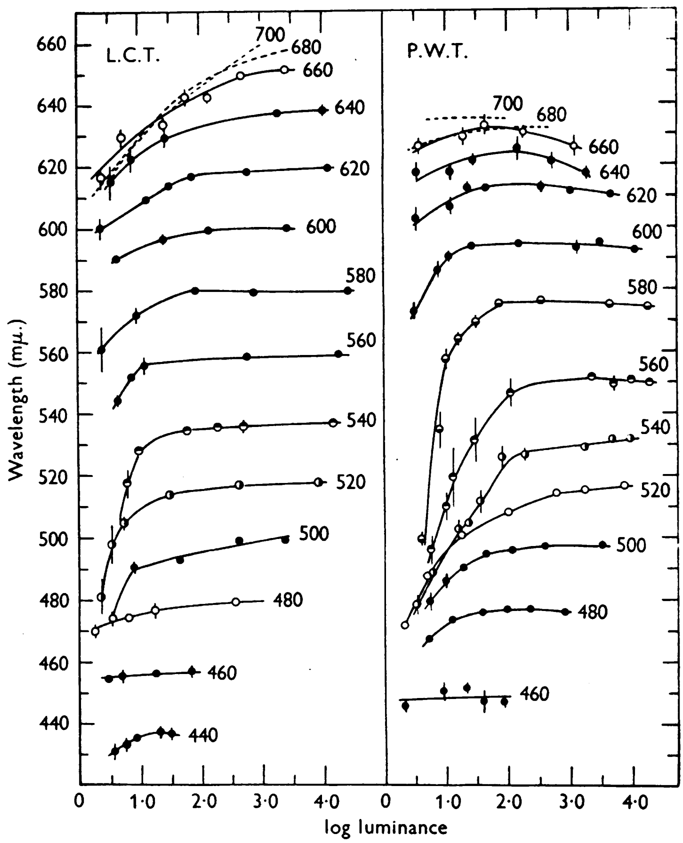

Fig. 1. The hue discrimination for two observers for various luminance levels. Steps taken in the blue direction. Ordinates indicate the mean wave-length of the test field when the measurement is complete. The figures to the right of each curve give the wave-length of the comparison field. The vertical bars indicate the value of the standard error of the mean at the points shown.

RESULTS

In Figs. 1 and 2 the ordinate records the wave-length of the lower field, and the abscissa log intensity, adjusted so that the zero position corresponds with the energy required at each wave-length to reach the threshold of vision. Since the spectral sensitivity curve was of constant shape for the field size and range of

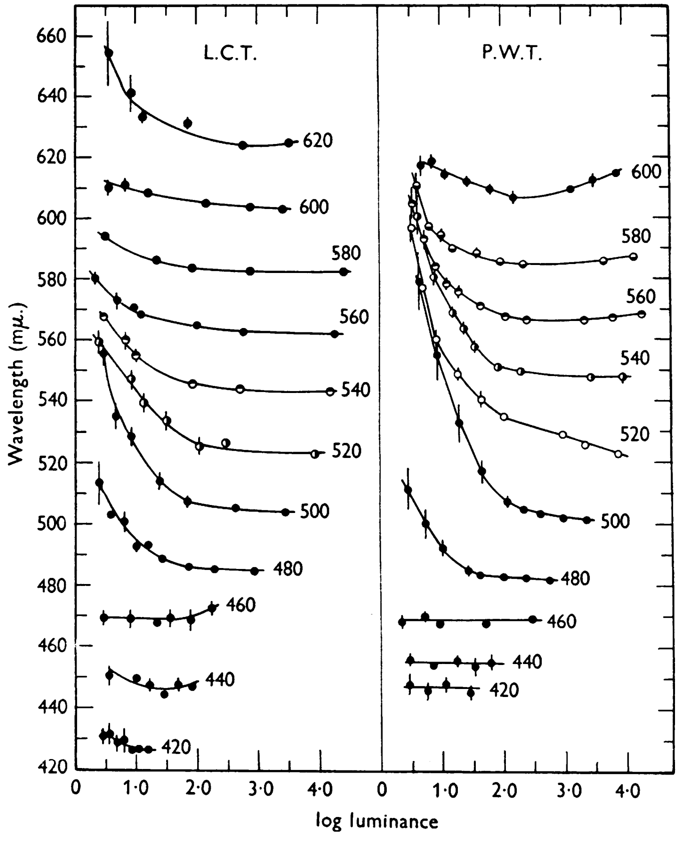

Fig. 2. The hue discrimination for two observers for various luminance levels. Steps taken in the red direction. Ordinates indicate the mean wave-length of the test field when the measurement is complete. The figures to the right of each curve give the wave-length of the comparison field. The vertical bars indicate the value of the standard error of the mean at the points shown.

energy values used, any abscissal value represents the same luminance for all wave-lengths. Each point, which is the mean of three readings, represents, at the luminance level shown, the mean wave-length of the lower field when the upper comparison field has the wave-length value shown at the right-hand side of the diagram. The size of the wave-length step $\Delta\lambda$, corresponding to a just noticeable hue discrimination step, is thus the difference between the ordinate value at any point and the value shown to the right of the series in which that point occurs. The smooth curves were drawn free-hand to be a good fit to the points.

In Fig. 1, curves for wave-lengths 680 and 700 mμ. are shown for clarity as dotted lines as they lie almost exactly over the 660 mμ. curve. Thus the spectrum on the red side of 660 mμ. cannot contribute anything to hue discrimination.

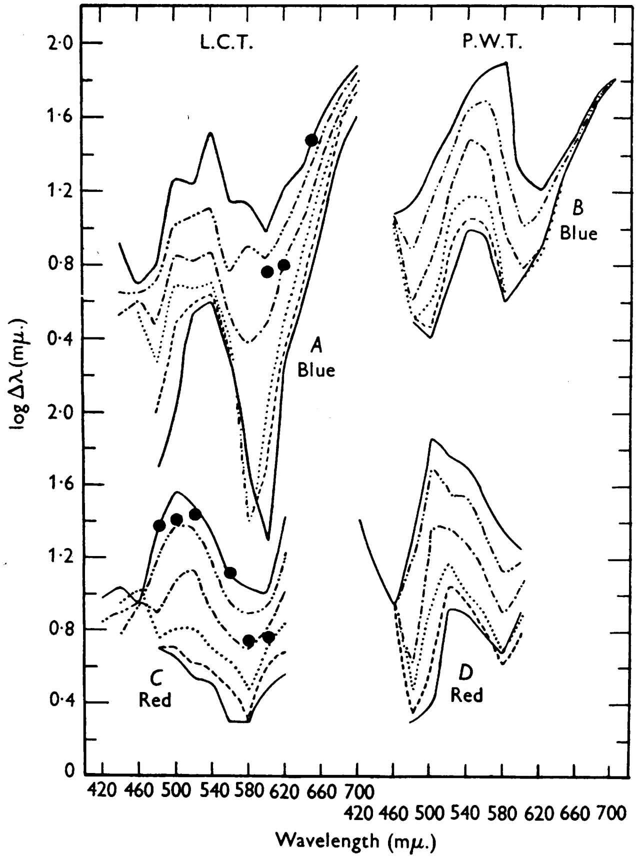

Fig. 3. The variation of log $\Delta\lambda$ with wave-length for two observers and for six luminance levels. Steps in the blue direction shown above and in the red direction below. The black points give the values of log $\Delta\lambda$ found with a field of size 15′ in observer L.C.T. by Thomson & Wright (1947).

Log units above the threshold of vision: —— =3·0; – – =2·5; ····· =2·0; –·– =1·5; –··– =1·0; —— =0·7.

The standard error of the mean, determined from the formula $\sqrt{\Sigma(x)^2/n(n-1)}$ where x is the difference of wave-length between an individual reading and the mean of the group in which it occurs and n the number of readings (three in this case), is plotted, where appreciable, as a bar above and below the mean.

In considering the magnitude of the standard error, it should be remembered that the mean is taken from three readings made on different days. It would thus be expected to have a larger value, but to be a better estimate of total errors, than if the three readings had been made consecutively. Another advantage of taking the three readings on different occasions and using a random order of presentation, is that the mean cannot be affected by any tendency on the observer's part to set the colorimeter 'by hand' instead of 'by eye'.

Fig. 3 shows the values of log $\Delta\lambda$ (the use of the log scale is merely for convenience) against λ, the wave-length of the comparison field, for various luminance levels and for both directions of observation in each observer. The values for this figure have been obtained by interpolation in Figs. 1 and 2 by means of the free-hand curves.

Combination of red and blue steps. It has been the practice, in the past, to combine in some way the results obtained when moving towards the red, with those measured when moving to the blue, so that a total hue discrimination curve may be presented for the whole spectrum without the need to specify in which direction the measurements are to be made. Such a combination must be, to some extent, artificial, since any combination curve has to deal with the middle region of the spectrum in which steps are measured in both directions; the red end in which steps can only be measured in the blue direction and the blue end where the movement is towards the red.

Pitt & Wright (1934) made the combination in the following way. At a wave-length λ, the just perceptibly different wave-lengths are λ_R in the red direction and λ_B in the blue. Then for the central region of the spectrum, $(\lambda_R-\lambda_B)/_2$ was plotted against $(\lambda_R+\lambda_B)/_2$. In the red, $(\lambda-\lambda_B)$ was plotted against $(\lambda+\lambda_B)/_2$. In the blue, $(\lambda_R-\lambda)$ was plotted against $(\lambda_R+\lambda)/_2$. Using this method of calculation, the final hue discrimination curve cannot be considered as one curve. Furthermore, the different parts do not always join smoothly, leading to secondary minima.

In the case of observer P.W.T., a graphical combination of results was possible as shown in Fig. 4*A*. Here the values for log $(\lambda_R-\lambda)$ have been plotted against $(\lambda_R+\lambda)/_2$ together in the same diagram with the values for log $(\lambda-\lambda_B)$ against $(\lambda+\lambda_B)/_2$. Since there is substantial agreement between these two sets of data a smooth combination is easily effected graphically, but in the case of observer L.C.T. such a combination was impossible as may be seen in Fig. 4*B*.

With the viewing technique adopted by this observer, irregularities in the spectral sensitivity of the retina may have affected the values obtained for $\Delta\lambda$. If the upper (comparison) field had a spectral sensitivity relative to the lower such that a given wave-length appeared more red, then instead of the wave-length of the upper field being λ it would effectively be $\lambda+\delta\lambda$, i.e. some other redder wave-length which, if applied to the lower field, would match it exactly in colour. Steps on the red side would then be measured as $(\lambda_R - \lambda)$ when physiologically they were $\{\lambda_R - (\lambda + \delta\lambda)\}$ and steps on the blue side would appear as $\lambda - \lambda_B$ when they would really be $\{(\lambda + \delta\lambda) - \lambda_B\}$. Evidence for such a red displacement of the appearance of the comparison field has already been published for this observer (Thomson, 1946), and it seems probable that the discrepancies shown between red and blue steps in these results can be accounted for by such a displacement.

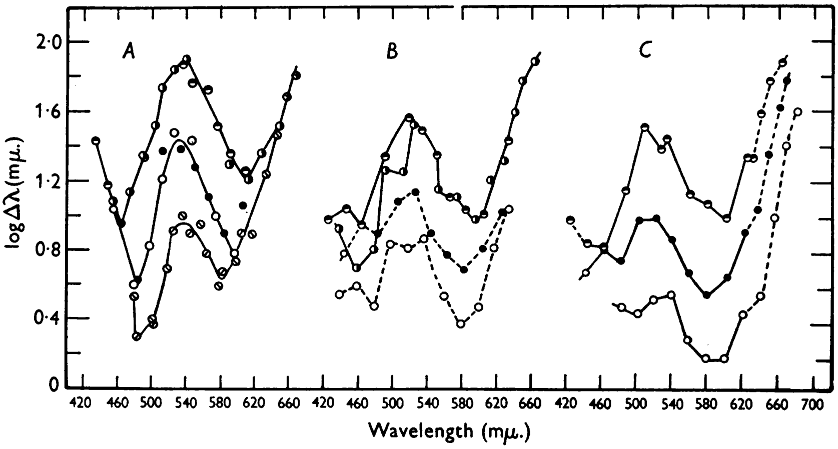

Fig. 4. A combination of the results for steps towards the blue with those towards the red. *A*, a graphical combination for observer P.W.T.; *B*, an attempt at the same graphical combination for observer L.C.T., showing the impossibility of combining the two full curves or the two dashed curves; *C*, a combination for observer L.C.T. by the method of Pitt & Wright (1934). The dotted portion of the curve is derived from steps in either the red or blue direction only.

Symbols:

A, log. lum. 0·7	◑ Blue;	◒ Red.
log. lum. 1·5	○ Blue;	● Red.
log. lum. 3·0	⦸ Blue;	⊘ Red.
B, log. lum. 0·7	◑ Blue;	◒ Red.
log. lum. 1·5	○ Blue;	● Red.
C, log. lum. 0·7	◒.	
log. lum. 1·5	●.	
log. lum. 3·0	○.	

By using the combination method of Pitt & Wright this displacement error can be eliminated over the central spectrum since neither the effective nor the real value of λ, the wave-length of the comparison field, is used in the calculation. Such a combination is shown for three luminance levels in Fig. 4*C* and the ends of the curve, to which only red or blue steps contribute, are shown as dotted lines.

There is, at each wave-length, a range of luminance levels within which the value of $\Delta\lambda$ is unaffected by luminance. This range corresponds to the minimum value of $\Delta\lambda$ for that wave-length. A hue discrimination curve, showing the value of $\Delta\lambda$ taken from such a range at each wave-length, has the advantages that, unlike the curves for the highest luminance level, it covers the whole spectrum, and, at the same time, gives the minimum discrimination step throughout the whole spectrum; it is least critical to variations in the energy content of the field. For certain wave-lengths the energy setting is so uncritical that a factor of 100 produces no appreciable change in $\Delta\lambda$. For the most critical wave-lengths, a factor of 2 may produce a 30% variation in $\Delta\lambda$. Fig. 5 shows curves derived in this way and it is these which may best be compared with that published by Pitt & Wright (1934) for observer W.D.W. For L.C.T. the combination of red and blue steps has been performed by the method of Pitt & Wright and for P.W.T. by the graphical method outlined above.

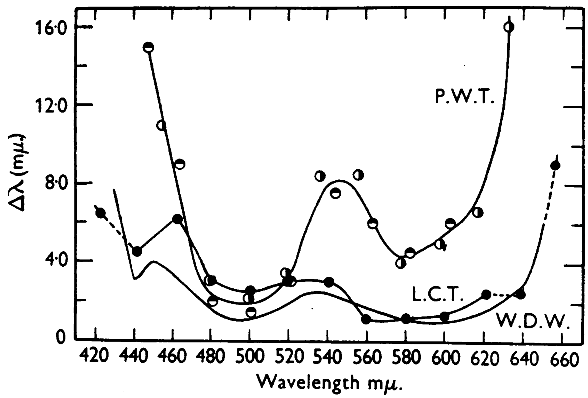

Fig. 5. The hue discrimination curves for the two observers derived by the most suitable method, as discussed in the text, and compared with the curve for W.D.W. as given in Pitt & Wright (1934).

The protanomalous nature of vision in observer P.W.T. is well shown.

DISCUSSION

The grouping of the curves at the ends of the spectrum. The deterioration of hue discrimination with lowering of the luminance level shown in Fig. 3 appears to be in the same proportion for all wave-lengths except those at the ends of the spectrum. The preservation of discrimination in the red and blue leads to a grouping together of the curves in Fig. 3.

The grouping in the red may be explained as follows. It was found that discrimination did not exist between wave-lengths 660 (approx.) and 700 mμ. Thus a step measured from the far red towards the blue will be composed of $\Delta'\lambda$, which does not contribute to the discrimination, and $\Delta''\lambda$, which does.

If on lowering the luminance level the size of the discrimination step is increased in the same proportion for all wave-lengths, then one would expect only $\Delta''\lambda$ to be affected. If $\Delta'\lambda$ is much larger than $\Delta''\lambda$ this would result in a grouping of the curves. Since the results in Fig. 3*C* and *D* have been taken as far as possible into the red without entering the region of no discrimination beyond wave-length 660 mμ., and since these results do not show grouping of the curves in the red, it is probable that the grouping shown in this region in Fig. 3*A* and *B* is due to the large contribution made by $\Delta'\lambda$ to the value of $\Delta\lambda$. Such an effect might be expected to occur again in the blue, but the grouping of the curves here is shown in the graphs for steps taken in both directions. This means that discrimination is possible further into the blue than the point at which grouping occurs, and the explanation given above is insufficient. The preservation of discrimination at low luminance in the blue and violet suggests that the visual mechanisms responsible for hue discrimination at these wave-lengths are different from those which cover the rest of the spectrum, where they are such that with decreased luminance there is an increase in $\Delta\lambda$ which is in the same proportion for different wave-lengths.

Foveal tritanopia. Hartridge (1947) regards the changes of visual performance produced by lowering the light intensity in a field of normal size (1° 20′ say) as sensibly equivalent to those given by maintaining the light intensity and reducing the size of the viewing field (say to 15′). The present results do not support such an idea, since they show that lowering the intensity with a field size of 1° 20′ gives the same proportional increase in the size of $\Delta\lambda$ in the yellow (580 mμ.) and in the blue-green (500 mμ.). Reduction of field size has a different effect, which is shown in Fig. 3 by the points which should be compared with the curves for the lowest luminance levels. These values of log $\Delta\lambda$ are taken from a paper by Thomson & Wright (1947) and refer to a field size of 15′ and light of medium intensity. Although reduction of the field size produces a deterioration of discrimination which is comparable in the blue-green with that produced by lowering the luminance of a 1° 20′ field, there is relative sparing of discrimination in the yellow and orange region of the spectrum. The deterioration of discrimination at 500 mμ. with relative sparing at 580 mμ. is characteristic of the colour blindness defect known as tritanopia.

The number of minima in the hue discrimination curve. The number of minima in a hue discrimination function have often been taken as indicative of the number of visual mechanisms contributing to colour vision under the conditions in which the curve was measured. If a small change of wave-length causes a reduction of response in one mechanism and, at the same time, a comparable increase of response in another, it is usually held that at such a spectral position there will be a point of good hue discrimination, i.e. a minimum in the curve. Thus it is important to decide how many minima the curve shows.

The present results demonstrate the three established minima in the curve at 440, 495 and 595 mμ. and also throw light on the disputed minimum between 610 and 640 mμ. This latter minimum has been found by Steindler, Jones and Laurens & Hamilton but not by König & Dieterici, Pitt & Wright nor MacAdam (see Wright, 1946). In our results this red minimum appears to be due to the way in which the results are presented. In Fig. 5 the portion represented by the dotted curve at red wave-lengths is derived from data which refer to steps in the blue direction only. This part is joined, in the method of Pitt & Wright, to the central portion of the curve, which is calculated from data derived from steps in both directions. At the point of junction a small inflexion is shown which can be altered in spectral position by combining the curves at another point. Such an inflexion never occurs when either the red or the blue steps are plotted separately. On the other hand, the same argument might apply to the minimum at 440 mμ. This minimum remains, however, at 440 mμ. no matter what point is used to join the curves together.

Since it is not possible, at any rate for the present size of field, to obtain data for steps in the red direction for wave-lengths beyond 620 mμ., it seems probable that the minima previously reported in the red are, in fact, produced by adopting a method of presentation of the results which is not justified.

SUMMARY

1. The hue discrimination of the eye has been measured with a 1° 20′ field in the Wright Colorimeter at various luminance levels for two observers, one with normal and the other with protanomalous vision.

2. With reduction of luminance, discrimination deteriorates in the same proportion for all wave-lengths between 620 and 490 mμ. In the red the deterioration, for experimental reasons, appears to be less than it actually is. In the blue the deterioration is also small but here the difference of behaviour from the central spectral region is probably due to differences of visual mechanisms.

3. Tritanopia is not found with the 1° 20′ field at low luminance levels.

4. A possible explanation of the apparent presence of a minimum in the curve, reported by some previous writers, between 610 and 640 mμ. has been given.

Our thanks are due to Dr W. D. Wright for the unrestricted use of his apparatus and department and also for much valuable discussion. We should also like to thank the Medical Research Council for their continued support for Visual Research at Imperial College.

REFERENCES

Hartridge, H. (1947). *Philos. Trans.* B, **232**, 566.

Pitt, F. H. G. & Wright, W. D. (1934). *Proc. phys. Soc.* **46**, 459.

Thomson, L. C. (1946). *Nature, Lond.*, **157**, 805.

Thomson, L. C. (1951). *J. Physiol.* **112**, 114.

Thomson, L. C. & Wright, W. D. (1947). *J. Physiol.* **105**, 316.

Wright, W. D. (1946). *Researches on Normal and Defective Colour Vision.* London: Kimpton.