

III

THE ANTAGONISM BETWEEN THE ON- AND OFF-SYSTEMS IN THE CAT'S RETINA¹

by Ragnar GRANIT

*The Nobel Institute for Neurophysiology,
Karolinska Institutet, Stockholm.*

My observations are dealing with the so-called on/off-elements which respond to both onset and cessation of illumination. In the cat's eye, studied with the micro-electrode technique, such elements are very common and not difficult to isolate (150-300 μ V in amplitude). It has been known for a long time that these elements are microcosmic nervous centres (see e. g. fig. 60 of my summary, 1947), final common paths for a large number of receptors bipolars and amacrine. There was also the possibility that, in addition, they might be synchronized final common paths but this possibility has been eliminated by a recent experiment by Rushton (1949) in this laboratory. They are thus unit final common paths.

Let us now consider a simple experiment that can be performed with these units (on/off-elements). We proceed to shorten the duration of exposure. Sooner or later the on- and off-component of the discharge must collide owing to temporal overlap. What happens then? Do the on- and off-components reinforce each other or are they mutually exclusive? Imagine the on- and the off-components to join up to the ganglion in exactly the same fashion. If so, there seems to be no reason why they should not summate and make the ganglion cell discharge at

1. It is a pleasure to contribute to the volume in honour of Professor Henri Piéron some observations on the retina, a theme which he is thoroughly familiar with having himself devoted years of successful research to problems of vision.

a higher frequency for a longer time. Again, if either of the two excludes the other one, then we have evidence in favour of a real antagonism between the on- and the off-paths somewhere on the route to the ganglion cell.

The experiment sounds extremely simple to perform. Nevertheless there are some pitfalls in it that have to be recognized. It is necessary to begin by taking some pure on- and pure off-elements in order to see how the components respond separately to the shortening of the exposure. The following exposures were chosen : 1.000, 295, 150, 65, 28, 21, 12 and 7.4 milliseconds. It was found that, near the threshold, the elements could not follow down to the shortest exposures but that they generally did so already at intensities from 10 to 100 times the threshold. A number of pure on-elements were found that were particularly slow and stopped discharging already with exposures around 30 milliseconds. These, however, were rare. It is therefore easy to select a level of intensity for which most elements discharge, even to a 7 msec. flash. The initial phase of the discharge is then often well preserved, generally it is shortened in duration and the latent period slightly lengthened. This lengthening of the latent period begins with the 12 msec. flash but may be absent at strong intensities. There is never any shortening of the latent period at short exposures. Thus, if, with regard to onset of illumination, the latency has shortened for the briefest flashes it means that the discharge actually has begun as an off-discharge.

It is well known that for the on/off-elements the off/on-ratio of the frequencies varies with level of intensity. Most interesting, from the present point of view, are the cases in which one succeeds in adjusting the intensity so that both the on- and the off-component are of about equal strength in terms of spike frequency and number but, even when this is done, the off-discharge generally has a shorter latent period. Thus a difference of some 20-30 msec. is quite common and this means that with flashes of the same order the on- and the off-discharges should be elicited at the same moment. One can shorten the latency by using higher intensities but at such intensities it is very common to find a generalized inhibition suppressing both the on- and the off-discharge. In such cases a shortening of the exposure removes this inhibition and the discharges become more vigorous, particularly the off-discharge. This, of course, is a serious source of error unless recognized. It makes it difficult

to use very high intensities. It should be noted that in addition to the large spikes there are small spikes in the cat's retina. These often have considerably shorter latencies. Again, with these elements isolation is far less satisfactory and, for this experiment, it is imperative to know that one is recording from a single unit. The on- and the off-discharge are more often than not characteristically different in the way the spikes are grouped.

The result of the experiment can be briefly stated. There was no case in which it was possible to assert with any sort of conviction that one had encountered real summation of the spike frequencies of the on- and off-components at short exposures. I do not wish to infer that such summation is excluded. There is a statistical element in all single spike work and one may not have encountered every possible spike and may not have struck its optimum intensity level for such effects to occur. But it is quite clear that the easiest finding to demonstrate, when shortening time of exposure, is the mutual exclusion of the one component by the other. Most common is then that the off-discharge excludes the on-discharge but one may, in the same element, find the opposite effect too, depending upon the particular off/on-ratio characteristic for the level of intensity chosen. Relatively stronger on-effects are capable of suppressing the off-effect. Very common is a type of element in which the off-component becomes stronger than the on-component at high intensities. The discharge at short exposures is then an off-discharge and the on-component is wholly suppressed.

It is perhaps best to illustrate this statement with some actual observations on a single element, one for which several intensity levels could be studied. It was of the not too common type for which both components were seen at all levels of intensity.

The experiment was begun at a very low level of intensity, 4.7 times the threshold energy in wave-length 5.000 Å. Latencies were of the same order for 'on' and 'off', 150-180 msec., and very variable, as they are likely to be at such low intensities. There were 2 — 4 spikes at 'on' for the two long exposures (1.000 and 295 msec.), 4 spikes at 'off', all within the first 0.1 sec. An off-effect was not seen at the 150 msec. exposure. Similarly it was absent at all shorter exposures. This finding can be interpreted to mean that the off-effect as such did not stand short exposures. More likely, however, is that the off-discharge was suppressed by the on-discharge.

The next level of intensity was 33 times the threshold and the spikes were counted per 0.1 sec. Three such periods were counted.

The on-discharge for the two long exposures in three such 0.1 sec. periods was 6 — 2 — 0 or 4 — 2 — 0, more commonly 6 — 2 — 0, after a latency of around 120-140 msec. The off-discharge gave 6 — 3 — 3 and maximally 7 — 3 — 1 for the long exposures, the latency being around 100 msec. At an exposure of 28 msec. the response was 6 — 1 — 0. For this exposure it was difficult to tell whether the remaining discharge was an on- or an off-effect. Both latencies fitted equally well. At any rate there was no summation. At 21 msec. the response was 5 — 1 — 0 and it was still difficult to say whether it was an on- or an off-effect. At exposures of 12 and 7.4 msec. there were 5 impulses only, all within the first 0.1 sec. The latent period for cessation of illumination was 120 msec. It seemed a little too long for an off-effect.

The following level of intensity chosen was 330 times the threshold. The on-latencies were still around 120-130 for the long exposures and the discharge had the character 5 — 1 — 0 and 3 — 1 — 0, these being the extremes. The off-discharge came after 100-110 msec. and was now stronger and of longer duration (for the long exposures). It had a very characteristic grouping of the spikes. Typical values were 5 — 3 — 3 — 2 or 5 — 4 — 2 — 1 and once 6 — 2 — 0. These counts are per 0.1 sec. and do not necessarily coincide with the grouping of the spikes. In this case it was quite evident that the off-effect took over the running of the discharge at short exposures. At 28 msec. exposure the total effect was 7 — 2 — 0 and the length of the latent period, counted as an off-effect, was 90 msec. thus suggesting that the first spike still was the first spike of an on-discharge, the rest of which was suppressed. At the 21 msec. exposure the whole effect was 6 — 1 — 0 and this value was obtained down to the shortest exposure 7.4 msec. The discharge had the typical grouping of the off-effect spikes and the latencies were so consistently between 100 and 110 msec., counted as off-effects, that the most reasonable explanation was that the off-effect was the winning part.

Finally an intensity level of 2,000 times the threshold was employed. Both on- and off-effect now had equally long latencies for the long exposures, 85-100 msec. The on-values for these exposures were 3 — 3 — 0, 4 — 2 — 0 and 5 — 1 — 0. The initial frequency was slower than in the previous series sugges-

ting that there was more inhibition at onset of illumination at this level of intensity. The off-discharge was further improved. It was now somewhat better at 295 msec. than at 100 msec. suggesting some 'generalized inhibition'. The complete series of off-frequencies follows :

<i>Msec.</i>	<i>Off-frequencies counted for each 0.1 sec.</i>
—	—
295	8 — 5 — 1 — 1 and 8 — 5 — 1 — 2.
149	8 — 5 — 1 — 0, preceded by on-discharge 4 — 1 — 0.
65	8 — 4 — 1 — 0, preceded by two on-spikes at on-latency.
28	7 — 3 — 2 — 0, preceded by two on-spikes as above.
21	8 — 3 — 1 — 0, first spike of first group may have been an 'on'-spike.
12	7 — 3 — 0
7.4	7 — 4 — 0

The latent period was constant, counted from cessation of illumination, and, as long as an on-discharge was visible, it too had a constant latency from onset of illumination and was separable from the off-discharge. Whilst it sometimes may be difficult to tell whether a discharge is an on- or an off-discharge, it is often very much easier than in the experiment mentioned. It is often possible to see a definite silent interval between the on- and the off-discharge. But such an interval is not a necessary condition for the suppression of the on-component by the off-activity.

This experiment throws some light on retinal inhibition. It suggests that during the latent period of the off-process something happens that inhibits on-spikes and, similarly, during the latent period of what will become a good on-discharge something happens that suppresses the off-component. The two processes are therefore somehow mutually exclusive. Whilst the mechanisms only can be explained by hypothesis it is easy to see some sense in an arrangement whereby light- and dark-responses, particularly when delivered by the same ganglion cell, are prevented from interfering with each other and forced to appear one at a time. As to further evidence for antagonism between on- and off-systems, see Granit (1950).

SUMMARY

Single spikes, isolated from the retina of decerebrate cats by the micro-electrode technique, have been studied at variable short exposures of illumination in order to find out whether on- and off-discharges overlap and mutually reinforce each other, or whether they are mutually exclusive in the sense that the final common path only can deliver one at a time. The latter was found to be the case.

REFERENCES

- GRANIT (R.). — *Sensory Mechanisms of the Retina*, Oxford University Press, 1947.
— The organization of the vertebrate retinal elements. — *Ergebn. Physiol.*, 1950, 46, 31-70.
RUSHTON (W. A. H.). — *Nature*, 1949, 164, 743.
-