IV. On the discovery of four transition points in the spectrum and the primary colour sensations

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To cite this article: Frank Allen Ph.D. F.R.S.C. (1919) IV. On the discovery of four transition points in the spectrum and the primary colour sensations , Philosophical Magazine Series 6, 38:223, 55-81, DOI: [10.1080/14786440708635929](https://doi.org/10.1080/14786440708635929)

To link to this article: <http://dx.doi.org/10.1080/14786440708635929>

Published online: 08 Apr 2009.

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If vapour is given off from the drop it will condense to form a primary composite surface, and this *being contractile* may pull the drop itself out to form a secondary surface. The fact that B.P. "paraffin" and castor oil do not spread at all on clean glass is due to their low vapour pressure, and is no evidence as to the tension of the glass-oil interface.

I confess I should not have expected that a film of fluid of the order of 1 micron in thickness on a solid face would be spontaneously contractile, but the migration of the drops of acetic acid appears to afford conclusive evidence on this point. Any primary composite surface will contract only if a further thickening of the film lowers the surface tension. A fully formed primary surface, that is to say one in which the film has thickened to the point at which the function $\frac{dT}{dx}$ (where T is the tension, and x the thickness of the film) changes its sign, would have no tendency to contract; indeed it would resist further contraction. The fact that primary surfaces saturated with fluid actually do contract spontaneously when exposed to air, is due frequently to the thinning of the surface film by evaporation. This is readily demonstrable with pure benzene on water. Substances such as benzene on water and acetic acid on glass behave in fact as though the film on a primary composite surface varied in thickness with variations in the vapour pressure of the fluid of which it is composed. If this be so the film on a composite surface cannot be always and of necessity one molecule thick as some writers suppose.

IV. *On the Discovery of Four Transition Points in the Spectrum and the Primary Colour Sensations.* By FRANK ALLEN, Ph.D., F.R.S.C., Professor of Physics, University of Manitoba, Winnipeg*.

THE researches in colour-vision which I have made from time to time have had for their secondary object the extension of our knowledge of the persistence of vision, and for their primary object the determination in an incontrovertible manner, if possible, of the number of fundamental colour-sensations, and the precise waves of light by which they are excited, concerning which there has been and still is much controversy.

In this communication I have gathered together some

* Communicated by the Author.

results previously published, and incorporated with them new investigations which appear absolutely to determine the number of the fundamental colour-sensations. With the method of study which I have used it does not yet seem possible to designate the exact waves of light which excite the primary sensations of colour; but it is possible to determine the limits between which these hues must lie.

The apparatus used for purposes of measurement was similar to that described in a former paper*, and essentially the same as that devised and used by E. L. Nichols†. Light from an acetylene flame passed through a disk with two opposite open sectors of ninety degrees each, whose speed of rotation was electrically recorded upon a chronograph. The flickering light was dispersed into a spectrum by a suitable spectrometer, and a shutter eyepiece enabled observations to be made as desired upon narrow strips of the spectrum. The speed of the disk was adjusted so that the flickering of the light became just imperceptible and then recorded. The arrangement is shown by the diagram in fig. 1.

Fig. 1.

By means of an arc-light and a second spectrometer with two prisms, a brilliant spectrum of considerable dispersion was formed, narrow portions of which were isolated by a shutter eyepiece, and used to fatigue the eye with which observations of the persistence of vision were made. An interval of time of about three minutes was allowed for fatiguing the eye before each measurement of the critical time of flicker was made. In this way a persistency curve

* Allen, "Effect on the Persistence of Vision of Exposing the Eye to Light of Various Wave-Lengths," *Phys. Rev.* xi. 1900.

† "On the Duration of Colour Impressions on the Retina," *Am. Journ. Sci.* xxviii. 1884.

for the whole spectrum was obtained which can be compared with a normal curve previously determined when the eye was adapted for diffused daylight. At various times these curves have been obtained, and in this paper seventeen of them are compared and discussed.

In two former investigations* curves were described for seven portions of the spectrum, viz.: for red, orange, yellow, green, blue, and violet, the wave-lengths of which were respectively $\lambda \cdot 680 \mu$, $\lambda \cdot 620 \mu$, $\lambda \cdot 589 \mu$, $\lambda \cdot 577 \mu$, $\lambda \cdot 520 \mu$, $\lambda \cdot 440 \mu$, and $\lambda \cdot 400 \mu$. These curves are all reproduced in this paper.

In a communication to the British Association† at its

Fig. 2.

Winnipeg meeting, I pointed out a very curious and remarkable effect occurring when the fatiguing colour was $\lambda \cdot 660 \mu$. It will be noticed from fig. 2 that the persistency

* "Effect on Persistence of Vision, etc.," Phys. Rev. xi. 1900. "Some Phenomena of the Persistence of Vision," Phys. Rev. vol. xxviii. 1909. Also Trans. Roy. Can. 1908.

† Report of B.A.A.S. 1909, p. 410.

curve obtained when the eye was fatigued with a pure red of wave-length $\lambda \cdot 680 \mu$ has in it a single characteristic elevation which corresponds to the red portion of the spectrum, the rest of the curve coinciding with the normal. It will also be noticed from fig. 8, that when the fatiguing colour was the wave-length $\lambda \cdot 589 \mu$, there were two elevations in the curve, one in the red as before, and the second in the part corresponding to green. It occurred to me that there must be in the spectrum a point of transition from the type of curve with one elevation to that with two, and that the curve obtained when this transition point was made the fatiguing colour would probably differ in some way from both. Accordingly, search was made for it. The eye was fatigued with the colour $\lambda \cdot 670 \mu$, and the readings in Table I. were obtained.

TABLE I.

λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 670 \mu$.	λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 670 \mu$.
$\cdot 733 \mu$	$\cdot 0340$ sec.	$\cdot 0380$ sec.	$\cdot 530 \mu$	$\cdot 0171$ sec.	$\cdot 0175$ sec.
$\cdot 695$	$\cdot 0248$	$\cdot 0266$	$\cdot 500$	$\cdot 0215$	$\cdot 0224$
$\cdot 663$	$\cdot 0198$	$\cdot 0214$	$\cdot 470$	...	$\cdot 0306$
$\cdot 601$	$\cdot 0156$	$\cdot 0155$	$\cdot 460$	$\cdot 0332$	...
$\cdot 564$	$\cdot 0157$	$\cdot 0155$	$\cdot 430$	$\cdot 0513$	...

These values are plotted in fig. 3, and give a curve with one elevation, similar to that for the wave-length $\lambda \cdot 680 \mu$. Similarly, curves were obtained for the wave-lengths $\lambda \cdot 651 \mu$ and $\lambda \cdot 625 \mu$, the data for which are tabulated in Table II. and Table III. respectively.

TABLE II.

λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 651 \mu$.	λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 651 \mu$.
$\cdot 733 \mu$	$\cdot 0318$ sec.	$\cdot 0353$ sec.	$\cdot 530 \mu$	...	$\cdot 0177$ sec.
$\cdot 695$	$\cdot 0232$	$\cdot 0254$	$\cdot 500$	$\cdot 0189$ sec.	$\cdot 0189$
$\cdot 663$	$\cdot 0185$	$\cdot 0197$	$\cdot 460$	$\cdot 0310$	...
$\cdot 601$	$\cdot 0144$	$\cdot 0145$	$\cdot 430$	$\cdot 0458$	...
$\cdot 564$	$\cdot 0147$	$\cdot 0153$	...	...	...

TABLE III.

λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 625 \mu$.	λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 625 \mu$.
$\cdot 733 \mu$	$\cdot 0318$ sec.	$\cdot 0364$ sec.	$\cdot 530 \mu$	...	$\cdot 0170$ sec.
$\cdot 695$	$\cdot 0232$	$\cdot 0249$	$\cdot 500$	$\cdot 0189$ sec.	$\cdot 0194$
$\cdot 663$	$\cdot 0185$	$\cdot 0190$	$\cdot 460$	$\cdot 0310$	...
$\cdot 601$	$\cdot 0144$	$\cdot 0144$	$\cdot 430$	$\cdot 0458$	...
$\cdot 564$	$\cdot 0147$	$\cdot 0162$	...	...	...

Fig. 3.

The corresponding curves are shown in fig. 5 and fig. 6. Both are of the same type, and exhibit two elevations similar to those in the curve for the wave-length $\lambda \ 589\mu$ in fig. 8. As these measurements are tedious to make, I yielded to the temptation to determine these curves, and a few others, as will be noticed, only for those parts where experience shows

the elevations can occur. There can be no doubt that the rest of the curve would coincide with the normal.

Fig. 4.

The transition point was thus narrowed down to the wave-length $\lambda \cdot 660 \mu$. The eye, therefore, was fatigued with this colour, and from the data obtained, Table IV., the curve in fig. 4 was plotted.

TABLE IV.

λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 660 \mu$.	λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 660 \mu$.
$\cdot 733 \mu$	$\cdot 0353$ sec.	$\cdot 0358$ sec.	$\cdot 530 \mu$	$\cdot 0171$ sec.	$\cdot 0170$ sec.
$\cdot 695 \mu$	$\cdot 0248$	$\cdot 0243$	500	$\cdot 0215$	$\cdot 0211$
$\cdot 663 \mu$	$\cdot 0198$	$\cdot 0196$	$\cdot 470$	...	$\cdot 0295$
$\cdot 601 \mu$	$\cdot 0156$	$\cdot 0155$	$\cdot 460$	$\cdot 0332$	...
$\cdot 564 \mu$	$\cdot 0157$	$\cdot 0156$	$\cdot 430$	$\cdot 0513$	...

Fig. 5.

No elevations at all appeared, and the abnormal curve coincided with the normal throughout their length. This surprising result at first was taken to indicate that the eye

had not been sufficiently fatigued or that the readings were not properly taken. With the greatest care the whole of the readings were repeated on the following day with exactly the same result. The remarkable conclusion follows, that fatiguing the eye with a narrow band of colour whose central wave-length is $\lambda \cdot 660 \mu$, has not the slightest perceptible effect on

Fig. 6.

the measurement of the persistence of vision for any part of the spectrum. This wave-length, $\lambda \cdot 660 \mu$, is therefore the transition point between curves of the single red elevation type and those of the double red and green elevation type.

Fig. 7.

Fig. 8.

The persistency curve obtained when the eye was fatigued with the wave-length $\lambda \cdot 620 \mu$ is here reproduced in fig. 7 from a previous paper to which reference has already been made. This curve is of the double red and green elevation type, similar to the curves of the two figures immediately preceding.

Fig. 9.

Further consideration led to the conclusion that a second transition point ought to exist between curves of the double red and green elevation type and those of the single green elevation type. Since the curve for the wave-length $\lambda \cdot 520 \mu$, fig. 13, was known from a previous investigation, persistency curves were successively determined with the fatiguing colours $\lambda \cdot 560 \mu$ and $\lambda \cdot 540 \mu$. The data for these are given

in Table V. and Table VI., and are plotted in fig. 9 and fig. 10 respectively. Both curves, it will be noticed, are characterized by a single elevation in the green.

Fig. 10.

TABLE V.

λ .	Normal Persistence.	Eye fatigued with λ .560 μ .	λ .	Normal Persistence.	Eye fatigued with λ .560 μ .
.735 μ	.0337 sec.	.0323 sec.	.522 μ	.0164 sec.	.0189 sec.
.690	.0221	.0224	.495	.0209	.0214
.647	.0167	.0164	.453	.0360	.0380
.593	.0137	.0144	.423	.0538	.0500
.553	.0141	.0164	.410	.0620	...
.535	...	.0169	...	...	...

TABLE VI.

λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 540 \mu$.	λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 540 \mu$.
$\cdot 735 \mu$	$\cdot 0337$ sec.	$\cdot 0318$ sec.	$\cdot 522 \mu$	$\cdot 0164$ sec.	$\cdot 0190$ sec.
$\cdot 690$	$\cdot 0221$	$\cdot 0218$	$\cdot 495$	$\cdot 0209$	$\cdot 0209$
$\cdot 647$	$\cdot 0167$	$\cdot 0161$	$\cdot 453$	$\cdot 0360$	$\cdot 0378$
$\cdot 593$	$\cdot 0137$	$\cdot 0138$	$\cdot 423$	$\cdot 0538$	$\cdot 0538$
$\cdot 553$	$\cdot 0141$	$\cdot 0161$	$\cdot 410$	$\cdot 0620$	$\cdot 0602$
$\cdot 535$	...	$\cdot 0171$	...	...	...

Since the persistency curve for the wave-length $\lambda \cdot 577 \mu$, fig. 11, had previously been determined to be of the double

Fig. 11.

red and green elevation type, it was evident that the transition point must be near $\lambda \cdot 570 \mu$. This hue was then used as the

TABLE VII.

λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 570 \mu$.	λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 570 \mu$.
$\cdot 735 \mu$	$\cdot 0337$ sec.	$\cdot 0320$ sec.	$\cdot 522 \mu$	$\cdot 0164$ sec.	$\cdot 0163$ sec.
$\cdot 690$	$\cdot 0221$	$\cdot 0224$	$\cdot 495$	$\cdot 0209$	$\cdot 0205$
$\cdot 647$	$\cdot 0167$	$\cdot 0165$	$\cdot 453$	$\cdot 0360$	$\cdot 0365$
$\cdot 593$	$\cdot 0137$	$\cdot 0137$	$\cdot 423$	$\cdot 0538$	$\cdot 0554$
$\cdot 553$	$\cdot 0141$	$\cdot 0146$	$\cdot 410$	$\cdot 0620$	...
$\cdot 535$	...	$\cdot 0153$	...	...	...

fatiguing colour, and the results given in Table VII. obtained from which the curve in fig. 12 is plotted.

This curve, like that for the first transition point, has no elevations, but coincides at all points with the normal.

Fig. 12.

It was now certain that two more transition points existed, one between the single green elevation type of curve, such as that for the wave-length $\lambda \cdot 520 \mu$, fig. 13, and the double green and violet elevation type, like that for the wave-length $\lambda \cdot 440 \mu$, fig. 16; and the other marking the transition from

this latter type of curve to the single violet elevation type exhibited by that obtained for the wave-length $\lambda \cdot 400 \mu$, fig. 17, which was known from previous work*.

Fig. 13.

In the process of narrowing down the third transition

* NOTE.—The readings obtained when the eye was fatigued with the wave-lengths $\lambda \cdot 440 \mu$ and $\lambda \cdot 400 \mu$ are given in the paper already referred to, viz.: "Effect on Persistence of Vision, etc.," *Phys. Rev.* vol. xi. By some oversight the corresponding normal persistency readings were omitted from that paper, and they are now given here:

λ .	Normal Persistence.	λ .	Normal Persistence.	λ .	Normal Persistence.
$\cdot 758 \mu$	$\cdot 0182$ sec.	$\cdot 622 \mu$	$\cdot 0113$ sec.	$\cdot 428 \mu$	$\cdot 0203$ sec.
$\cdot 715$	$\cdot 0156$	$\cdot 573$	$\cdot 0105$	$\cdot 409$	$\cdot 0249$
$\cdot 680$	$\cdot 0134$	$\cdot 507$	$\cdot 0120$	$\cdot 400$	$\cdot 0277$
$\cdot 647$	$\cdot 0121$	$\cdot 465$	$\cdot 0154$	...	...

region, the wave-lengths $\lambda \cdot 480 \mu$ and $\lambda \cdot 460 \mu$ were successively used as fatiguing colours, for which the results in Table VIII. and Table IX. were obtained.

TABLE VIII.

λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 480 \mu$.	λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 480 \mu$
$\cdot 735 \mu$	$\cdot 0230$ sec.	$\cdot 0234$ sec.	$\cdot 522 \mu$	...	$\cdot 0150$ sec.
$\cdot 690$	$\cdot 0171$	...	$\cdot 495$	$\cdot 0171$ sec	$\cdot 0168$
$\cdot 647$	$\cdot 0147$	$\cdot 0147$	$\cdot 453$	$\cdot 0246$	$\cdot 0244$
$\cdot 593$	$\cdot 0130$	$\cdot 0133$	$\cdot 423$	$\cdot 0312$	$\cdot 0309$
$\cdot 553$	...	$\cdot 0131$	$\cdot 410$	$\cdot 0368$	$\cdot 0361$
$\cdot 535$	$\cdot 0138$	$\cdot 0141$	$\cdot 400$	$\cdot 0432$	$\cdot 0423$

TABLE IX.

λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 460 \mu$.	λ .	Normal Persistence.	Eye fatigued with $\lambda \cdot 460 \mu$.
$\cdot 735 \mu$	$\cdot 0230$ sec.	...	$\cdot 455 \mu$	$\cdot 0171$ sec.	$\cdot 0176$ sec.
$\cdot 690$	$\cdot 0171$	...	$\cdot 453$	$\cdot 0246$	$\cdot 0249$
$\cdot 647$	$\cdot 0147$	...	$\cdot 423$	$\cdot 0312$	$\cdot 0311$
$\cdot 593$	$\cdot 0130$	$\cdot 0124$ sec.	$\cdot 417$	...	$\cdot 0341$
$\cdot 553$	...	$\cdot 0132$	$\cdot 410$	$\cdot 0368$	$\cdot 0378$
$\cdot 535$	$\cdot 0138$	$\cdot 0137$	$\cdot 405$	...	$\cdot 0415$
$\cdot 522$	...	$\cdot 0150$	$\cdot 400$	$\cdot 0432$	$\cdot 0426$

These curves are exhibited in fig. 14 and fig. 15 respectively. They show no elevations at all, but are coincident with the normal curves. The conclusion appears to be that this transition region is broader than those previously described, probably because the dispersion of the blue in the prismatic spectrum is greater than that of the red. The wave-lengths $\lambda \cdot 480 \mu$ and $\lambda \cdot 460 \mu$ may be regarded, therefore, as marking the edges of the transition band, the centre being the wave-length $\lambda \cdot 470 \mu$. For this colour no persistency curve was considered necessary. The curve with the wave-length $\lambda \cdot 480 \mu$, fig. 14, appears to retain a slight vestige of the green elevation which I have indicated by altering the curve at "b."

The fourth and last transition point obviously must lie between the wave-lengths $\lambda \cdot 440 \mu$ and $\lambda \cdot 400 \mu$, since the curve for the former, fig. 16, has two elevations in the green and the violet regions, and that for the latter, fig. 17, only one in the violet. The colour $\lambda \cdot 420 \mu$ was selected for the first trial. This proved to be the desired point, and no other

Fig. 14.

TABLE X.

λ .	Normal Persistence.	Eye fatigued with λ 420 μ .	λ .	Normal Persistence.	Eye fatigued with λ 420 μ .
705 μ	0.0262 sec.	0.0262 sec.	465 μ	0.0275 sec.	...
665	0.0169	0.0175	448	0.0336	0.0339 sec.
626	0.0144	...	430	0.0392	0.0385
577	0.0143	0.0145	424	...	0.0415
540	0.0156	0.0153	417	0.0450	0.0446
512	0.0183	0.0179	410	...	0.0487
488	0.0219	0.0215	405	0.0530	0.0536

colours on either side were tried. The readings are shown in Table X. and plotted in fig. 18. This curve is without any indication of elevations, and coincides throughout its course with the normal.

Fig. 15.

In order to exhibit the seventeen curves described in the preceding pages comprehensively in a simple figure (fig. 19), they have all been replotted so as to make the normal curve a straight line by reducing its scale in all

parts to the arbitrary value of 100, and the values of the abnormal curves in the same ratio. Slight departures of the abnormal from the normal curves have been ignored,

Fig. 16.

long experience having shown that they are without significance, and to be attributed rather to the inevitable errors of observation.

The elevations of the curves, both single and double, can be readily recognized and compared, and their limiting wave-lengths noted. As they are arranged in ascending order of wave-lengths, with the shortest, violet, at the bottom, the curves for the four transition points fall into their proper places, and show their relation to the curves of the other types. Each band of colour used for fatiguing the eye is indicated by a short vertical line just above the normal curve.

Finally, the seventeen curves have been consolidated into a single composite curve by taking the mean values for all the elevations of all the curves. These values are shown in

Table XI., and are plotted on an enlarged scale in fig. 20. The four transition points are indicated by short vertical

Fig. 17.

lines as before, and are arranged in pairs quite symmetrically situated in relation to the two minima of the curve.

Fig. 18.

The three elevations of this curve are strongly indicative of a trichromatic basis for the perception of colour.

TABLE XI.

λ .	Mean Ratio.	λ .	Mean Ratio.	λ .	Mean Ratio.	λ .	Mean Ratio.
400 μ	122	480 μ	104.7	566 μ	105	663 μ	106
415	114	490	106	600	100.7	677	108
423	110	500	107.5	620	100.7	695	110
433	107	515	109.5	630	101.7	715	111
455	100	523	112	640	102.5	733	112
470	102.7	550	109	650	104	758	110

The general results in this paper may be represented diagrammatically as in fig. 21. In this diagram the indicated wave-lengths mark the transition points and divide the spectrum into five parts. It is evident that the fundamental

Fig. 19.

red sensation corresponds to some hue between the beginning of the red and the point of transition at $\lambda \cdot 660 \mu$. Similarly, the fundamental green sensation is excited by some portion of the spectrum lying between the second and third transition

points at the wave-lengths $\lambda \cdot 570 \mu$ and $\lambda \cdot 470 \mu$. Finally, the third fundamental sensation, which must be violet and not blue as many colour-theorists allege, lies between the fourth point of transition at $\lambda \cdot 420 \mu$ and the end of the violet. It is to be regretted that this method of investigation does not yet enable us to discover the exact fundamental hues. It is possible that the method of fatiguing the eye with carefully selected pairs of colours at one time, such as I have used in another investigation*, or even with three colours

Fig. 20.

Fig. 21.

simultaneously, will bring the desired precision. Undoubtedly such investigations will elicit much new information on the complex and apparently inexhaustible phenomena of colour-vision.

One of the most persistent problems in colour-vision is the proper disposition of yellow. In purity of appearance it seems to have quite as much claim as red and green to be regarded as primary in its nature. Indeed, the psychologists quite universally recognize fully the primary quality of the sensation of yellow. But the five persistency curves obtained between the wave-lengths $\lambda \cdot 660 \mu$ and $\lambda \cdot 570 \mu$ are identical

* "Some Phenomena of the Persistence of Vision," *Phys. Rev.* vol. xxviii. (1909).

in their nature, and therefore in the conclusions to be drawn from them. This region includes orange as well as yellow. No one doubts that orange is a compound sensation; and since, according to the curves, the purest yellow has precisely the same effect on the eye, it must likewise be a compound sensation. The same reasoning applies to blue, which also must be compound in its nature.

The existence of three sharply-defined regions of the spectrum exhibiting curves of the single elevation type, corresponding to red, green, and violet, proves conclusively the existence in the eye of three primary sensations corresponding to these colours. The concurrent evidence that yellow and blue are compound sensations completes the proof.

The evidence presented in this paper for the existence of but three fundamental colour-sensations is entirely the result of experiments made upon the normal retina. This may be supplemented and greatly strengthened by comparison with persistency curves obtained by persons who are colour-blind. In a former investigation * I studied by this method twenty-seven cases of abnormal colour-vision; and in fig. 22, from that paper, there are shown six out of the seven representative classes into which cases of colour-blindness naturally fall. The persistency curves are drawn after the manner of those in fig. 19; the straight horizontal line at O is my own normal curve, and the other compared with it is that obtained by the colour-blind person. These curves were determined when the eyes were not fatigued, but were rested in ordinary daylight.

In fig. 22 Class I. is a curve with one elevation in the red, indicating red-blindness; Class II. shows one elevation in the green, the characteristic of green-blindness; Class III. shows two elevations, one in the red and the other in the green, indicating a type of blindness involving those two colours; Class IV. is a modification of the same type as Class III.; Class V. has two elevations, one in the red and the other in the violet, another type of colour-blindness involving two colours; Class VI. has two elevations, one in the green and the other in the violet, still another type, being the third possible variety of colour-blindness involving two colours; Class VII. is that of a totally colour-blind person, and shows the elevation of the whole curve. These persistency curves for eyes that are naturally colour-blind show exactly the same elevations that are obtained for the normal eye when fatigued

* "Persistence of Vision in Colour-blind Subjects," *Phys. Rev.* vol. xv. (1902).

by various spectral colours. These curves for colour-blindness, therefore, constitute strong additional evidence for the existence of three primary colour-sensations—red, green, and violet.

Fig. 22.

According to this theory seven general classes of colour-blindness are possible: three classes when any *one* colour-sensation is absent or defective; three classes when any *two* sensations are absent or defective; and one class when *all three* sensations are absent or defective. The seven types of

curves in fig. 22 show all these classes excepting only that for violet-colour-blindness, for which type I have not yet found a subject.

For the purpose of comparison, I have brought together the exact hues of the primary colours according to several investigators whose experiments were conducted on the basis of the trichromatic theory. With these are included the colours selected by Hering for his theory of colour-vision, and those determined for the same theory by the accurate experiments of Baird*.

	<i>Red.</i>	<i>Green.</i>	<i>Blue.</i>	
HELMHOLTZ...	Carmine-red; not in spectrum.	$\cdot 56 \mu$ to $\cdot 54 \mu$.	Ultramarine-blue.	
KÖNIG	Purple-red; just outside spectrum.	$\cdot 505 \mu$.	$\cdot 470 \mu$.	
EXNER	Red complementary to $\cdot 494 \mu$. (About $\cdot 66 \mu$.)	$\cdot 508 \mu$.	$\cdot 475 \mu$.	
ALLEN	Between end of spectrum and $\cdot 66 \mu$.	$\cdot 570 \mu$ to $\cdot 470 \mu$	Violet, between $\cdot 420 \mu$ and end.	
	<i>Red.</i>	<i>Green.</i>	<i>Yellow.</i> <i>Blue.</i>	
HERING	Purple-red; non-spectral.	$\cdot 495 \mu$.	$\cdot 5745 \mu$.	$\cdot 471 \mu$.
BAIRD	Purple-red; non-spectral.	$\cdot 490 \mu$.	$\cdot 570 \mu$.	$\cdot 460 \mu$.

There is no conflict necessarily arising between my own fundamental hues for red and green and those of Helmholtz, König, and Exner; there is divergence in the case of violet. But if it is at all justifiable for Helmholtz and the others to differ in their green hues by nearly $\cdot 06 \mu$, no exception need be taken to my violet determination because it differs from the others by an equal amount.

In endeavouring to connect the transition points with other colour-phenomena, I have found specially suggestive the colour-sensation curves obtained by Abney and Watson, fig. 23, and by König and Dieterici, fig. 24. On each of these figures I have indicated the transition points by short vertical lines with wave-lengths attached.

In the curves of Abney and Watson the transition points $\lambda \cdot 660 \mu$ and $\lambda \cdot 470 \mu$ are practically at the ends of the sensation curve for green; and the remaining transition points at $\lambda \cdot 420 \mu$ and $\lambda \cdot 570 \mu$ are near the ends of the sensation curve for blue. While the green and red sensation curves extend to the wave-length $\lambda \cdot 43 \mu$, yet their influence compared with blue seems quite negligible on the more refrangible side of $\lambda \cdot 470 \mu$. The transition point at $\lambda \cdot 570 \mu$ is also very close

* J. W. Baird, "The Colour Sensitivity of the Peripheral Retina," Carnegie Institution, 1905.

to the intersection of the green and red sensation curves. The transition point at $\lambda \cdot 420 \mu$ is shown by the curves to be practically outside the influence of the red and green sensations, and hence may be regarded as a region of a single

Fig. 23.

Normal Sensation Curves. (Abney and Watson.)
(From Parsons's 'Colour Vision,' p. 244.)

Fig. 24.

Sensation Curves. (König and Dieterici.)
(From Parsons's 'Colour Vision,' p. 222.)

pure-colour sensation. Similarly, the spectral region from the transition point $\lambda \cdot 660 \mu$ to the end of the spectrum is pure red free from the influence of the other two sensations.

The sensation curves of König and Dieterici, fig. 24, show some differences. The ends of the green sensation curve are the transition points $\lambda \cdot 660 \mu$ and $\lambda \cdot 420 \mu$, while the transition point $\lambda \cdot 470 \mu$ is still the more refrangible end of the sensation curve for red. The transition point $\lambda \cdot 570 \mu$

marks one end of the sensitive curve for violet. It will be noticed that the regions between the transition points $\lambda \cdot 660 \mu$ and $\lambda \cdot 420 \mu$ and the respective ends of the spectrum are, as before, characterized by purity and simplicity of colour-sensation. The transition point at $\lambda \cdot 570 \mu$ is again at the intersection of the red and green sensation curves, that is, where the two sensations balance the influence of each other, without sufficient of the third sensation to make itself perceptible. In both figures one can see reasons why the regions between $\lambda \cdot 420 \mu$ and $\lambda \cdot 470 \mu$, and between $\lambda \cdot 570 \mu$ and $\lambda \cdot 660 \mu$, should be characterized by compound sensations. But it is difficult to understand why the exceedingly complex region between $\lambda \cdot 470 \mu$ and $\lambda \cdot 570 \mu$ should exhibit, as it does, persistency curves with only one elevation in the green.

The occurrence of the four transition points at the boundaries of the sensation curves cannot be in any sense accidental, and is certainly not intentional, since the transition points were discovered long before any examination of the sensation curves was made in this connexion.

The cumulative effect of all the experimental evidence presented in this paper seems to warrant most strongly the conclusions already expressed, that there are but three colour sensations, which correspond to red, green, and violet, and that these sensations are primarily excited by hues which lie between the limits set by the four transition points.

V. *The Persistence of Vision of Colours of Varying Intensity.* By FRANK ALLEN, Ph.D., F.R.S.C., Professor of Physics, University of Manitoba, Canada*.

IN a former communication to the Philosophical Magazine† a method of measuring the luminosity of the spectrum was discussed, which may also be used for the determination of the persistence of vision of colours of varying intensity. The arrangement of apparatus employed in the present investigation is very similar to that described in the paper referred to, and is shown diagrammatically in fig. 1.

Light from the acetylene flame (A), after concentration by a lens (B), passed through an open sector (90°) of the disk (C) which was rotated by an electric motor, then through two Nicol prisms (D and E) arranged with their principal

* Communicated by the Author.

† "A New Method of Measuring the Luminosity of the Spectrum," May 1911.