THE INFLUENCE OF DIFFERENT SPECTRAL WAVELENGTHS ON ROD AND CONE SENSITIVITY UNDER CONDITIONS OF LOW ILLUMINATION *

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Introduction

Inspite of vast improvements in radar and instrument flying, aircrew are dependent on some contact flying, even in the most advanced aircraft of today. For instance, formation flying and final stage of interception in combat flying and avoidance of collisions in commercial flying especially with increasing airport density, entail maximum air-to-air visibility at night, particularly under conditions of poor visibility (low illumination). In many missions, apart from the varied, requirements of visual tasks within the aircraft (general orientation, reading instruments, monitoring radar etc.) fine visual acuity outside the aircraft (target detection and identification, details of colour and terrain) may, indeed be critical. Proper choice of cockpit illumination therefore, has to be based on such varying visual requirements.

Before dealing with the essential considerations for cockpit lighting, a discussion on certain characteristics of visual function in general will be relevant.

Dual Retinal Mechanism (Rod and Cone Vision)

Histologically and functionally the retina has two types of sensory end organs—the rods and the cones. The cones operate at intensities (.004 mL upto 10000 mL) and are responsible for sensations of colour and fine detail (photopic vision). The rods function differentially at low intensities (.004 mL to .000001 mL) and initiate achromatic sensations with little or only gross detail (scotopic vision).

Spectral Sensitivity

The rods and cones differ in their sensitivity over the entire visible spectrum under different levels of illumination (fig. 1). Rods are much more sensitive than cones to radiation from the short wave end of the spectrum, and are about as sensitive as the cones to radiation from the long wave end, 600—660 m μ (red).

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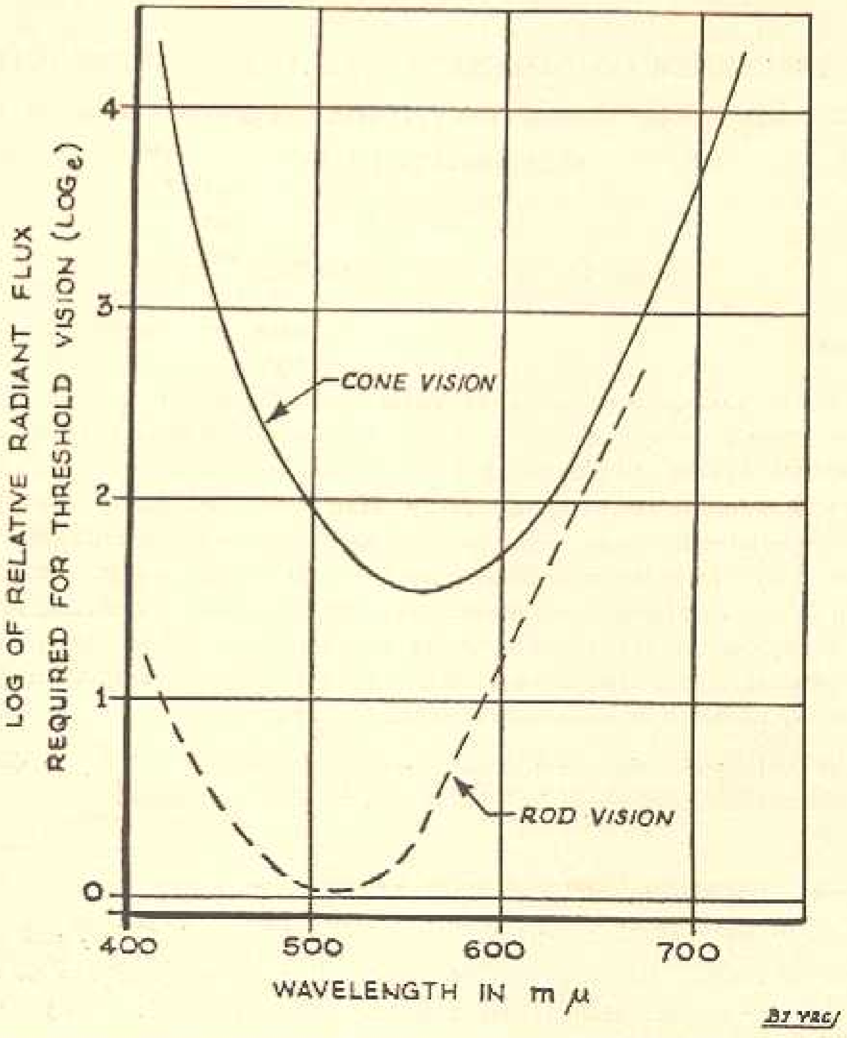
* Project completed at A. F. School of Aviation Medicine in April, 1961.

FIG. 1



Spectral Sensitivity Curve [13] Relative amounts of radiant flux required to stimulate rods and cones

Consideration for Cockpit Illumination

The two primary considerations in cockpit illumination are the intensity and colour of the light which should be sufficient for optimal cone vision within the aircraft, with the least effect on rod sensitivity for detection tasks outside. Also, the system should be flexible so that the lighting can be easily adapted to the special needs of each crew member.

Studies of Rock [7] showed that for maximum performance of visual tasks with minimum brightness as in cockpit lighting, illumination should be adjusted to a value of approximately 0.05 ft. L to 0.1 ft. L. This was based on the subjects, ability to perceive motion, judge depth and perform an addition task. Even with these low levels of illumination there is considerable loss of dark adaptation and of rod sensitivity [10].

In the choice of colour, the results of several experiments on comparison between red and white light of low and equal brightness for readability showed a faster rate of dark adaptation with red. [3, 4 & 8] Investigations [1, 5] on dark adaptation after pre-exposure to light of different colours indicated that as the wavelength of light is increased, the less the rod sensitivity was affected. Seitz and Orlansky [9] found that instantaneous threshold to red was lower than that for white, the intensity of the adapting field in both being 0.725 mL. On the basis of these data it has been generally accepted that for optimal rod adaptation, the cockpit lighting should be of red colour (cut off at 640 m μ) of an intensity of approximately 0.1 ft. L.

Purpose of the Present Study

While generally red light appears to be better for maximum dark adaptation, information is relatively scanty as to how much and how significant is its superiority in this respect, compared to lights of shorter wave lengths, especially at low intensities, which may be sufficient for minimal acuity tasks such as general orientation within the cockpit. In the present day aircraft, figures and indicators of instrument dials are irradiated with ultra violet and the general red flood lighting serves in illuminating the consoles and controls. As can be seen from the spectral sensitivity curve (fig. 1) the intensity required to stimulate the rods is much lower (of the order of 1 in 200) at the spectral range of about 500 m μ, than at the red end, in the region of 600—650 m μ. This indicates that a smaller intensity alone may suffice for cockpit orientation, if light of wavelengths within this range (about 500 m μ) is used. Whether such lower intensities of shorter wave-lengths will have the same or better effects on rod adaptation, compared to red light, is the aim of the present study. It was felt that the instantaneous threshold of the integral retina should be the criterion in the evaluation of the various test colours, as this reflects the pilot's ability to spot an extraneous object, after being adapted in the cockpit illuminated by a particular colour and intensity of light.

Method

The integral retina adaptation was recorded using a Goldman Weekers Adaptometer. This supplies flashes at regular intervals into a uniformly diffusing sphere. The intensity of the flashes is adjusted by means of a knob connected to a recording arm for marking on a logarithmic graph paper, which is attached to a revolving drum. The subject faces the sphere with his chin on a chin rest and for integral retinal dark adaptation the intensity of the flashes is progressively increased till the subject perceives the flashes and indicates by tapping the adaptometer desk.

For light adaptation, two additional sources of light of high intensity are provided inside the sphere, two 40 watts bulbs, providing an overall intensity of 1400 Lux.

The intensity of illumination of the exciting field (test flashes) in the examination of integral dark adaptation and that of the luminance of the sphere in preadaptation to light can be measured on a built-in lux meter, by suitable manipulation of a lever for operating the photo cell.

Light Sources

Illumination of the test field was provided by two sources (housed in rectangular wooden boxes) connected in parallel to 12 volts (stepped down from the main A. C. supply by a transformer with a rheostat within the circuit.) The sources were so placed in front of a white screen that a uniformly illuminated area of approximately 40 inches in diameter was produced.

Experiment I

The subjects comprised of nine airmen between the ages of 25 and 34 with normal visual acuity and colour vision.

The test target consisted of a simulated air speed indicator with white markings on a black background, kept at the centre of the field. The markings subtended a visual angle of 1.25°.

The four colours chosen for study were blue, bluish green, green and red obtained by using filters in the spectral range 410-490, 440-540, 500-570 and 610-670 m μ respectively. The level of illumination was adjusted for each colour to minimum intensity for bare legibility of the dial markings at an eye distance of 12 inches, after dark adaptation for 30 minutes. The intensity was reduced by interposing neutral filters with the coloured filters and/or adjusting the rheostat. The different level for each colour was standardised before the experiment on the basis of the mean of readings for four of the subjects. The number of neutral filters and the rheostat position were noted for each colour.

The values of illumination for the different colours were :—

Blue	—	0.0667 ft. L
Bluish Green	—	0.0018 ft. L
Green	—	0.0032 ft. L
Red	—	0.0061 ft. L

Each subject was fully briefed about the experiment and shown the test flashes in the adaptometer at relatively high intensities in the dark, to give an idea of the subjective feeling. He was instructed to maintain a single criterion for denoting a 'Yes' response by tapping the table. Each threshold was recorded using the ascending series only. The flashes used throughout were of white light.

One experimental session consisted of the following schedule :—

5 minutes — Room illumination
2 minutes — Complete darkness
5 minutes — Light adaptation to 1400 Lux.

Switch off light adaptation, and mark the end of light adaptation. Immediate commencement of threshold determination every 15 seconds for the first 8 — 10 minutes and then, every minute, for a total of 30 — 35 minutes. After this, switch on coloured illumination of predetermined intensity and the subject views the target and screen for 20 minutes. Switch off coloured light. Subject faces the sphere of the adaptometer with chin on chin rest.

Determine instantaneous threshold.

Proceed the same way for the other colours.

To determine the effect of colour on the recovery of dark adaptation after an intense prolonged flash, the subject was then put through the following schedule:

5 minutes — light adaptation to 1400 lux.
Off adaptation light.
4 minutes—on coloured light.
Off coloured light.
Record instantaneous threshold
Repeat procedure again for the same colours
Proceed the same way for other filters.

Thus two thresholds were recorded in each case and the average was taken as the threshold.

The colours were tested on each subject in random series. At the end of the experiment, the subject was asked to denote their order of preference of colours on the basis of purely personal appeal regardless of any other considerations.

Experiment II

The subjects comprised of five individuals with normal visual acuity and colour vision.

The test target consisted of two groups of white figures on black background — one small and the other big, subtending visual angles of 2.3° and 4° respectively — the latter being considered as the minimum for purposes of orientation.

The level of illumination was adjusted for each colour so that the smaller figures were barely legible and the larger group clearly visible.

The values of illumination for the different colours were :—

Blue	....	0.0012 ft. L
Blue Green	—	0.00067 ft. L
Green	—	0.00025 ft. L
Red	—	0.0034 ft. L

Each session consisted of:

- — Dark adaptation for 15 minutes in moderately illuminated room with red goggles and the next 15 minutes in completely dark room.
- — Three successive records of threshold.

— On coloured light for 10 minutes and subject views target.
— Off coloured light.
— Three successive records of thresholds.

Repeat for the other filters. The threshold arrived at was the average of the lower two of three readings in each case.

The effect of colour on recovery from intense prolonged flash was studied by light adapting the subject for 5 minutes and at the end of it, the coloured light switched on, and the times taken to read the larger groups and smaller groups on the target were separately noted. This was done by pricking the graph paper at the end of light adaptation and when the subject indicated he could read any two of the three lines in each group.

Results

The data of basic rod threshold (i. e. final rod threshold at the end of dark adaptation for 30 minutes[1]) and threshold above basic after preadaptation to various colours for eight subjects in the first experiment are presented in Table I. From the mean values, the threshold above basic is minimum in the case of red (5.9 m μ L) and maximum with blue (8.9 m μ L). Thus red seems to affect the rod sensitivity the least, next best being bluish green with a mean value of 7.4 m μ L. However, the coefficients of variations show that the readings are distributed more consistently around their mean in the cases of blue and blue-green, and rather high variance with red, in our sample of subjects.

TABLE I

Rod threshold above basic after preadaptation to Colours

Sl. No.	Subject	Basic Rod threshold in m μ L.	Rod threshold above basic after preadaptation to colour for 20 mts. (in m μ L).			
			Blue	Blue Green	Green	Red
1.	P. C. B.	22.0	6.0	6.0	8.0	3.0
2.	M. J. R.	11.0	10.0	3.0	9.0	1.0
3.	P. K. U.	16.0	8.8	8.0	8.0	4.0
4.	D. H.	10.0	13.0	8.0	13.0	10.0
5.	C. R. P.	20.0	5.0	5.0	4.0	3.2
6.	T. K. A.	14.0	10.0	10.0	9.2	10.0
7.	N. S. V.	22.0	3.0	5.0	1.0	5.0
8.	K. D.	9.0	14.2	14.0	14.0	11.4
	Mean	15.5	8.9	7.4	8.3	5.9
	S. D.	5.3	3.0	3.5	4.3	3.9
	C. V.	34.0	43.0	47.0	52.0	66.0

Table II gives the figures for visual thresholds after preadapting to the various colours following exposure to intense brightness for the four colours. These vary very little between themselves, the minimum being in the case of red, with 1.1 μ L. It can also be seen that coefficients of variation (C. V.) of readings around their respective means, with each colour, vary to a large extent, being as high as 87 with blue-green and only 29 with green. No conclusion can therefore be drawn, from this experiment, on the effect of different wavelengths on the rate of cone adaptation.

TABLE II

Visual Threshold after Preadaptation to Colours
Following Exposure to Intense Brightness
(98 mL for 5 minutes)

Sl. No.	Subject	Visual threshold after preadaptation to colours, following exposure to intense brightness (figs. in μ L).			
		Blue	Blue Green	Green	Red
1.	P. C. B.	3.6	6.0	1.0	0.6
2.	M. J. R.	1.4	1.6	0.5	0.6
3.	P. K. U.	1.0	1.6	1.2	1.3
4.	D. H.	1.2	0.5	1.4	0.8
5.	C. R P.	1.1	1.3	1.3	1.1
6.	T. K. A.	0.4	1.9	1.4	1.4
7.	N. S. V.	0.8	0.8	0.8	2.0
8.	K. D.	1.6	1.7	1.3	1.0
	Mean	1.4	1.94	1.11	1.1
	S. D.	0.96	1.7	0.32	0.47
	C. V.	68.0	87.0	29.0	43.0

The values of basic rod thresholds, and rise in threshold above basic, after preadaptation to the different colours (intensity equated for general orientation) for five subjects in the second experiment are given in Table III. The minimum rise in threshold is with blue and green being 2.6 m μ L, and maximum in the case of red (4.2 mμL). Compared to blue and green, blue-green shows a higher rise in threshold value of 3.9 mμL. The C. V. for each of the four colours indicate that the distribution of the readings is almost uniform.

TABLE III

Rod Threshold above basic after preadaptation to Colours.

Sl. No.	Subject	Basic Rod threshold (in m μ L)	Rod threshold above basic after preadaptation to different colours for 10 minutes (in m μ L)			
			B	BG	G	R
1.	P. M. S.	10.0	1.0	1.4	1.0	5.0
2.	P. S. D.	9.0	1.0	2.0	2.0	5.0
3.	C. S. N.	10.0	4.0	5.0	2.0	0
4.	T. G. J.	12.0	3.0	4.0	2.0	4.0
5.	C. A. V.	8.0	4.0	7.0	6.0	7.0
	Mean	9.8	2.6	3.9	2.6	4.2
	S. D.	1.5	1.5	2.2	1.9	2.6
	C. V.	15.0	58.0	56.0	73.0	61.0

Table IV shows the time taken after exposure to intense brightness (98 mL. for 5 mins) to read small and big figures. The time to read both small and big figures is lowest with red, being 1.8 and 0.95 mins respectively. However, compared to the remaining colours, blue-green appears to be relatively better.

TABLE IV

Time Taken to read Figures Following Exposure
To Intense brightness (98 mL for 5 minutes)

Sl. No.	Subject	Time taken to read figures following exposure to intense brightness (figs. in minutes)							
		Large Figs.				Small Figs.			
		Blue	Blue Green	Green	Red	Blue	Blue Green	Green	Red
1.	P. M. S.	5.25	3.25	5.5	0.75	7.5	4.5	7.25	1.5
2.	P. S. D.	4.0	4.5	6.5	0.5	5.5	5.75	11.25	1.0
3.	C. S. N.	5.0	4.0	6.5	1.0	8.5	7.5	9.0	2.0
4.	T. G. J.	4.5	6.0	4.5	1.5	7.5	8.0	7.0	2.5
5.	C. A. V.	3.0	3.0	6.5	0.5	4.0	4.0	9.0	2.0
	Mean	4.35	4.15	5.9	0.85	6.6	5.95	8.7	1.8
	S. D.	0.89	1.2.	8.89	0.42	1.8	3.5	1.7	0.57
	C. V.	20.0	29.0	17.0	49.0	27.0	58.0	19.0	32.0

The results of the opinion survey regarding psychological preference to the four test colours on 14 subjects are indicated in table V. While none gave red as his first choice, 11 listed it as their last choice. Comparatively blue-green appears to have appealed to many, 5 indicating as their first choice, and 8 their second.

TABLE V

Order of Psychological Preference of Colours
Among 14 Subjects

Colours	No. of subjects and order of preference.			
	1st choice	2nd choice	3rd choice	4th choice
Blue	4	2	6	2
Blue green	5	8	—	1
Green	5	3	6	—
Red	—	1	2	11

Discussion

The main basis of most of the earlier studies was time taken to reach final rod threshold of the subjects, after exposure to the test colours [4 & 8]. Hecht and Hsia in one of their studies 4 had measured dark adaptation using a 3° circular blue fluid placed 7° off centre, while Rowland and Sloan 8 used 1° white stimulus located in the nasal field 15° from the fixation point. Thus these studies were testing the performance of a particular portion of the retina only. Rod densities may differ in individuals, and may be more elsewhere, than the areas chosen in these studies. Also, the intensities used were relatively high, the lowest ranging from 1.1 to 2.8 mL for white and 3 to 3.4 mL for red in the above experiments, and 0.1 to 0.3 f. c. in other studies [8].

In the present series of experiments, instantaneous threshold of the integral retina has been taken as the measure of dark adaptation. By adopting the integral retina examination one can be certain of testing the response of the most sensitive parts of the retina as a whole. In the case of a pilot trying to detect an extraneous object, he has to make use of his entire retina, finally bringing the object to the most sensitive part for better perception. Integral retinal examination would therefore serve as a better index of the individual's effective dark adaptation at a given moment. Also, in a detectability task outside the aircraft, it is the instantaneous threshold which is of significance, more than the time taken for recovery to final rod threshold.

In the first experiment, the intensity chosen for each colour was for bare legibility of figures (instead of maximum legibility [10]) of a simulated instrument panel. This was done with a view to discover changes, if any, in the relative merits of red over the other colours, for such intensities. The results indicate that even under these conditions red remained better than other wavelengths. The rise in rod threshold was lowest with red, being 1.5 mμL below that of blue-green, which was the next best. The speed of recovery of retinal adaptation after exposure to high brightness level was also faster with red than with other colours.

In the light of the above, it was decided to conduct a second experiment to study the effects of still lower intensities which would be sufficient for tasks involving general orientation inside the cockpit. It was considered that such a criterion would be more relevant, as the reading of instrument panels in the present day aircraft is generally independent of cockpit flood lighting, being facilitated by ultra violet illumination.

The results of the second experiment indicate that at the lower intensities required for orientation, blue and green effected lesser rise of threshold of 2.6 mμL each, than red (4.2 mμL). However, blue-green produced a higher rise (3.9 m μ L) than with either blue or green. For this experiment, green and blue required only very low intensities (0.00025 ft. L and 0.0012 ft. L respectively) compared to red (0.0034 ft. L) for the criterion employed in the experiment. Blue-green required an intensity of 0.00067 ft. L and the higher rise in threshold it effected compared to green is difficult to explain.

In the study of the effects of these colours on the rate of adaptation following exposure to intense brightness, red was found to be most favourable, producing nearly five times faster recovery than other colours, to read big figures. In this and in the first experiment, exposure to such prolonged and high brightness (98 mL for 5 mins) was employed to magnify the effects of short term flashes which may occur during night flying, such as lightning, aircraft on blaze, nuclear explosion etc.

But the pattern of recovery with each colour may vary depending upon the duration of exposure to high brightness. Further work therefore needs to be done in this regard, before establishing the superiority of red in the rate of adaptation of the cones following intense flash of short durations.

Red illumination is already known to have certain disadvantages in map reading, reading of instrument panel etc. In red light, contours of objects get distorted, red markings disappear, orange and brown markings become very difficult to see and green markings become grey The eye is more hypermetropic to red and reading in red light may cause eye strain and headaches. [2, 8 & 10]. One of the advantages of red is its lesser visibility to distant observers (the enemy) compared to other colours [2 & 6]. This, however, is of little consequence in the context of modern high speed aircraft. Further, if shorter wave-lengths were used for cockpit flood lighting, much lower intensities would only be required, and chances of enemy detection would then be considerably less.

The pilot opinion survey on the psychological preference to the various colours tested revealed a general aversion to red. This finding, though based purely on personal appeal, is interesting and needs to be further investigated. Whether red colour by itself, has any ill effects on psychomotor performance, under prolonged illumination, will be an interesting venue of study.

In the light of the above, acceptance of red colour for cockpit flood lighting, needs to be made with certain reservations. The present series of experiments, though at best, can be termed only as a pilot project, suggest that colours of shorter wavelengths may prove to be better, on the basis of further research.

Conclusions

The results of the present study tend to indicate that if legibility of instrument panel be the criterion in cockpit lighting, red colour appears to be the best, with least effect on dark adaptation.

However, the superiority of red over other colours seems to be questionable, when the criterion used is for purposes of orientation within the cockpit, requiring lower intensities. In the present series, under such conditions, blue and green appear to possess significant advantage over red, with lesser effects on rod sensitivity. The level of intensity in this case based on the level required for maximum clarity of a group of figures, each subtending a visual angle of 4°, which, it was thought would cater for worst conditions. Further work is needed, using simulated cockpit controls, consoles etc., for standardising the level of intensities for purposes of orientation. The experiment may then be repeated for a better evaluation of the different colours in cockpit flood lighting.

On the basis of experience gathered during the present series of experiments, the following general recommendations are made:

(a) In experiments on visual function in which the criterion mostly depends on the subjective sensations of the individuals tested, careful selection and continuous training of the subjects before the conduct of the experiment are of utmost importance.

(b) Instruments for accurate measurement of low levels of illumination (Macbeth's Illuminometer) is indispensable if errors are to be kept to the minimum.

(c) Standard filters with suitable sources such as mercury, sodium etc., are necessary on experiments on wavelengths.

Acknowledgement

The writer wishes to express his appreciation to Wg. Cdr. T. G. Jones for his guidance of the study reported and Shri. P. L. N. Rao, Statistician, for analysis of results and to the subjects without whom the study could not have been made.

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