MAXWELL'S SPOT AND LOCAL DIFFERENCE OF COLOUR RESPONSE IN HUMAN RETINA

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A reddish spot is seen around the fixation point when a uniform white surface is looked at by a normal observer through a purple filter transmitting red and blue lights. This phenomenon is called Maxwell's spot and interpreted usually as an entoptic phenomenon due to an extra-high loss of the blue component of the purple light by a yellow pigment standing in front of the receptor layer, thus permitting the red component to be observed by itself.

The non-vascularized part of the retina at the posterior pole of the human eye—the so-called macula lutea—shows anatomically a yellow colour. Assuming that the same colour was prevalent in the living eye, a number of visual phenomena difficult to explain otherwise were ascribed by many investigators (1, 2, 3) to the local filtering action in the yellow pigment.

Gullstrand (4), however, brought forward an interpretation that the yellow pigment was a post mortal phenomenon, and encountered objections by Dimmer (5), Vogt (6), Holm (7) and others. Nordensen *et al.* (8) at the clinic in Upsala promoted Gullstrand's experiment and denied the existence of macular pigment during life. This idea received support from Hartridge's experiment (9).

Despite these experiments, it is generally believed that intravital colour of macula does in fact occur in the retina. Wald (10) extracted the pigment from human maculae, and found that its absorption curve corresponded to that of xanthophyll. Further he estimated the optical density of the macular pigment *in vivo* by comparison of the parafoveal and foveal photic sensitivities for cones.

It is teleologically curious that a pre-receptor filter, causing a heavy absorption of blue light, should be present in a retinal region which is highly developed, but it may be possible, as suggested by Dartnall and Thomson (11), that the macular pigment is playing a role in carrying oxygen to those regions of the fovea which have no capillaries.

Naylor (12) investigated the cause of Haidinger effect, measured the areal distribution of orientated macular pigment and inferred that the macular pigment was responsible for Maxwell's spot. Miles (12) reported a good method to plot detailed structure of Maxwell's spot and measured its subtense of arc. He compared this subtense with the anatomical distribution of macular pigment determined by Polyak and inferred that the cause of Maxwell's spot consists in blue absorption in the pigment.

Based on a large amount of entoptic data in normal and colour-defective subjects, Walls (13) presented his hypothesis of non-uniform distribution of the

Received for publication December 2, 1954.

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receptor types in the fovea; he pointed out that most deuteranopes can not perceive Maxwell's spot, although evidence is lacking that there is no macular pigment in deuteranopes.

This hypothesis seems to receive support from the experiment by Motokawa *et al.* (14) indicating that the excitation of the blue receptor was decidedly small at the foveal centre compared with that of the red receptor. In order to provide more conclusive evidence for the theory, we had our subject plot Maxwell's spot with a purple filter, and explored spatial distribution of retinal processes by means of Motokawa's method in one and the same subjects under comparable experimental conditions.

METHODS

Colour vision test

Tests of colour vision were made with Ishihara's test and Nagel's anomaloscope. The former test was used for rough screening. The final decision was made on the basis of a systematic survey with the anomaloscope.

Method for plotting Maxwell's spot

The method was almost the same as that used by Walls. The subject was seated at a table, and his head was supported by means of a chin rest. In front of the subject a light box with an opal glass window stood at the level of the head. The distance from the observer's eye to the illuminating window was set at 114.6 cm., so that a tangent distance of 20 mm. on the opal glass corresponded to 1° in visual angle. The window was illuminated from within by a 100 W Mazda tungsten lamp. A small cross on the opal glass served as a fixation point. The purple filter used was a piece of Wratten filter, no. 2389, 1 cm. square in size, which was mounted edge to edge with a similar square of Wratten filter, no. 96 (neutral). The subject looked at the fixation point alternately through the two filters, taking note of what he saw whenever he was looking through the purple filter. Shifting the filters at intervals of 2 to 4 seconds should give an almost continuous display of the entoptic figure, showing the same boundary or boundaries.

Motokawa's method for exploring retinal processes

The method has been fully described elsewhere (15, 16), so that only a brief résumé will be given here. Following a brief illumination, the electrical sensitivity of the dark-adapted eye is measured with electrical phosphenes as an index. The sensitivity increases above normal after an initial brief depression, reaches a maximum in a few seconds and decreases gradually to the resting level. The time course of this change depends on the sort of the receptors excited, and the degree of supernormality varies approximately in proportion to the logarithm of the intensity of the light used. For convenience, percentage increases in electrical sensitivity over its resting level were denoted by ζ . ζ values at 1, 1.5, 2 and 3 seconds after termination of a photic stimulus represent the magnitudes of the red (R), yellow (Y), green (G) and blue (B) processes for the reasons stated in the previous papers (15). Accuracy of measurement

was such that most subjects could reproduce their data with error of 2 in terms of ζ at different sessions.

RESULTS

Maxwell's spot

As is shown in fig. 1 and table 1, normal entoptic figures may be classified into 6 categories.

TABLE 1

Type	I	II	III	IV	V	VI	Investigator
Number of subjects	26	7	5	11	6	2	Walls
	33	12	1	12	8	2	Isobe

The commonest one (type I) looks like an archery target, consisting of symmetrical circular form made up of 3 concentric zones designated as a spot, a clearing and a halo from the centre to the outside. The colour usually reported for the central spot and the halo are reddish, while that of the clearing is a bright unsaturated lavender, identical with the background field. The three average subtenses of the spot, the clearing and the halo, measured by Miles and Walls, and also in the present experiment, were, without great difference, about $33'$, $1^{\circ}10'$ and 2.5° in diameter respectively. Nearly 50 per cent of normal subjects belong to this type. The other types are distinguished from one another according to the width of the clearing and the area of the central spot. Both clearing and central spot are lacking in type V. The clearing exists, but the spot is lacking in type VI.

FIG. 1. Classification of normal Maxwell's spot.

- Type I: halo, clearing, central spot.
- Type II: halo, narrow clearing, central spot.
- Type III: halo, cut up clearing, central spot.
- Type IV: halo, no clearing, central spot.
- Type V: homogeneous disc.
- Type VI: halo, clearing, no central spot.

Walls reported that protanopes and protanomals saw Maxwell's spot, whereas the majority of his deuteranopes and deuteranomals did not. Our investigation also shows that all of 4 protanopes and all of 3 protanomals saw Maxwell's spot, while no trace of it could be found in 8 deuteranopes and in 5 out of 8 cases of deuteranomals.

Spatial distribution of receptor responses in the fovea and parafovea

1. *Normal subjects.* As the purple filter used for exploring Maxwell's spot transmits only red and blue lights it is important for understanding the physiological mechanism of Maxwell's spot to know the responses of the red and blue receptors at each part of the retina, especially at the fovea and thereabout. Motokawa's method described above enables us to map the distribution of the

response of the red receptor by measuring the electrical excitability at 1 second after exposure of each retinal area to a minute spot of red light. Similarly, the response of the blue receptor may be obtained from excitability measurements at 3 seconds after exposure of each area to a minute spot of blue light. When a mixture of red and blue lights is used as in the present experiment, both kinds of receptor, red and blue are excited simultaneously, but the response of each kind of receptor can be measured by the procedure mentioned above, independently of the other, because the red and the blue processes have different time courses in such a way that the former reaches a maximum at 1 second, and the latter at 3 seconds. Measurements were carried out along the horizontal meridian, using a 2' preilluminating target. The spatial distribution of the R and the B responses of the commonest type (subject T.K.) is illustrated together with Maxwell's spot in fig. 2. Corresponding to the deep red spot at the foveal centre, the response B was decidedly small compared with the response R, while both processes were of equal magnitude at the lavender clearing. An example of type II (subject K.M.) is illustrated in fig. 3. As to the spot and

FIG. 2 (*left*). Spatial distribution of red (R) and blue (B) processes in fovea (upper diagram) and Maxwell's spot (normal type I) (lower diagram). Densely hatched area: deep red. Less densely hatched area: red. White area: purple or lavender.

FIG. 3 (*right*). Type II of normal Maxwell's spot and corresponding distribution of retinal processes. Explanation as in fig. 2.

the clearing the same can be said, although the clearing was a little narrower. In the area corresponding to the halo, the response B was found greater than at the foveal centre, but still smaller than the response R. This distribution accounts for the reddish tone of the halo. It is to be noted that distribution is uneven not only of B but also of R. The regional variation of the R process cannot be explained in terms of macular pigment, because this pigment does

not absorb red light. In fig. 4 another normal type is illustrated (type V). The structure of Maxwell's spot is much simpler in this case in good agreement with the less complicated pattern of the R and B distributions.

FIG. 4. Type V of normal Maxwell's spot and corresponding distribution of retinal processes. Explanation as in fig. 2.

2. Colour-defective subjects. Protanopes show no red response, but instead, a yellow response, as has been shown in the previous experiment (16). Therefore the Y and B processes were measured in protanopes in the present experiment. An example is illustrated in fig. 5. Maxwell's spot visible to this subject was dark blue, and corresponding to this visual property, the B response was especially small and uneven at the fovea. Fig. 6 represents the distribution of R and B in a deuteranope. The two processes R and B did not display any regional variation, as expected from the absence of Maxwell's spot in this subject.

FIG. 5. Maxwell's spot in protanope and corresponding distribution of the yellow (Y) and the blue processes. Central spot: dark blue. White area: pale. Halo: intermediate in colour between the two.

FIG. 6. Spatial distribution of retinal processes in deuteranope.

DISCUSSION

The data obtained above give neither evidence for the existence of macular pigment *in vivo*, nor any answer to the question what is the physiological significance of the macular pigment, if it is present. But the present experiment has established that Maxwell's spot is not due to selective absorption of blue light by the pigment, and that the new hypothesis by Walls as Maxwell's spot

is correct whether the macular pigment exists *in vivo* or not.

According to anatomical studies of Holm (7), the macula lutea is in size 6.7° (horizontal) by 5° (vertical); his illustration of a typical pigmentation shows that the central area is colourless and subtends no less than 3.4° by 1.5° of arc.

According to Polyak (17), the yellow pigment is confined to the ganglion and inner nuclear layers and, therefore, most saturated along the slopes of the foveal pit, where these layers increase in depth, and the foveal floor, whose angular subtense is $1^\circ 20'$, is colourless, because these layers are absent in this region. The pigmentation extends as far as the large blood vessels surrounding the non-vascular area. As mentioned above, Wald made an estimation of the optical density of macular pigmentation on the basis of relative photosensitivities of peripheral and foveal areas, but this method does not seem relevant, because the retinal areas he used in his experiment should lack macular pigment, judging from the anatomical findings provided by Polyak and others, and furthermore he has not taken into consideration the possibility that photosensitivity might depend upon some uneven distribution of receptor types. Naylor's estimation of the extent of macular pigmentation on the basis of Haidinger's phenomenon is in agreement with the anatomical findings, but the extent is too great to account for the apparent size of Maxwell's spot, for the diameter of the area containing macular pigment is about 6° in visual angle, while the outside diameter of the halo is of angular subtense only from 2° to 3° . The anatomical and optical researches on macular pigmentation hitherto made have unanimously shown that the centre of the fovea lacks pigmentation. The sensory fact that the central part of Maxwell's spot looks reddish is usually explained by the pigment theory in such a way that the reddish outlook is due to selective absorption of blue light by macular pigment, but explanation is obviously untenable in view of the anatomical evidence mentioned above.

Miles supported the pigment theory, because the red halo well corresponded to the foveal slope where the pigment is most abundantly present. As is shown in fig. 3, the red response is in the area corresponding to the red halo much larger than elsewhere in this subject. Therefore, the reddish tone of the halo may be ascribed to the prominence of the red process rather than to the weakness of the blue process. The same subject showed the same prominence of the red process in an experiment by Motokawa *et al.* (14) who were, at that time, not aware of any relation of this finding to Maxwell's spot. Since there is no ground to assume that the macular pigment should have any effect upon the sensitivity of the red receptor, the red halo of Maxwell's should not be accounted for in terms of the pigment.

So long as evidence is lacking that deuteranopes have no macular pigment, no one can claim to explain the absence of Maxwell's spot in deuteranopes from the pigment theory. But this fact can easily be explained from Walls' theory, because it has been established by the present experiment that the deuteranope shows no regional variation of the red and the blue processes in the fovea and thereabout.

SUMMARY

1. Maxwell's spot has been investigated by means of Motokawa's method of electrostimulation of the eye in comparison with sensory structures of the spot.

2. It was shown that the extent and the inner structure concerning colour-ation of Maxwell's spot were determined by the spatial distribution of the red and the blue processes which were elicited by exploring light from a purple filter, Wratten no. 2389.

3. Protanopes perceived Maxwell's spot and in agreement with this, the distribution of the retinal processes in the fovea and thereabout was shown to be uneven.

4. On the contrary, deuteranopes could not perceive any Maxwell's spot, and their retinal processes were found to be distributed uniformly in the fovea.

5. Based upon these findings and other anatomical data, the widely believed hypothesis that Maxwell's spot is due to selective absorption of blue light by macular pigment was rejected, and instead, Walls' new hypothesis of non-uniform distribution of receptor types was accepted.

The author wishes to express his hearty thanks to Prof. K. Motokawa for his kind guidance and encouragement.

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