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STIMULUS INTENSITY IN RELATION TO EXCITATION AND PRE- AND POST-EXCITATORY INHIBITION IN ISOLATED ELEMENTS OF MAMMALIAN RETINAE

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Since the demonstration of inhibition in the whole optic nerve by Granit & Therman [1935] and in single fibres of the frog's eye by Hartline [1938], it has been evident that the primary effect of illumination of the light receptors emerges in the optic nerve, after passage through the synaptic layers, in the shape of complicated patterns of excitation and inhibition. Such complications do not occur in the simple non-synaptic retina of the horseshoe crab *Limulus* [Hartline & Graham, 1932] where the discharge—just as in other sense organs—is an even flow of impulses, at higher intensities of stimulation interrupted by a brief silent period.

In the frog's optic nerve inhibition—below to be termed pre-excitatory inhibition—is present in its purest form in about 30% of the fibres which merely respond with an off-effect when the stimulus is withdrawn and which always are completely inhibited by illumination. Pure excitation is present in less than 20% of the fibres; these respond with an even flow of impulses as in *Limulus*; in other words, they are elements which behave as if they merely had transmitted the primary excitation pattern of the initial receptor mechanism. But the majority, more than 50%, are of the combined excitation-inhibition type responding with both on- and off-discharge. The on-off response is therefore the typical and characteristic discharge in the single fibres of the frog's optic nerve. The percentages given are from Hartline's work in which the types described also were found to be stable.

In the course of work on colour reception with mammals [summarized by Granit, 1943*a*], I have had occasion to observe a large number of isolated fibres in the optic nerves of, particularly, cats [Granit, 1943*b*] and guinea-pigs [Granit, 1942], the former a mixed (rod-cone) eye with impressive rod dominance, the latter a pure rod-eye. These observations have later been supplemented with a number of systematic intensity series in the two states of adaptation. These two types of retinae were very different, both when compared with each other and when individually compared with the frog's eye. In particular, the inhibitory phenomena, which in an interesting manner connect this field with general neurophysiology, turned up with new aspects. This work is a presentation of the results.

METHOD

The cats were decerebrated, the guinea-pigs anaesthetized with 20% urethane (4–6 c.c.). In some experiments rats were used [cf. Granit, 1941]. After decerebration the cats were also given a small dose of urethane (about 10 c.c.) to keep eye movements in check. Cornea and lens were removed and a platinum wire micro-electrode, isolated with glass down to the tip, was inserted under a binocular preparation microscope with the aid of a micromanipulator. Leads were taken to amplifier, cathode ray, and loud-speaker in the usual manner.

In the standard experiments the animals were dark-adapted (scotopic animals) and the whole eye stimulated with a lamp at 892 m.c. with an energy distribution corresponding to 2,800° K. Ilford neutral filters and a neutral wedge were used for weakening the strength of this stimulus. Light-adaptation (photopic animals) for 10 min., when needed, was carried out with the lamp mounted in the preparation microscope (2,400 m.c.). This light was also sometimes used as maximal stimulus.

RESULTS

1. *The guinea-pig's retina*

All three mammals studied in the colour work (cat, guinea-pig, rat) share the property of having very few fibres that could be characterized as pure off-elements. Against the 30% of such elements in the frog's eye stand 1 or 2%, as a rough estimate, in the mammals studied. These pure off-fibres generally have had very high thresholds, in the neighbourhood of 1000 m.c.

The pure rod-eye of the guinea-pig differs from the mixed retinae of the cat and the frog in that the great majority of the isolated spikes belong to the pure excitation type, illustrated in Fig. 1. The discharge is an even flow of impulses, as in the eye of *Limulus*, at higher intensities often, though not always, interrupted by a silent period after the initial high-frequency start. These elements are of two types: (i) the upper type, illustrated in *a*, responds precisely as the *Limulus* fibres, with high initial frequency and little or no after-discharge; in the lower type, illustrated in *b* (continued in third record), the discharge ends with an after-discharge which in this case is particularly well developed. The same element responds in *c* after light-adaptation. A typical effect of light-adaptation is the shortening of the after-discharge. The diminution of spike height in the middle of the record is probably caused by a minute eye-muscle contraction. The after-discharge in record *b* should be clearly distinguished from an off-effect (see Fig. 8). The latter represents a real increase in frequency of the discharge at 'off' and is wholly or temporarily inhibited by re-illumination. The after-discharge, however, is a gradual disappearance of the effect of the stimulus. It is uninfluenced by re-illumination unless the pause of darkness is long enough for recovery of the element and fresh on-discharge.

These pure on-elements, which respond with a continued discharge as soon as stimulus intensity is sufficiently high, form about 90% of the elements in the guinea-pig's eye. The rest of the elements are practically all of them on-off elements such as those in the cat's eye, but responding within a considerably smaller frequency range.

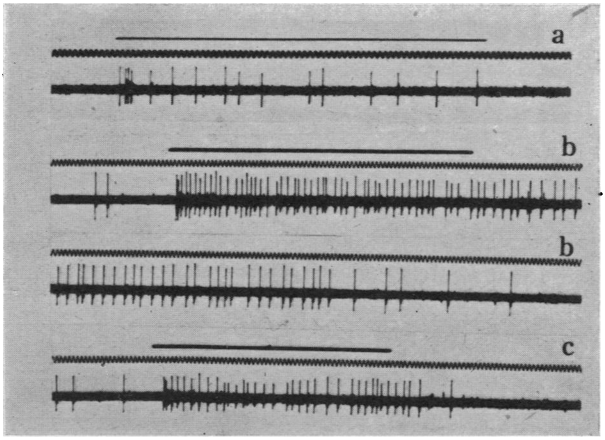

Fig. 1. Micro-electrode record from the optic nerve of the guinea-pig serving to illustrate pure on-elements giving continuous discharge. Light signal and time in 1/50th sec. above each record in this and all figures to follow: *a*, scotopic retina and element responding to 12·3 m.c.; *b* and *c*, from another experiment, *b* scotopic, *c* photopic, in both cases responding to 18·2 m.c. See text.

The characteristic relations between stimulus intensity and impulse frequency are illustrated in Fig. 2 for four such on-elements in the dark-adapted state (filled circles), the lowest, D, over a range of 6 logarithmic units. The variations in the absolute threshold probably depend upon the degree of anaesthesia, which is difficult to control as animals react very differently. The uniform results are: that the variations in impulse frequency take place over a range of about 1–100 impulses per sec., and that the curves very soon cease to rise with increasing intensity, some even bending down at intensities of a relatively moderate order of magnitude (1000 m.c.).

The elements B, C and D were light-adapted and the same experiment repeated (empty circles). Light-adaptation pushes up the threshold so that the frequency range of up to 100 impulses per sec. is compressed within a smaller intensity range. In B light-adaptation was continuous and merely interrupted for a few seconds during which the test stimulus at different intensities was introduced. In the curve marked 'circle with cross' each observation followed 1 sec., in the other one (empty circles) 2 sec. after cessation of the light-adapting stimulus.

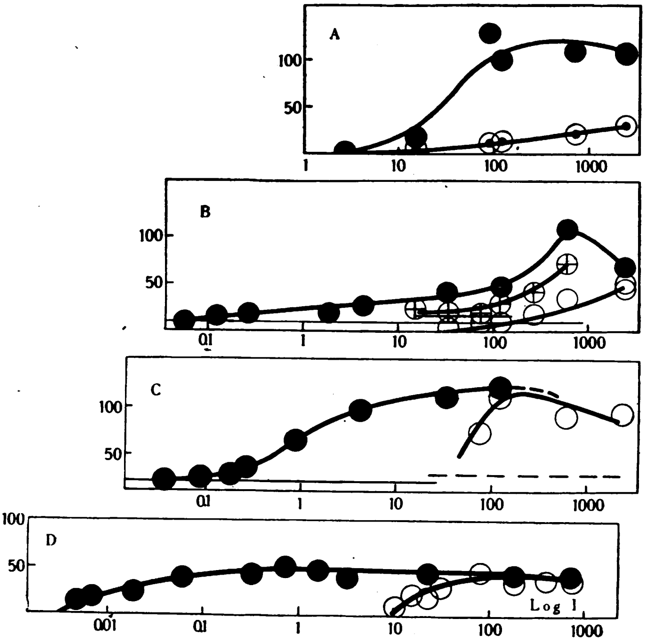

Fig. 2. Guinea-pig. Micro-electrode. Frequency of the discharge of isolated elements plotted in impulses/sec. against log intensity in meter candles. A, scotopic; upper curve initial frequency, lower curve frequency counted after silent period or corresponding interval. B, filled circles scotopic, open circles photopic (see text). In this and the following curves ordinates =initial freq. Frequency of spontaneous activity, when present, indicated by horizontal lines, separately for scotopic and photopic state. C and D, separate experiments marked as in B.

The effects of light-adaptation may now be briefly summarized: (i) after-discharge is reduced, (ii) threshold increased, (iii) on an average, the frequency-log intensity curves would probably also rise at a slightly steeper gradient than in dark-adaptation.

2. *The cat's retina*

General observations. The cat's retina proved to be a far more complex organ than that of the guinea-pig. Some 20% of the elements are of the pure excitation on-type, described above for guinea-pigs. But their upper frequency limit is higher than in the guinea-pig. The rest of them are of the on-off type. These behave in a complex manner when stimulus intensity is varied.

In both cats and guinea-pigs some spontaneous activity is common in the spike located by the electrode. They differ in this respect from the frog, in which spontaneous activity is less marked, though it often turns up after some dark-adaptation. This slow spontaneous activity can be made very useful for the experimenter: inhibitory phenomena, which otherwise would be unsuspected, are recognized by the decreased or fully inhibited spontaneous rhythm. In order to illustrate this, Fig. 3 should be consulted. The intensity is increasing downwards and the numerals on the right indicate the densities of the filter-wedge combination in front of the 892 m.c. stimulus. In the two lowest pictures (1·38 and 0·09) the spontaneous frequency has decreased somewhat, due to a protracted inhibitory after-effect of the strong stimuli used. The rate of discharge in the on-effect increases continually downwards and reaches frequency values around 300 per sec. The frequencies but rarely surpass this figure though individual receptors have reached 400. The off-effect behaves in a very complicated fashion. The frequency first increases slightly above the spontaneous rhythm, then diminishes, rises a second time (at density 1·38) and

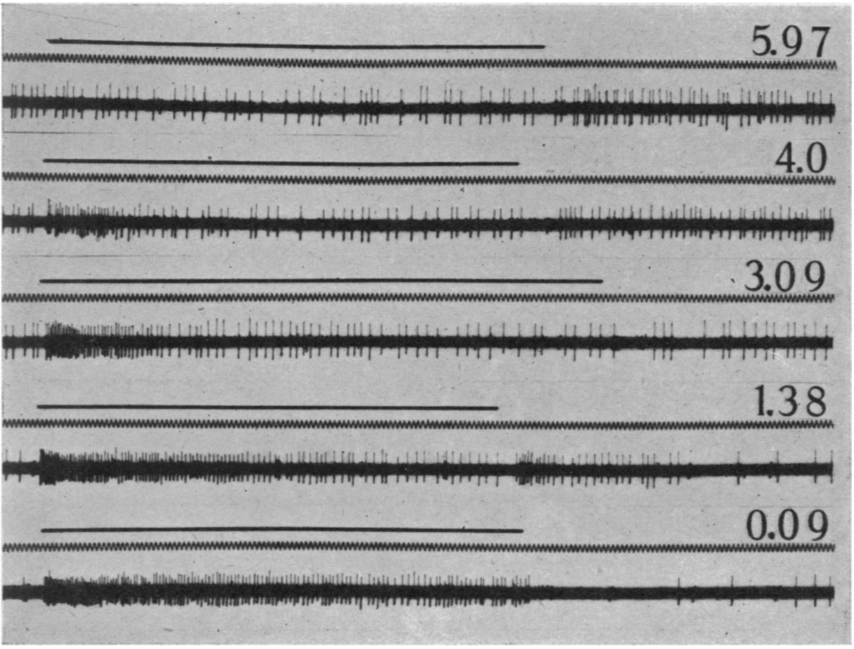

Fig. 3. Cat. Isolated spontaneously active element responding to downwards increasing intensities. The numerals to the right show the extinction (densities) of the filter-wedge combination used in front of a light of 892 m.c. Owing, partly, to some light-adaptation caused by stronger stimuli the spontaneous rhythm decreases downwards.

is finally completely blocked at the highest intensity. The pause in the spontaneous rhythm shows that it then is actively inhibited.

Another element is shown in Fig. 4. In this case there is very little spontaneous activity. The on-effect increases in frequency downwards, reaches a maximum, decreases (at density 3·01) and in the final lowermost record at the highest intensity, the whole on-discharge is very much delayed, as if somehow it had managed to escape an initial inhibition. The off-effect increases in frequency until a maximum is reached at density 3·01 and then slightly decreases at the maximal intensity. This type of element is very common in the cat's eye, probably the most common type. In the background of the same record is seen a brief initial discharge of short latency, caused by other elements less well localized by the micro-electrode but sufficiently many to give a small group of spikes of brief latency. This is often noticed.

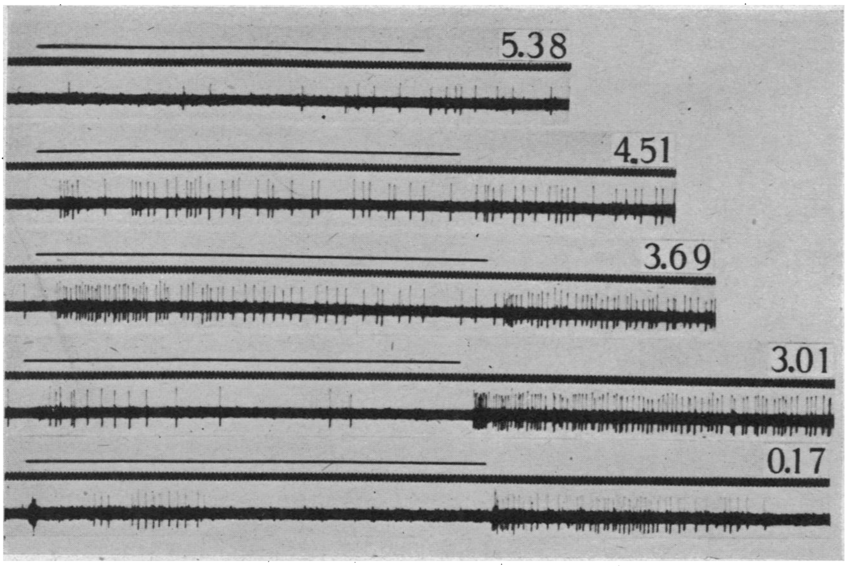

Fig. 4. Cat. As in Fig. 3, but another experiment with another type of on-off element.

Intensity-frequency curves for the two states of adaptation. Some experiments on the effect of stimulus strength upon the frequency and the total number of impulses at 'on' and 'off' have been quantitatively analysed in Figs. 5 and 6 for the two states of adaptation. Light-adaptation of the animal (wide open pupil) has been achieved with the aid of the lamp (2,400 m.c.), used for insertion of the micro-electrode. There is a full description of the experiments in the figure texts. In Fig. 5 B the two lines parallel with the abscissa represent the frequency level of the spontaneous activity of the spike studied. The broken horizontal line refers to light-adaptation, the line drawn in full to dark-adaptation. Thus when the curves go below these lines there is active inhibition of the spontaneous rhythm. The curves should be compared with the much simpler curves of Fig. 2 for the guinea-pig. Clearly rivalry between excitation and inhibition plays a much greater role in this mixed retina than in the guinea-pig's pure rod retina.

Pre- and post-excitatory inhibition. These two terms are easily understood. By *post-excitatory inhibition* is meant the kind of inhibition that follows *after* excitation (by light) and which leads to suppression of spontaneous activity and off-effect, if an off-effect has been present at some lower intensity level. This kind of inhibition is common in the retinae of *both* cats and guinea-pigs, perhaps more common in the latter. It is illustrated in Fig. 3, lowermost record, and in Fig. 5 B it is seen to press the intensity-frequency curve for the off-effect in the dark-adapted state below the level of spontaneous activity (in the region of about 1 m.c.). Post-excitatory inhibition thus cuts down after-effects of excitation which otherwise may have occurred. In Fig. 7 post-excitatory inhibition is illustrated for a pure on-element with some spontaneous activity (guinea-pig).

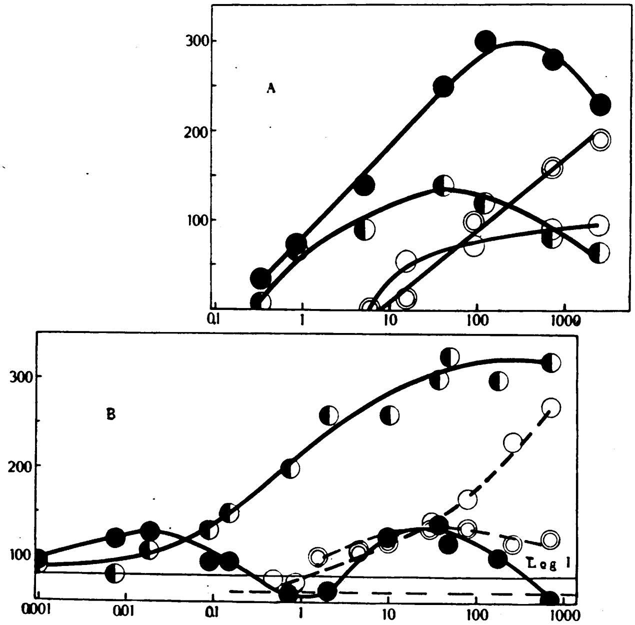

Fig. 5. Cat. Frequency of discharge of isolated elements plotted in impulses per second (initial freq.) against log intensity (m.c.). Light- and dark-adaptation compared for two elements (A and B). Scotopic on-discharges = semi-filled circles; scotopic off-discharges = filled circles; photopic on-discharges = open circles; photopic off-discharges = circles with double contour. Spontaneous frequency present for element B and marked by horizontal line in full (scotopic) or interrupted (photopic).

Post-excitatory inhibition explains a number of earlier observations by other authors: with the eye of the horned toad Meservey & Chaffee [1927] noted that the fast positive off-effect of the electroretinogram diminished at higher intensities, as also found by Wrede [1937] and Therman [1938] with the frog's electroretinogram. Hartline [1938] showed that the off-effect in single fibres of the optic nerve of the frog also diminished at higher intensities, as would be expected from the general correspondence between the fast positive phases (due to the retinal component potential P II) of the electroretinogram and the discharge in the nerve. The difference in Fig. 1 between the two types of pure on-elements in the retina of the guinea-pig is probably also due to a different

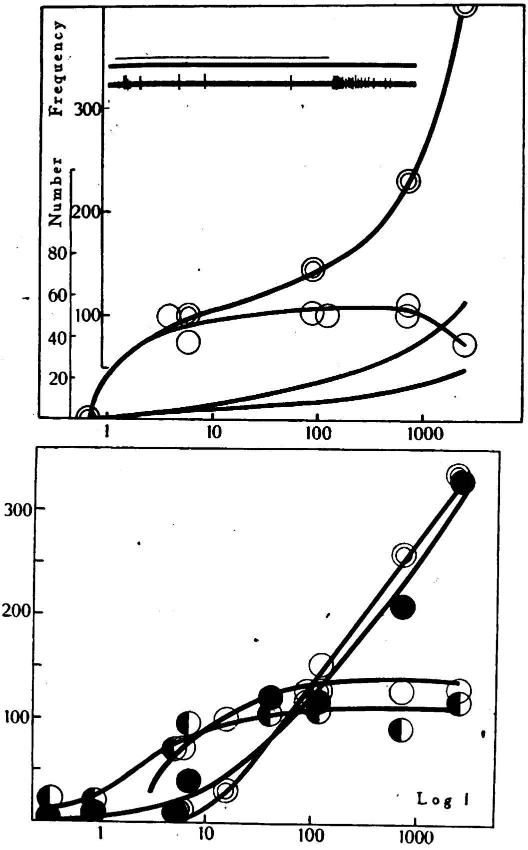

Fig. 6. Cat. Same as in Fig. 5 for two elements, but in addition has been measured, in upper picture, the total number of impulses of the photopic element reproduced in the inset. The discharge in this case was relatively brief at 'on' and 'off'. The lower pair of curves in this picture, for which the individual readings have been left out, show total number of impulses in the records that were used for frequency measurements in the upper pair. Upper curve, off-discharge; lower curve, on-discharge.

degree of development of post-excitatory inhibition in them. The one type (*a*) had no after-discharge whatever, whereas the other type (*b*) still discharged some time after cessation of illumination. Lack of after-discharge may be due to prominent post-excitatory inhibition.

Post-excitatory inhibition may be identical with the 'local stimulatory inactivation', noted after electrical stimulation of the cerebral cortex by Dusser de Barenne & McCulloch [1937] and by them termed *extinction*. It is most conveniently observed in the 'simple' discharge of the guinea-pig's retina when a spontaneously active pure on-element has been localized with the aid of a micro-electrode (as in Fig. 7). These fibres generally stop their spontaneous activity for a while after illumination of the retina with a sufficiently strong light.

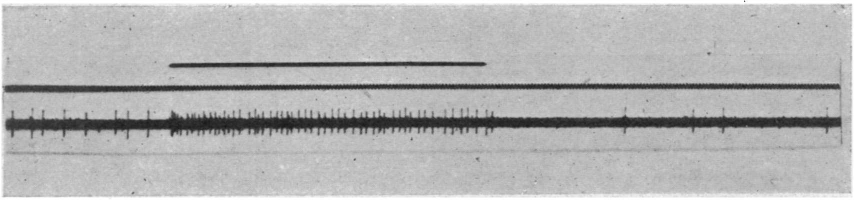

Fig. 7. Guinea-pig. Spontaneously active element giving a pure on-discharge to illumination with 892 m.c. The discharge is followed by post-excitatory inhibition silencing spontaneous rhythm for a while.

Pre-excitatory inhibition is the type of inhibition originally described by Granit & Therman in this *Journal* [1935]. It has the interesting property of reflecting the behaviour of the slow retinal component potential P III [cf. Granit, 1938]. In order to differentiate it from post-excitatory inhibition it is termed *pre*-excitatory, the term emphasizing its brief latent period, briefer than the latent period for excitation, as is best demonstrated by re-illumination on top of an off-effect. In work, now in progress, the two forms of inhibition have been found to possess very different properties with respect to diverse agents.

In order to be demonstrable pre-excitatory inhibition needs the background of excitation which, for post-excitatory inhibition, was provided by spontaneous activity. But for pre-excitatory inhibition the best background is the off-discharge following cessation of illumination, and the test for the efficiency of the inhibition therefore consists in re-illumination after a brief pause of darkness. The pure off-element that is inhibited by light and set free by cessation of illumination exhibits pre-excitatory inhibition in pure form. In this element it is so effective that every sign of a discharge to illumination, started by the primary sense-cell, is curtailed in the synapses before it has had a chance of turning up in the optic nerve. The off-effect is therefore also immediately and completely inhibited by re-illumination.

Two elements illustrating typical aspects of pre-excitatory inhibition in cats are shown in Fig. 8. There is a slight spontaneous discharge in *a* which is increased into an on-discharge upon illumination and again accelerated into a vigorous off-effect upon cessation of illumination. The on-effect is insignificant compared with the off-effect. The stimulus is here 892 m.c. diminished by *red* filter and neutral filter (density 1·25). In *b*, when illumination is repeated after removal of the neutral filter, pre-excitatory inhibition is relatively stronger than excitation so that at 'on' there is merely inhibition, as demonstrated by the decreased spontaneous activity. A part of the film has been cut out and then follows the off-discharge. Re-illumination after a brief pause completely inhibits this off-discharge, shown again as control at the end of record *b*. The red filter is finally removed in *c* so that light from the whole spectrum stimulates the eye. There is now in response to illumination a very much delayed discharge, looking as if it barely had succeeded in escaping from pre-excitatory inhibition. The final record *d* is another element from another experiment. It shows re-illumination during the off-discharge of an on-off element. Here the pre-excitatory inhibition, elicited by re-illumination, merely succeeds in causing a brief pause of inhibition in the off-discharge. This pause is interrupted by a fresh on-discharge of this on-off element.

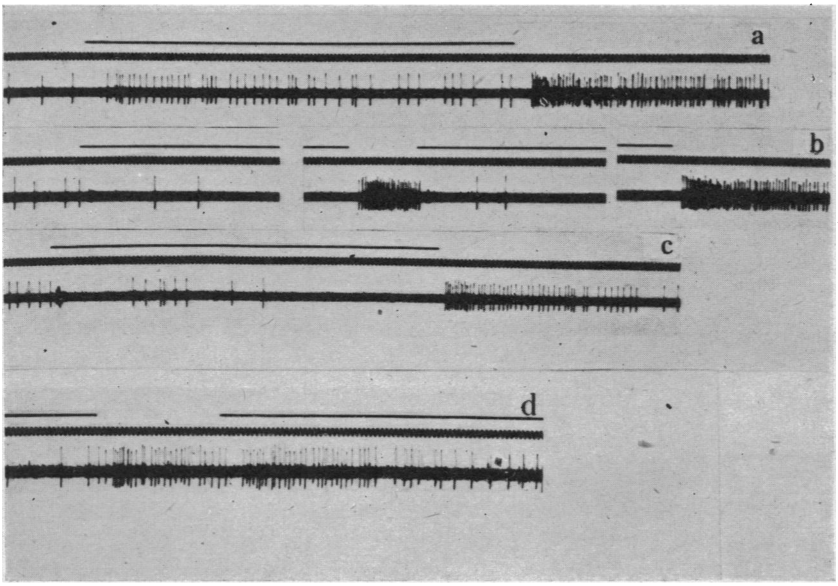

Fig. 8. Cat. Analysis of pre-excitatory inhibition by re-illumination during off-discharge of on-off element. Fully described in the text. The records *a*, *b* and *c* belong to the same element, record *d* to another.

What would now in cats be the *typical* behaviour of pre-excitatory inhibition in the test by re-illumination? Would it be a *complete inhibition* as in *b* or merely a *brief inhibitory pause* as in *d*? Actually the large majority of elements are of the latter type, giving merely a brief inhibitory pause. Pre-excitatory inhibition in the cat's retina is better developed in the upper intensity ranges (cf. Figs. 5, 6).

Pre-excitatory inhibition presupposes on-off elements and is maximally developed in the pure off-elements. For this reason it is of far less significance in the rod retina of the guinea-pig which chiefly contains on-elements. Again, in the retina of the frog (rods to cones about 50 : 50), pre-excitatory inhibition is far more prominent than in the retina of the cat where the cones are few, though sufficiently many to give a Purkinje shift [Granit, 1943*b*].

The degree of development of the off-discharge in a given retina is a rough index of the use it makes of pre-excitatory inhibition. The reason for this statement is that the off-discharges can be regarded as a consequence of pre-excitatory inhibition. The pure off-elements are inhibited by light and are piling up inhibition during illumination so that the longer the duration of the exposure the greater, within limits, the frequency and duration of the off-effect. In the cat's eye pure off-elements are rare and consequently complete inhibition of the off-effect by re-illumination is far less common than the brief inhibitory pause, illustrated in Fig. 8*d*.

Stable and labile units. In the frog's eye Hartline [1938] found on-fibres, off-fibres, and on-off fibres to preserve their type despite variations in intensity of the stimulus. The suppression in this eye of the off-discharge by high intensities does not mean that the isolated unit has changed type but is probably due to post-excitatory inhibition, as suggested above. In the retinae of cats and rats the pure on-elements have also been found to be stable. However, the on-off elements in the cat's retina are variable. At high intensities they often behave as pure off-elements, sometimes also as pure on-elements (as in Fig. 3); at low intensities the on-effect may predominate, and as the frequency-intensity curves show, rivalry between excitation and inhibition may at different intensity levels give the discharge a very different aspect. The few pure off-elements in the mammalian eyes are also stable but, since their thresholds as a rule are very high, they can only be studied within a very limited range of intensities.

In the cat's eye the on-off elements behave as if they were a combination of pure on-elements with pure off-elements. At the moment it is impossible to explain the variability of these elements. But the facts (i) that the negative component P III of the electroretinogram is a high-intensity component in cats and (ii) that this component generally is associated with inhibition suggest that the great increase of pre-excitatory inhibition at high intensities may account for at least some of the complex changes in the on-off elements at such intensities.

DISCUSSION

Comparison with electroretinogram

The off-effect in the slow retinal potential (the electroretinogram) is well developed in the frog, which has a large number of pure off-elements represented in its optic nerve; it is much smaller in the cat's electroretinogram. The first effect of re-illumination on top of a retinal off-effect is a large negative *a*-wave (component P III) in the electroretinogram of the frog, but merely a slightly delayed, sub-normal positive *b*-wave (component P II) in the electroretinogram of the cat. In the frog this negative *a*-wave of P III is coincident with pre-excitatory inhibition in the nerve. This inhibition, according to Hartline [1938], is complete for the pure off-elements of this animal. However, in the cat, which has chiefly on-off elements, the inhibition, caused by re-illumination, is generally a brief pause in the off-discharge (Fig. 8*d*) followed by the discharge of the reactivated 'on'-fraction of the complex on-off element. Complete inhibition is rare in this animal. These comparisons suggest that the negative *a*-wave of the electroretinogram (component P III) in re-illumination is well marked merely when—as in the frog—pre-excitatory inhibition in the individual elements is so well developed that a large fraction of the off-discharge of the whole retina is completely inhibited by light. Similarly the off-effect of the electroretinogram also is well developed in retinae in which a large number of individual elements actually respond merely at 'off'. It was shown by Granit & Therman [1937] that in this case there is also in the off-effect of the electroretinogram re-activation of the positive component P II. This fact has been incorporated in the recent analysis of the electroretinogram of the frog's eye, published by Bernhard [1942].

In all comparisons between the electroretinogram and the discharge of isolated elements it should be remembered that the former is an average effect and that it is necessary in such comparisons to be able to distinguish the common from the atypical in the properties of isolated units. Records from the whole nerve supplement the information from single fibres. Recently Adrian [1941] has taken such records from the whole optic nerve of cats and points out that bright light tends to give a brief on-discharge followed by inhibition, as in Fig. 4 (lowermost record). This is in good agreement with my experience that pre-excitatory inhibition at high intensities characterizes most isolated units in the optic nerve of the cat. Furthermore, it agrees with the fact that the component P III (in the electroretinogram), which is associated with pre-excitatory inhibition, is a high-intensity component in cats [Granit, 1933] and that the cat's electroretinogram at high intensities often has a diminished *b*-wave of P II, followed by a negative phase of P III.

Rods and cones, duplicity theory

The duplicity theory comes into the foreground because of the differences between cats and guinea-pigs. Since these differences are post-synaptic, interpretation of the results in the light of the theory presupposes the assumption that the synaptic organization is different for rods and cones, an assumption well justified by retinal histology. The main conclusion that would be suggested by these experiments is that from the functional point of view the synaptic organization of the rods is simpler and for this reason more likely to transmit the receptor effect without other modifications than those caused by summation, due to convergence, and by post-excitatory inhibition—which, after all, may be paralleled with similar phenomena in peripheral nerve. Hence would arise the absolute dominance of the simple on-elements in the rod-retina of the guinea-pig. The presence of a few off- and on-off elements in the guinea-pig's rod-retina would then serve to emphasize that these as well as all other experiments with the micro-electrodes, those on colour reception [Granit, 1942–3] as well as those on adaptation (unpublished), suggest that there are transitional forms between rods and cones (in the strictest sense of the terms). The guinea-pig has no Purkinje shift and few if any so-called red modulators, elements sensitive to red within a relatively narrow spectral region, and thus can hardly be held to have any cones.

The cat has cones, though these still are in the minority but, functionally, they are easily detected with the micro-electrode technique. A certain number of the elements of the cat's retina show a definite Purkinje shift and, after light-adaptation, respond to spectral light with the sensitivity distribution of the so-called photopic dominator of the cones with maximum at $0{\cdot}560\mu$ [Granit, 1943*b*]. Pure cone-eyes have only been studied in cold-blooded animals [Meservey & Chaffee, 1927; Bernhard, 1941] but these have all had prominent off-effects and prominent negative components in their electroretinograms, as the many correlations between this component (P III) and pre-excitatory inhibition would have led one to believe. Thus there are reasons for assuming pre-excitatory inhibition to be a feature of the synaptic organization of the cones. Nevertheless we must ask whether the differences between cats and guinea-pigs could be due to the heavier anaesthesia of the latter.

The rat, anaesthetized with urethane, as the guinea-pig, has a somewhat greater percentage of on-off elements than the latter and for this reason was chosen for some experiments on the effect of this drug. Three urethanized rats, in which first a place giving a well marked on-off discharge of a number of elements had been localized with the micro-electrode, received three times the normal dose in two intraperitoneal injections at an interval of 10 min. The elements under the electrode continued to react as on-off elements despite the abnormally deep anaesthesia. A similar experiment with the same outcome was performed with a cat which was given successive doses of urethane until its respiration stopped. These experiments showed that very much larger doses of urethane than those used for guinea-pigs did not succeed in removing off-discharges. It is therefore improbable that the small number of on-off elements in the guinea-pig could be due to selective removal of off-discharges by this drug, even if a small effect of this type were present and served to emphasize the difference between cats and guinea-pigs with respect to pre-excitatory inhibition.

The striking differences in the intensity-frequency curves between cats and guinea-pigs are quite in harmony with what we should expect on the basis of the assumption that frequency is the main determinant for visual effects depending upon intensity. All visual work, on brightness discrimination, flicker fusion, visual acuity, etc., also shows that these functions plotted against log intensity are characterized by much steeper slopes in the cone-region than in the rod-region of stimulus intensities, as would be a direct consequence of the differences in the frequency-intensity curves for cats and guinea-pigs. Still, in this case, it is very probable that the curves actually have been somewhat distorted by the anaesthetic given to the guinea-pigs. The urethanized guinea-pig may not have been able to respond with as high frequencies in the upper ranges as the decerebrated cats could do.

From the point of view of visual discrimination it is clear that a retina possessing the variable receptive pattern of the cat's eye must respond to every fluctuation in intensity with a transformation of the pattern delivered to the cortex. Hardly two elements in this eye are exactly alike! The question as to how retinal interaction can co-exist with a high degree of discrimination, first raised by Adrian & Matthews [1928] and Granit & Harper [1930] and still occupying Bartley [1941], can now be answered. The retinal discharge from the smallest area is differentiated to a degree that was not understood ten years ago. Hartline's work on frogs [1938, 1940*a*, *b*] and these results with the cat's retina place impulse frequency and transformation of pattern into the foreground in every explanation of discrimination.

In connecting the differences between the individual elements of cats and guinea-pigs with an extended duplicity theory incorporating inhibition, I do not wish to convey the impression that this interpretation, based on so few types of retinae, needs be final. I would rather like to express the hope that sooner or later similar experiments will be carried out in other laboratories with other retinae and the same technique. The duplicity theory is, after all, the first purely visual theory that has to be put to a test with the new technique, the more so as this first attempt to do it has shown that striking differences between different retinae can be demonstrated.

SUMMARY

1. In the pure rod-retina of the guinea-pigs an overwhelming majority of the elements merely discharge to onset of illumination. Some of them stop their discharge abruptly upon cessation of illumination, others possess a definite after-discharge gradually diminishing in frequency.

2. In the mixed retina of the cat the great majority of the elements respond as on-off elements, i.e. to both onset and cessation of illumination. Some 20% of the elements behave as pure on-elements. Pure off-elements, merely responding to cessation of illumination, are rare in the eyes of both cats and guinea-pigs.

3. The relative preponderance of on- and off-discharges in the isolated on-off elements of the cat's eye varies a great deal with stimulus intensity.

4. Light-adaptation influences the discharges of the different elements in the following manner: (i) the threshold increases, (ii) an after-discharge, when present, shortens in duration, (iii) similarly the discharges at onset and cessation of illumination are shortened in duration, (iv) the same maximal frequencies are reached in both states of adaptation but the increased threshold in the light-adapted state compresses the range of intensities within which the frequency of the discharge can vary. Hence the frequency-intensity curves will, on an average, rise at a steeper rate in the light-adapted state.

5. In both animals spontaneous activity of the isolated element is common, and suppression of this activity is a good index of inhibitory phenomena which otherwise would escape notice.

6. *Post-excitatory inhibition* is a kind of extended suppression of all activity following *after* the activation of a single element, especially well marked if the stimulus has been strong. It is found in both eyes and in all types of elements.

7. *Pre-excitatory inhibition* has a briefer latent period than excitation and is responsible for the inhibition that in its purest form is found in the pure off-elements which are silenced by illumination and released into activity upon cessation of illumination. Off-effects are thus a sign that pre-excitatory inhibition is present in a given case. Pre-excitatory inhibition leads to suppression of the off-effect by re-illumination. In some on-off elements (cats) this suppression is complete, in most elements, however, merely a temporary block preceding re-excitation.

8. Pre-excitatory inhibition coincides with an active negative component P III of the electroretinogram.

9. The differences in the distribution of excitation and pre- and post-excitatory inhibition over the different elements in the retinae of cats and guinea-pigs are discussed in the light of an extended duplicity theory.

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