COMPARATIVE STUDIES ON THE PERIPHERAL AND CENTRAL RETINA

VI. Inhibition, Summation, and Synchronization of Impulses in the Retina

C. H. GRAHAM and RAGNAR GRANIT

From the Eldridge Reeves Johnson Foundation for Medical Physics, University of Pennsylvania

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It has been pointed out in a previous communication of this series (Granit and Hammond, 1931) that there is a sufficient body of evidence to warrant our taking the standpoint that, under simple conditions, the fusion frequency of an intermittent light is determined by purely retinal factors. There is therefore no reason for believing that the higher centres should split up and synchronize a discharge which arrives through the optic nerve as an asynchronous continuous discharge (Adrian and Matthews, 1928) except in the case where the two eyes are stimulated by lights flickering in varying phase, as in the classical work of Sherrington (1904–5) on binocular flicker. But even in this case it appears that the fusion frequency was altered little in any except a few well specified cases. Similarly, Allen's (1919) method of studying the effect of "fatigue" on flicker may introduce complications.[1] It therefore seems necessary to begin with to select conditions which give reasonable assurance that only retinal factors are involved.

Previously in this series (Granit, 1930; Granit and Harper, 1930) it was shown that two or more separated flickering areas interacted so as to give a higher fusion frequency for all of them stimulated simultaneously as compared with the value obtained with each area alone. Here we are raising

[1] With his procedure of "fatiguing" the flickering area, adjoining areas and even the other eye, Allen has obtained a number of interesting and curious results which we hesitate to discuss because of our lack of experience with the conditions under which the experiments were made. Allen takes, for example, the normal fusion frequency curve for the spectrum as his reference standard. Then the eye is "fatigued' for one wave-length, and in testing again for the fusion frequency throughout the spectrum, he finds that it is lowered for certain colors. This amounts to finding *selective fatigue* for these colors. The difficulty met with in interpreting such results is that selective fatigue has not been found in the excised eye. Fatiguing with one color affects equally the action currents for all colors (Chaffee and Hampson, 1924). As to Allen's explanation, see the discussion.

the question as to whether the fusion frequency of a given area can be increased also by illuminating an adjacent area with steady light. Further, considering that histologically the retina is a nervous centre it would seem reasonable to expect inhibitory processes in it. This, with the flicker method would amount to a search for conditions where one area would influence another so as to lower the fusion frequency in the latter. The experiments to be summarized demonstrate this latter activity as occurring under conditions which are slightly different from those productive of summation.

METHOD. Figure 1 shows the arrangement of apparatus. The light from the Pointolite lamp, L, is divided by four 45° totally reflecting prisms into two beams which are centered on semicircular apertures in the opaque screen, A (cf. arrangement in fig. 2). Adjustment of the outer prisms allows for the focussing of the rays upon the semicircles at any separation. A series of screens A (shown separately in fig. 2) with opaque graded distances between the semicircles provides opportunity for determining inter-

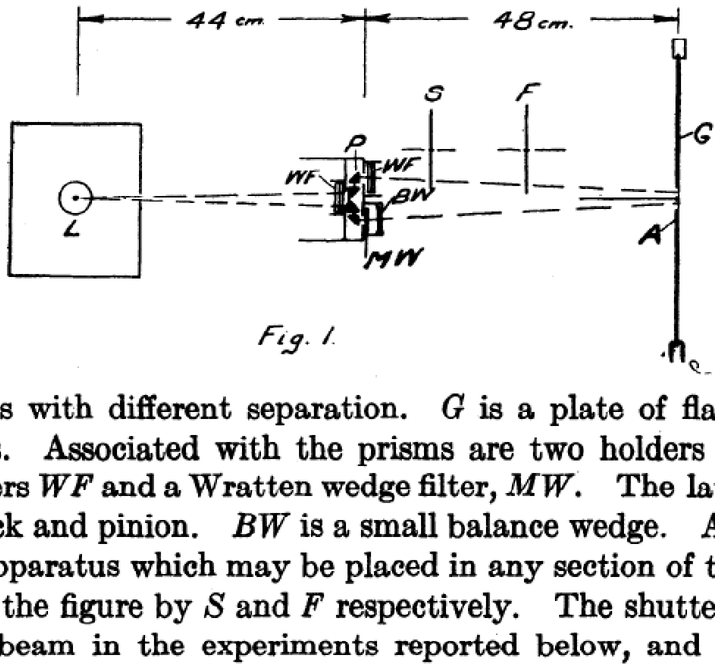

Fig. 1.

action effects with different separation. G is a plate of flashed opal or frosted glass. Associated with the prisms are two holders for standard Wratten filters WF and a Wratten wedge filter, MW. The latter is adjustable by a rack and pinion. BW is a small balance wedge. A shutter and the flicker apparatus which may be placed in any section of the beams are indicated in the figure by S and F respectively. The shutter has been in the unsplit beam in the experiments reported below, and used only in those described in table 1. Long exposure was found to enhance the effects to be described.

Figure 2 shows the removable section of the opaque screen A with the semicircular openings. Their radius corresponds to 1° of visual angle. The fins FF prevent reflection from D at glancing incidence. In the same figure appears the mechanism of the shutter. SS is the shutter shaft driven through reduction gears by a Telechron synchronous motor in the direction shown until stopped by the pin, SP. At this point the mercury switch MS is opened by the cam C. When the button B is closed by the observer, the relay R operates. This releases the pin SP and closes the contacts CP, CP, thus shunting the mercury switch and starting the motor. As soon as the shaft has turned slightly the cam C allows the switch MS to close and the motor continues to run until the shaft SS has made one complete revolution.

The technical perfection of the apparatus described is due to Mr. A. J. Rawson to whom the authors wish to express their thanks.

Devices for measuring and controlling the flicker apparatus and the general conditions of the experiments have been described previously (Granit and Harper, 1930). The lamp was run on a high capacity storage battery. Monocular vision was employed throughout the work. High intensities have been used because only under these conditions is it possible to deal with effects which are unquestionably beyond the range of experimental variations.

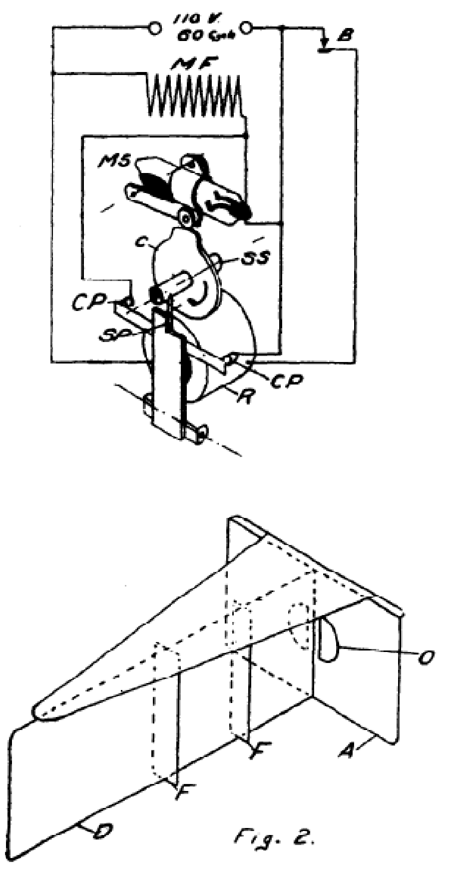

Fig. 2.

Synchronization and summation. In table 1, as in all the following tables, the fusion frequency is given in flashes per second as an average of results obtained with a number of observers (3–4). Two flickering semi-circles of equal intensity (rotating sectors in unsplit beam) give, if taken together, an increase in fusion frequency of 5.9 per cent over either singly, when regarded in the fovea, and 13.7 per cent in the periphery at 10°. Comparing these values with the results obtained when one semi-circle alone is flickering (rotating sectors in split beam), and the other one steadily illuminated and matched with the flickered patch as fused, it is evident that the foveal interaction has been reduced to 2.9 per cent and the peripheral to 6 per cent.

We may thus conclude that interaction via lateral paths is greatly favored by intermittent stimulation. Part of the interaction may therefore be a matter of synchronization of impulses within the individual areas stimulated (Granit and Harper, 1930). There is, however, no method for deciding with sensations as criteria, whether this synchronization involves summation or not since direct comparison, a relative method, only gives information as to the differences in the two areas compared. But the fact that a continuous discharge of impulses in one area is also capable of raising the fusion frequency in an adjacent flickering area shows that synchronization of impulses in the adjacent area is not essential for the effect. At least in this latter case, and probably in the former also, the interaction must be a true spatial summation which implies that a higher state of excitation may be produced in a given area through the agency of impulses from any area reasonably near to it (cf. the results by Lythgoe and Tansley, mentioned in the discussion).

Inhibition. The fact that two flickering semicircles some minutes apart on the retina may give practically maximal summation and yet appear

TABLE 1

Conditions: Both semicircles at 35.0 millilamberts, background at 0.012 ml. Semicircles about 4 minutes of visual angle apart. In this and in all the following tables the percentage increase or decrease is the difference between the "doubles" and the "singles" in per cent of the "singles."

	ONE SEMICIRCLE FLICKERING, THE OTHER STEADY				BOTH FLICKERING			
	Centre		Periphery		Centre		Periphery	
	Single	Double	Single	Double	Single	Double	Single	Double
Fusion frequency	49.1	50.5	46.7	49.5	49.5	52.4	46.7	53.1
Percent difference	2.9		6.0		5.9		13.7	

TABLE 2

Conditions: Left semicircle always at 139 ml., background at 0.012 ml. Both flickering and about 4 minutes of visual angle apart. Central fixation.

SINGLES	DOUBLES	PERCENT DIFFERENCE
Both equally bright		
55.8	60.6	+8.6
Right 50 per cent darker than left. Fusion frequency of right determined		
54.7	53.9	−1.5
Right 50 per cent darker than left. Fusion frequency of left determined		
55.8	58.8	+5.4

distinctly separated has been noted in a previous paper (Granit and Harper, 1930). It was also pointed out that it is difficult to understand how visual acuity can increase with the intensity of the stimulus when the summative process also becomes more marked at these higher intensities. The same difficulty holds for brightness discrimination. These facts suggest that, as soon as the excitatory processes in adjacent retinal areas are at different levels, conditions may be present which differ fundamentally from those productive of maximal summation. Fortunately the experimental test is easy to make.

Two flickering semicircles (sectors in unsplit beam) are kept at different levels of brightness. The darker semicircle will give a lower fusion frequency owing to its lower intensity. But the difference between the two can be made negligible by working the whole experiment at a high intensity where the fusion frequency is practically independent of intensity (Granit and Harper, 1930). Thus in table 2 the one semicircle alone gives 55.8 f.p.s. When the illumination on it is diminished by 50 per cent, the reduction in fusion frequency only brings it down to 54.7 f.p.s. If both then are equally bright, as is the case in the upper part of the table, here

TABLE 3

Conditions: Right semicircle flickering and at a brightness of 13.9 ml. (upper part of table) which in the lower part of the table is reduced by 33.3 per cent, whereas left is kept unaltered throughout the experiment and matched to give the brightness of the right patch fused at 13.9 ml. The semicircles are about 4 minutes of visual angle apart. Background at 0.012 ml. Central fixation.

RIGHT ALONE	RIGHT WITH LEFT ILLUMINATED	PERCENT DIFFERENCE
Both equally bright, when right fused		
47.8	50.0	+4.6
Right reduced by 33.3 per cent in intensity. Left as above		
45.6	42.2	−3.1

is a summation on either of them amounting to 8.6 per cent. But if the one semicircle is at a 50 per cent lower intensity its fusion frequency does not increase in the least when the brighter half is simultaneously illuminated. As a matter of fact it has diminished by 1.5 per cent[2] as shown by the second line of the table. This becomes particularly striking by comparison with the behaviour of the fusion frequency read on the brighter semicircle in the same experiment, shown in the lower third of the table. When the darker semicircle is illuminated it raises the fusion frequency of the brighter by 5.4 per cent. The result is clear cut and shows that when two adjacent areas are at different levels of brightness the interaction is of such a nature as to exaggerate the difference between them.

[2] The diminution owes its appearance in the averaged values to one of the observers (E. H.) who constantly gave it with intensity differences between 25–50 per cent. Two of the observers repeated with the doubles and the darker determined the value obtained with the darker single. The fourth observer (R. G.) often had a just measurable decrease with the darker in the double constellation.

It is interesting to note that the result essentially corresponds to the picture of contrast and that we probably have here a retinal component of this complicated mechanism. It seems necessary to classify the phenomenon as inhibition since the total effect of the interaction on the darker is removed and since part of it at least, as has been shown, is excitation. Two "darker" semicircles if *equally* "dark," in this experiment would give a summation somewhere between 5.4 and 8.5 per cent. This, as it were, is the background against which the inhibition has to be pitted in order to become recognized.

This general type of experiment was repeated many times under somewhat different conditions. Inasmuch as the experimental variations were found to shed light on some aspects of the problem they are reported below.

TABLE 4

Conditions: Right semicircle in upper part of table at 139 ml. reduced by 25 per cent and by 33.3 per cent respectively in middle and lower part of table. Left steadily illuminated and unaltered throughout the experiment as matched to give the brightness of the right patch fused at 139 ml. Semicircles about 8 min. of visual angle apart. Background at 0.012 ml. Peripheral fixation.

RIGHT ALONE	RIGHT WITH LEFT ILLUMINATED	PERCENT DIFFERENCE
Both equally bright, when right fused		
52.4	55.4	5.7
Right reduced by 25 per cent. Left as above		
51.5	54.4	5.6
Right reduced by 33.3 per cent. Left as above		
50.8	53.6	5.5

Table 3 gives data obtained with the one semicircle steady and the other one flickering, central fixation again being employed. The summation with both equal was 4.6 per cent. Then the intensity of the flickering patch was reduced by 33.3 per cent. Alone it now gave a fusion frequency of 45.6 f.p.s. as against 47.8 before the reduction. When the brighter semicircle was illuminated as in the upper half of the table its fusion frequency fell to 44.2 f.p.s. The fall below the value obtained with the single is mainly due to one observer. With the other ones the inhibition only removed the summated surplus.

In the periphery this type of experiment is difficult to perform if both patches are flickering, since it presupposes a degree of discrimination between flicker and non-flicker in adjacent areas which the periphery does not possess. But it can be performed as above, with one area steady and the other flickering, although preferably with the patches somewhat farther apart. Such an experiment is shown in table 4. Independent of whether the patches are equal or the flickering one is reduced in brightness by 25–33.3 per cent they sum and the summation is fairly constant, 5.5–5.7 per cent. Similar results are always obtained in the periphery, even with larger differences in brightness.[3] Inhibition therefore appears to be chiefly a foveal property, at least at higher intensities. In accordance with this observation is the fact that visual acuity and brightness discrimination

TABLE 5

Conditions: Both flickering and at 23.3 ml. in the upper part of the table. In the lower part the right is reduced in brightness by 2 per cent. The semicircles are separated by a very thin line. The background is at 0.195 ml. Central fixation.

Both equally bright

SINGLES	DOUBLES	PERCENT DIFFERENCE
44.9	47.5	5.8

Right reduced in intensity by 2 per cent, left unaltered

RIGHT ALONE	RIGHT WITH LEFT ILLUMINATED	PERCENT DIFFERENCE
45.0	46.0	2.2

Right reduced in intensity by 2 per cent, left unaltered

LEFT ALONE	LEFT WITH RIGHT ILLUMINATED	PERCENT DIFFERENCE
45.0	47.4	5.3

are also special functions of the fovea and very much less developed in the peripheral eye.

For brightness discrimination much smaller differences are required than those hitherto studied. The just perceptible difference with a thin line of separation between the patches as in our apparatus amounts to a diminution of the intensity in the one patch of about 2 per cent for medium and high intensities. Table 5 shows how the fusion frequency of one semicircle is altered by the presence of *1* an equally bright adjacent semicircle (upper line), and *2*, of a just perceptibly brighter semicircle (second line).

[3] With diffusing surfaces such as ground or flashed opal glass it is impossible to work with very great differences in brightness between adjacent areas uuless the line of separation cuts through the glass. In the centre levels of brightness differing as much as 1:100 were tried and the result was very much the same as when the patches differed only by a relation of 1:2.

With both equally bright there is a summation of 5.8 per cent. As soon as the right semicircle is made just perceptibly darker than the left, the fusion frequency read on the darker shows the summation reduced to 2.2 per cent, whereas if the readings are taken with the brighter there is still a summation amounting to 5.3 per cent.

Discussion. The interesting fact that synchronous stimulation of adjacent areas favours lateral interaction between retinal neurones is at present a rather isolated observation in the field of central nervous physiology. There is, however, the finding of Adrian and Matthews (1928) that synchronization of discharge may develop spontaneously in the eel's retina if large parts of it be stimulated. On the motor side Adrian and Bronk (1928) found the respiratory centre to discharge rhythmically, if strongly stimulated by asphyxia. Above it was suggested also that, vice versa, the establishment of synchronization, as by flicker, increases the excitatory activities of a centre and that, hence, the facilitated interaction means increased summation. The relations between our results and those mentioned above may be incidental, but taken together they all stress the importance of a factor in reflex work which hitherto has received but little attention.

The presence of inhibitory processes in the retina brings in one more connecting link between the physiology of sensory and motor neurones. It seems necessary to conclude that there is in the retina an inhibitory pathway and furthermore, that this pathway is especially well developed in the fovea. There is, indeed, in this region a system of cells, the amacrines, which here is more developed than elsewhere in the retina (Greeff, 1900), and which is joined to the efferent fibres in opticus. These fibres as well as the amacrines must have some special function. Whether the inhibitory effects have descended from higher central stations or not is of no immediate concern, but our results certainly give a great deal of justification for localizing the inhibitory functions in the amacrines. Allen (1923) holds that the efferent fibres carry both excitatory and inhibitory effects.

The fact that inhibition requires different levels of excitation in adjacent neurones in order to appear would seem to have the practical significance that visual acuity and brightness discrimination are possible in spite of summation over lateral channels. It is another indication of the extreme complexity of the processes underlying these visual functions. The theoretical significance of the observation seems to be that the inhibitory system is excited relatively more and more as the intensity of the excitatory process in a group of neurones increases. Consequently the inhibitory effect passing from the more intensely stimulated area to the adjacent less stimulated area will be greater than the inhibitory effect passing in the opposite direction. Thus only is it possible to picture in general terms the conditions which make inhibition measurable.

Our results may be said to describe a mechanism of contrast in the retina, but it should be borne in mind that such phenomena as binocular contrast and contrast in the blind spot show that there are essential cerebral factors in contrast which can hardly be measured by the flicker method. Sherrington's (1897) ingenious experiments with the flickering "contrast discs" in our opinion do not show once for all that contrast-effects can be measured by this method. They may be explained by the fact that phase-differences were introduced between the adjacent flickering areas or they may be effects of the type described above. That contrast effects as a rule cannot be measured by the flicker method is shown by the work of Lythgoe and Tansley (1929), who found the fusion frequency to *decrease* when the illumination on the background was diminished. By contrast the test patch at the same time must have appeared brighter. The summation, however must have diminished, as shown above, and this factor may account for the results they obtained.

Finally it should be noted that on the strength of the evidence in this paper the low visual acuity and brightness discrimination in the periphery may be explained as being due chiefly to summation. In a previous paper in this series (Granit and Harper, 1930) we hesitated to take this standpoint because of the fact that summation is present in the centre also. Seeing now that the centre possesses an additional mechanism for rendering the summation inactive under conditions where visual acuity is called for this point of view appears rational. At 10° the frontal convergence of receptors is too low to account alone for the low visual acuity (cf. Chiewitz's table in the previous paper). As a matter of fact the visual acuity begins to decrease rapidly from the middle of the fovea (Wertheim, 1894) before the frontal convergence in the periphery can be made to account for it and before the increased peripheral scatter of light is of immediate significance.

SUMMARY

An apparatus has been used in which two beams of light led to two adjacent semicircular test patches can be varied independently with regard to intensity and flicker.

When the two semicircles are of equal brightness and flickered synchronously they give a higher fusion frequency than each taken singly. When only one beam is flickered and the other one adjusted to give the same brightness as the flickered patch when fused the presence of the steadily illuminated semicircle raises the fusion frequency of the flickering semicircle. In this case, however, the effect is less than in the case when both are flickered.

It is concluded that synchronization of impulses favours interaction over lateral channels. Since a steadily illuminated area is capable of rais-

ing the fusion frequency in an adjacent area, it is further concluded that part at least of the interaction, but probably the whole process, involves a true spatial summation.

When the two semicircles are at different levels of brightness the fusion frequency of the darker is unaltered or lowered by the presence of the brighter, whereas the fusion frequency of the brighter is increased by the presence of the darker, provided the difference between them is not too great. The removal of the summation on the darker must be due to inhibition, since the results obtained with the brighter show that summation is bound to appear unless actively inhibited. Also the "darker" semicircle would sum with an equally "dark" adjacent patch.

By showing that when two adjacent areas are at different levels of brightness, the brightness difference is exaggerated by a specific mechanism, which well may be a retinal form of contrast, the results explain how it is possible at high intensities to retain visual acuity and the faculty of discriminating brightness in spite of the increased summation over lateral channels.

The inhibition is especially well developed in the fovea. No evidence of inhibition at high intensities in the periphery has been obtained.

The predominance of summation in the periphery explains its low visual acuity and deficient brightness discrimination at degrees of eccentricity where convergence of receptors and scatter of light are of less significance.

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