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PROPERTIES OF AN INFRA-RED RECEPTOR

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The remarkable facial pits of pit vipers (*Crotalidae*) have long excited interest. Lynn (1931) discusses seven theories which have been proposed as to their functional meaning, and concludes that they are most likely mechanoreceptors specialized for the detection of 'air vibrations'. Noble & Schmidt (1937) clearly showed by behavioural experiments that none of these theories is correct and instead that the pits '...serve to detect the body temperature of the snakes' prey...', but they further believed that the pits '...have the additional function of detecting air vibrations'. The essential demonstration was that snakes, with the other principal sense organs of the head non-functional, can still strike correctly at moving objects and can discriminate between warm and 'cold' (thermoneutral) ones so long as the pits are uncovered. They had no conception of the organ as a radiant heat detector, however, and described its sensitivity in terms of the reading of a mercury thermometer in the air at the position of the snake's head. However, it seems indicated by their conditions that radiant energy was the effective stimulus. We have undertaken an analysis of those properties of the organ which can be revealed by recording the activity of its nerves.

The thin membrane which is the innervated sensory surface (Pl. 1, fig. 1) may be regarded as a special case of a temperature detector (see Discussion for a defence of this view). Receptors for this modality are almost unknown physiologically except in man and cat and in the ampullae of Lorenzini of the ray. From this knowledge we have come to distinguish among temperature afferents, 'cold' and 'warm' fibres, i.e. those whose principal discharge is elicited by a lowering of temperature in the physiological range and those whose response is elicited by an increase of temperature in this range. In each of the two cases studied electrophysiologically (elasmobranch, Sand, 1938; Hensel, 1955: cat, see Hensel, 1952*b*; Zotterman, 1953), there is a continual ('spontaneous' or 'resting') discharge in most of this range, which passes through a maximum at a certain temperature and declines at higher and lower maintained temperatures.

We may say that a temperature receptor, in the two species previously studied and in agreement with the present findings, has either or both of two features: a high coefficient of phasic discharge to temperature change or a high coefficient of tonic discharge to maintained temperatures. The former may be positive or negative, the latter is bound to have a reversal at a temperature of maximum discharge which may be high (warm fibres) or low (cold fibres) in the physiological range. Warm and cold units are hence sharply separated by their phasic properties while their tonic discharge, when specialized at all, distinguishes them only by the position of the temperature of maximum frequency along a continuous scale.

We shall see that the nerves of the facial pit organ are composed of an essentially homogeneous population of warm fibres. This is a receptor type which in mammalian nerves is far scarcer than cold units and has been seldom recorded from; our electrophysiological knowledge of warm receptors is essentially based upon the report of Dodt & Zotterman (1952*a*). In the present case, the normal stimulus is chiefly radiant and not conducted heat and several anatomical peculiarities adapt it to a high sensitivity in terms of caloric flux. But it will be concluded, after detailed consideration of the alternatives, that this is superimposed on a basically temperature detecting receptor not necessarily different from those in mammals in the fundamental transducer mechanisms, though quite different quantitatively in several properties.

Preliminary reports have appeared (Bullock & Cowles, 1952; Bullock & Faulstick, 1953; Bullock, 1953, 1954; Bullock, Cohen & Maynard, 1954).

MATERIALS AND METHODS

Most of the experiments were done upon specimens of *Crotalus viridis*, the Pacific rattlesnake, but a number of other species were occasionally used—*C. ruber*, *C. mitchelli*, *C. cerastes*, *C. atrox*, *C. horridus*, *C. adamanteus* and a few water moccasins, *Agkistrodon piscivorus*, which also belongs to the family Crotalidae. No differences between the species were noted in the properties under study. The examples of *Agkistrodon* were notably difficult to paralyse suitably with curare, in contrast to *Crotalus*; large doses had no effect (approx. 1·4 mg/kg dimethyl-tubocurarine chloride intramuscularly) and then suddenly killed. The pit membrane of these animals was invaded here and there by black pigmented areas, making more difficult direct microscopic viewing of the sensory surface, whereas in the species of *Crotalus* so examined the membrane was usually quite free of pigment.

The animals used were chiefly 60–150 cm in snout-vent length, weighing 100–2200 g. They had usually been kept in the laboratory for some weeks and were acclimated to the temperature range, 23–27° C.

The snakes were satisfactorily paralysed with 0·4–0·6 mg/kg dimethyl-tubocurarine chloride ('Mecostrin', Squibb), injected intramuscularly in one dose. The epaxial muscles respond first and the respiratory, abdominal and tongue muscles are more resistant. Respiratory movements are so infrequent and slow that observation of the outside of the body usually fails to confirm their presence, and we routinely watched the glottis, which remains closed most of the time but opens clearly during a breath.

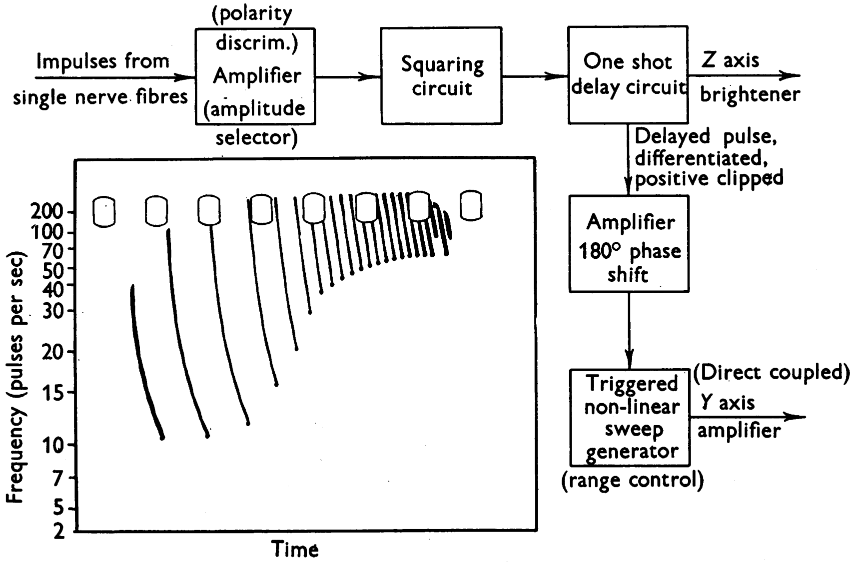
The facial pit innervation has been described by Lynn (1931). There are three branches of the trigeminal nerve, the ophthalmic from which we have never recorded, the superficial and the deep branches of the supramaxillary division, both of which we have used but chiefly the former. These cutaneous sensory nerves supply little but the pit itself. The ophthalmic is small but the other two are large nerves containing together about 6000 fibres, mainly in the range of 5–8 μ in diameter and virtually all myelinated. The anatomy will be described in a separate communication by Bullock and Fox. About 15–20 mm of the superficialis is readily exposed, tied, cut centrally and brought out by an exposure behind and below the eye. This leaves the region of the pit untouched so that circulation of the sense organ is intact.

Many experiments were done with the whole nerve since the pit innervation overwhelmingly dominates it and its spontaneous activity, entirely attributable to the pit, is so clear. Especially clear is the cessation of this activity upon termination of an adequate stimulus. But the amplitude of activity is small in the whole nerve and quantitative comparison of responses is difficult. As has been found by others, dividing the nerve does not improve the situation until a very fine bundle containing 5–10 fibres is reached when the amplitude abruptly becomes much larger and the signal-to-noise ratio favourable. Further subdivision, by splitting the bundle, was usually done at the frayed, free, central end, and was continued until a functionally single-fibre or preferably two-fibre preparation was obtained. This type of dissection was done in a chamber consisting of a clear plastic box with glass floor against which the needles could be pushed without scratching, with a paraffin-sealed hole in one corner admitting the nerve, the whole mounted close against the snake's face, under a dissecting microscope and over a good light. The dissected bundle was lifted by forceps mounted on a rack and pinion movement into an oil layer floating on the physiological salt solution, which was composed of equal parts of frog and mammalian Ringer's solutions (Prosser *et al.*, 1950, tables 9 and 15). The forceps and a wire in the bath served as leads. Fibres lasting 30–120 min were obtained in a fair percentage of animals; occasional preparations lasted 4–5 hr.

While this was the most satisfactory method of preparation, two others were used at times. The fibres in the whole nerve trunk were penetrated by slowly advancing into it a glass microelectrode of some fraction of a micron in tip diameter. Many definitely single units could be obtained in this way from each nerve but in our hands the longevity of each unit was from seconds to a few minutes. The pit membrane is only 10–15 μ thick and consequently offers little shunt, so that we found rather better amplitude of spikes by picking up with a needle in the membrane than from the whole trunk. Uninsulated steel needles of about 3–7 μ tip diameter were the most successful size. These, like larger needles, pop through the membrane at any insertion angle available without drastic surgery. Finer needles, including glass micropipettes, failed to enter the membrane, which is a tough, cuticle-covered, slack-suspended structure. The needles which penetrated often picked up nothing. When they showed activity it was always from many units, virtually as complex as whole trunk records. We conclude that the shaft of the needle picks up from nearby bundles of fibres but when not near a bundle is too large to detect activity of units.

Nerve impulses were amplified and recorded with standard apparatus. Since most of the desired information depends on comparing the frequency of impulses at different moments, graphs of frequency against time were prepared. This was often done by measuring under the dissecting binocular the intervals between every spike and the next on the original film. In many cases this was done by a commercial data reduction firm using analog computing equipment. Log reciprocal interval was plotted to give a proportionate frequency ordinate. In some cases frequency fluctuations were smoothed by averaging every two intervals or counting the number of spikes in each 0·1, 0·2, or 1·0 sec. For many experiments the integration was done by a simple RC circuit and photographed during the experiment. This was most satisfactory when the amplified impulses were used to trigger a single-shot pulse generator giving uniform, controllable pulses without noise or base-line sway. By amplitude and frequency discrimination this triggering could selectively ignore electrocardiographic and other forms of noise.

To circumvent the memory effect of integration and to record automatically the instantaneous frequency as a function of time, a simple pulse-interval plotter (P.I.P.) was devised on principles similar to some cardiotachometers (Tiitso, 1937; Whitehorn, Kaufman & Thomas, 1935; Djourno, 1938; Johnsen, 1945). The nerve impulses appear as bright spots on the oscilloscope; the *Y* axis is swept at a selected speed between impulses, downwards from a base-line near the top of the screen. Each impulse brightens the manually darkened beam and then trips a flyback to restart the vertical sweep for the next interval. Thus each spot appears at a vertical position determined by the interval since the last impulse. The *X* axis is used as a time-base, provided by a slow sweep or by the film movement, as the P.I.P. plots continuously. The functional diagram of the circuit, for whose construction we are indebted to Mr Aaron Klain of this department, is given in Text-fig. 1. Various forms of radiant and conducted heat stimulators have been used and will be described in the appropriate section of the 'Results'.



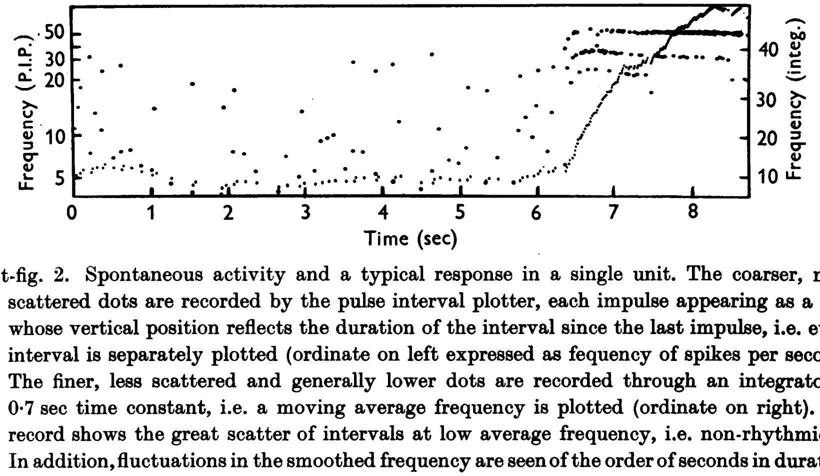
Text-fig. 1. Functional diagram of pulse-interval plotter (P.I.P.). The spikes are selected from the noise level by the discriminator and then trip a monostable multivibrator (one-shot delay circuit). This produces a pulse fixed at 0·2 msec duration which brightens the beam for that period. The end of that pulse serves to trip the vertical sweep generator, returning the beam, now extinguished, to its vertical base-line and the start of a new downward sweep which continues until the next nerve impulse intervenes. By crowding the ends of the ordinate scale, a ratio of maximum interval/minimum interval of 100, with useful resolution in the middle is provided. This range can be set by the sweep speed, e.g. at 1–100, expressed as frequency of impulses per second, or 3–300. The inset shows the vertical sweep with the beam not extinguished between impulses.

Syndrome of oxygen lack. Occasionally the airway became plugged with mucus or the dose of curare was too great and ventilation ceased for some time. In other cases we have deliberately isolated the head or clamped the carotids to observe the effect of anoxia. In all these instances a characteristic pattern of activity appears after approximately 30–60 min. First the response to mild stimuli, which normally adapts in a few seconds, maintains itself and outlasts the stimulus far beyond a normal after-discharge. Later this becomes aggravated and the response actually builds up during some seconds under stimulation or even after its cessation. Thus loss of the postexcitatory depression is a conspicuous feature. Gradually the hyperactivity becomes more pronounced until even in the absence of stimulation, periods of intense discharge develop rather suddenly, last many seconds or a few minutes and slowly pass off. Although response is abnormally great, sensitivity falls drastically. The intervals between discharges become more silent and longer and finally neither spontaneous nor evoked activity occurs. This sequence takes 20–40 min or longer. Apart from this clear and easily recognized condition, we have observed no signs of abnormality, and the behaviour of the sense organ is the same under curare as in a spinal preparation without anaesthetic.

RESULTS

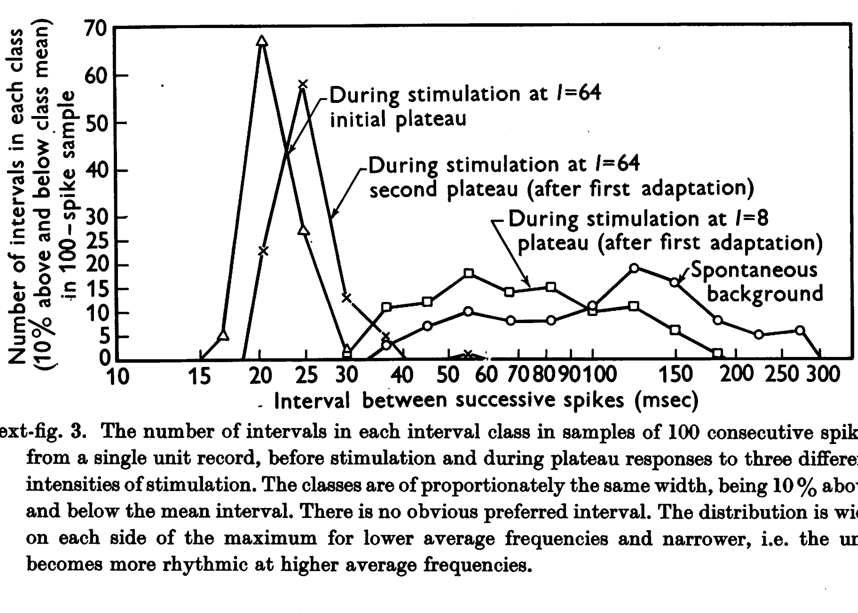
The phenomenon of spontaneity and its nonrhythmicity

During leading off from a whole nerve or a small bundle or the membrane itself, continual discharge in the absence of any intentional stimulation is the first prominent feature. However, not all fibres are continually active; it is not uncommon for a functional single unit preparation after some minutes suddenly to reveal a second spontaneous unit. In small bundles where only one or two fibres are discharging spontaneously, we have seen several times a new non-spontaneous unit enter with stimulation. There are, then, at least at any given moment, some units not firing spontaneously but, from the scarcity of these two observations, they must be a minority. The spontaneous or room-temperature resting discharge is in most cases quite aperiodic (Text-fig. 2). The intervals between successive spikes in a single unit record vary between wide limits, e.g. 40 and 250 msec (Text-fig. 3), and no fundamental interval has been detected of which the rest could be simple multiples. Occasional units are more nearly rhythmic and this is always true when the average frequency rises, as under stimulation (Text-fig. 3, cf. Buller, Nicholls & Ström, 1953; Hagiwara, 1954; Tokizane & Eldred, 1956).



Text-fig. 2. Spontaneous activity and a typical response in a single unit. The coarser, more scattered dots are recorded by the pulse interval plotter, each impulse appearing as a spot whose vertical position reflects the duration of the interval since the last impulse, i.e. every interval is separately plotted (ordinate on left expressed as fequency of spikes per second). The finer, less scattered and generally lower dots are recorded through an integrator of 0·7 sec time constant, i.e. a moving average frequency is plotted (ordinate on right). The record shows the great scatter of intervals at low average frequency, i.e. non-rhythmicity. In addition, fluctuations in the smoothed frequency are seen of the order of seconds in duration Upon stimulation the prompt response is shown by the P.I.P. record, the integrator following with a lag. The rhythmicity becomes evident and the phenomenon of preferred intervals—three horizontal lines of dots.

Many times we have seen a curious feature during high frequency, rhythmic response under stimulation. This may be called the phenomenon of preferred frequencies. The scatter of intervals is not random but certain intervals besides the most frequent one tend to recur (Text-fig. 2). At first we thought these must be multiples of the shortest interval, i.e. skipped impulses. But closer examination shows that the preferred values may not bear a simple relation to the principal, which is always the shortest interval, the maximum frequency. For example in Text-fig. 2 the frequencies at the time marked 7 sec on the abscissa are about 48 for the dominant and 33 for the second most common with a few spikes at intervals corresponding to a frequency of 24/sec. This phenomenon has also been seen by C. von Euler & U. Soderberg (personal communication, 1956) in stretch receptors.



Text-fig. 3. The number of intervals in each interval class in samples of 100 consecutive spikes from a single unit record, before stimulation and during plateau responses to three different intensities of stimulation. The classes are of proportionately the same width, being 10 % above and below the mean interval. There is no obvious preferred interval. The distribution is wide on each side of the maximum for lower average frequencies and narrower, i.e. the unit becomes more rhythmic at higher average frequencies.

What is the normal stimulus?

Tests with different forms of stimulation. Ineffective forms of environmental change include sound, vibration of the substratum, a series of common odours, touching the head and face up to the margins of the pit (sometimes the upper lip immediately below the pit was sensitive to touch), and well heat-filtered light. Thermoneutral water in the pit, with or without salts or acid (5 % acetic), is ineffective in exciting or depressing activity. This can be taken to mean that the cuticle is impermeable.

Two general forms of stimuli are effective. The first is change in heat flux, whether the steady state of flux is in or out, and whether the change is an increase or a decrease. The second is mechanical deformation of the pit membrane. The latter may be produced by contact, as with a wisp of cotton, or by air movement. Distinct puffs of air close to the face and from certain directions are necessary to elicit change in the spontaneous discharge; gentle waving of a thermoneutral object near the head is ineffective. A fine jet of air from a glass tube is effective in some positions and ineffective in others adjacent, in a complex pattern. Some single units have been unaffected by camel-hair brush probing. Sometimes, when recording from a 3μ steel needle penetrating the sensory membrane, we have been able to distort the membrane visibly by movements of the micromanipulator without any change in the level of spontaneous discharge. It seems doubtful whether detection of air movement or touch can be an important function of the organ.

Adequate change in heat flux to increase or decrease the level of discharge noticeably is produced by warm or cold air currents very gently wafted toward the head, or by warm or cold radiation from objects, e.g. glasses of water, differing in their temperature as little as 1° C, if quickly substituted and held close to the pit, or by objects a few degrees warmer or cooler than the background suddenly introduced at greater distances, e.g. a hand at 20–50 cm.

That the latter stimuli are really radiant and not conducted via air temperature is shown by simple tests. An emitter such as a hand or a lamp is ineffective in certain positions outside the cone of reception, even though close to the head and warming the air; a first surface mirror placed so as to reflect into the pit immediately makes the emitter effective.

The intervening air temperature may be low or high or even changing, e.g. downward, without influencing the response to a warm or cold object; but without changing the air temperature we can abolish the stimulation simply by placing a glass plate in front of the object. The stimulating object does not have to be warm or cold relative to the snake's body temperature but only relative to the surface temperature of the other objects in the background.

Changing the body temperature without altering the field of view of the pit, for example, by immersing the body up to the neck in warm or cool water changes the level of maintained discharge in the same direction but with a low sensitivity. The latter is doubtless due to the relative slowness of the change (see below). A change of about 1° C in the temperature of tissue adjacent to the pit elicits a minimal detectable response in either whole nerve or single unit activity, when achieved by sudden immersion of the body. Presumably the sensory membrane changes temperature less than other tissues but its mass is too small to permit direct measurement.

The directionality of the reception is marked. Moving a stimulating object within the receptive field causes clear alteration in the intensity of the response. If the object is small, e.g. a Nernst glower (an incandescent ribbon without glass envelope) the importance, in limiting the angle of reception, of the shadows thrown by the margins of the pit upon the deeply situated membrane can easily be demonstrated.

We had hoped to record from single fibres and at the same time determine the exact location and area of the receptive field in the sense organ using fine spots of light. In this we have been disappointed. Such focused spots are as stimulators quite ineffective owing to the severe filtering of long infrared rays by the glass of the lens system.

The cone of reception for a given unit or a whole nerve is easily determined. The former is much smaller than the latter, and the latter is smaller than the sum of the cones of the two large nerves supplying the organ. The cone for the whole organ appears to coincide with that obtained by sighting with one eye into the pit and looking for the limiting angle where the pit margins permit an edge of the membrane to be seen. It has an irregular shape (Pl. 1, fig. 2) extending in the frontal plane about 10° across the middle in front and almost at right angles to the body laterally from the pit. In a vertical plane lying obliquely between transverse and long axes and passing through the pit, it extends forward only and from about 35° below to about 45° above the frontal plane, varying somewhat among individuals.

It has been suggested (Block, 1950) that the adequate stimulus is deformation of the membrane by expansion of gas in thei nner chamber. This suggestion was based on the remarkable similarity of the anatomy of the pit organ to a Golay radiometer, which absorbs radiant energy inside a chamber with a transparent window and measures the increased pressure due to warming of the gas. We have tested this hypothesis and believe it can be excluded. First, it is contrary to the Golay cell mechanism that individual unit receptors have quite different and sharply defined cones of reception. Secondly, the membrane is not extremely sensitive to pressure; sudden changes in barometric pressure in the room, as by opening the door, are quite ineffective, and even gentle air puffs are often ineffective in eliciting response. These events produce pressure changes of 1 part in a few hundred, or several mm of mercury (measured with a Statham gauge, P. 97). But a supraliminal, radiant stimulus which warmed the membrane 0·014° C (see below) could increase the product, pressure × volume, by a factor of only about 5×10^{-5} if air in the inner chamber were all heated to this degree. Finally the sensory membrane can be cut so as to open widely the inner chamber, yet responsiveness is still good. These considerations do not exclude the possibility that some Golay detector effect may operate at very high intensities; but from our experiments with flowing water, it may be said that temperature change alone, with mechanical movement greatly damped, appears adequate to account for the response.

The purity of modality. The pit organ appears to be virtually pure in being composed of warm fibres only. We have seen no cold fibres in a rather large number of preparations. Touch reception has many times been shown to occur in the same unit as warm reception and has never been seen by itself. Since the warm reception is the more specialized and sensitive, we may regard the touch stimulus as 'inadequate', i.e. incidental and not the normal mode of activation. This purity, in contrast to most of the organs of special sense, means the absence, apparently, of units with markedly different action spectra or with only on or off response or other essential subdivisions of the modality. Our information cannot yet exclude the possibility of significant differences in the temperature range or in the sensitivity of different units. In a number of cases we have seen smaller spikes, in a few-unit bundle, recover earlier, exhibit a shorter latency or lower threshold than large spikes. This recalls the kind of difference Katsuki, Yoshino & Chen (1950*a*, *b*) described in the lateral line and in other cases where thick fibres serve receptors of higher threshold, adaptation rate and maximum frequency, thinner fibres serving receptors of lower threshold, slower adaptation and low maximum frequency (see also Bullock, 1953).

The range of the action spectrum. It has been possible to obtain some information on the effective wave-lengths though not to plot quantitatively the response to different wave-lengths with equal energy doses or the doses required for equal response. The reasons for the difficulty of such quantitative determination will be clear in the sections below on fluctuation of background frequency and of response frequency under given conditions. With a rock salt infra-red monochromator and Nernst glower as source, strong response was obtained in the range 1·5–4·0 μ peak wave-length, while no response occurred at 1·0, doubtful responses at 5–7, and none at 10·0 μ. The source emits strongly at 2·0 μ and falls off steeply on either side so that the stimulus available at 10 μ was weak, but the absence of response at 1·0 μ is probably significant as the lower limit.

By the use of heat filters which pass almost all the visible light (slightly greenish to the eye) and cut off more efficiently above 1·5 μ, especially the Schott-Jena BG 21, quite strong beams of light are rendered completely ineffective, for example, a direct, focused beam from a B and L spherical microscope lamp at full iris with a 100 W bulb. A zirconium arc of 100 W with a glass condensing lens or stronger incandescent sources will still deliver some stimulus through such filters, indicating that although visible wave-lengths are probably quite ineffective the near infrared (0·7–1·0 μ) is weakly effective. Inserting the Schott-Jena RG 7 (opaque to visible rays, but passing nearly all infrared) does not reduce the effectiveness of such beams noticeably, but a slight response when the filter is removed indicates that some visible or near infra-red is stimulating.

Naked sources such as the Nernst glower or a match (with peaks at about 2–2·3 μ) are rendered completely ineffective by a filter of a few mm of glass, or of water in glass, which cut off energy longer than 1·5–2·6 μ so that these longer wave-lengths must be part of the action spectrum. Glass-enclosed sources such as incandescent lamps fitted with condensing lenses have already suffered virtually complete removal of energy longer than 2·6 μ, but are still useful stimulators when sufficiently intense owing to radiation from the glass.

By the use of filters, wave-lengths longer than 3 or 4 μ are almost impossible to deliver without contamination of energy at 2 to 3 μ. Our monochromator has too little energy in the long infra-red region for us to expect stimulation. But the efficacy of such sources as the hand, small mammals and black bodies at 1° C above a neutral temperature is good evidence that wave-lengths at least as long as 15 μ must be effective, for these low temperature emitters have their peak in this region. It will be shown below that the calculated threshold flux from a rat is the same as or lower than that from a Nernst glower, whose peak of emission is at 2 μ.

It is reasonable to conclude that the action spectrum does not extend below 1·5 μ, at least not with a sensitivity above a small fraction of that at 2 μ, and that it extends at least out to 15 μ where sensitivity is as great as at 2.

What is the character of the response to step functions?

From the information given in a later section, we can treat as step functions, i.e. stimuli effectively square in rate of application, any changes in heat flux which reach their new equilibrium in a few tenths of a second. This principally admits the use of common shutters and radiant sources, but certain forms of application of warm or cool fronts of flowing water probably satisfy this requirement. These latter will be cited here for two purposes: (1) to try to establish the actual temperature of the sensory membrane corresponding to a certain radiant stimulus; and (2) to extend to higher intensities the range of stimulus strengths readily applied. It is difficult to apply radiation sufficient to warm the membrane 5° C above room temperature: high Watt sources are necessary which are hard on diaphragms, shutters and accessories.

The character of the response to step functions of short duration is shown in Text-figs. 2 and 6 for various intensities. We will consider briefly the principal or typical findings for nine aspects of this response.

(1) *The sensitivity in degrees and in calories.* The threshold dose of radiant heat varies for different unit preparations and even for whole nerves by a factor of about ten. Among the more sensitive preparations the following measurements have been made.

In records from a whole nerve, a Nernst glower elicited a response distinctly visible on the oscilloscope with a 0·1 sec exposure at 54 cm (flux $= 3{\cdot}15 \times 10^{-4}$ cal/cm²/sec) which means that approximately 10^{-6} cal of energy of all wave-lengths emitted, including the visible, fell on the pit membrane (2 mm in diameter) or about 5×10^{-10} cal on each 1600 μ^2, the approximate area within which the average fibre distributes its branches, including areas of overlap with other endings, according to silver-stained whole mounts (Bullock & Fox, unpubl.). If all this energy were absorbed and none reradiated, and if the membrane has the heat capcity of water, this quantity would raise the temperature of a membrane 15 μ thick by 0·02° C. in 0·1 sec. (We are indebted to Dr K. Buettner for the formula applicable to a thin membrane, assuming no loss to blood or to air:

$$\Delta T = \text{flux in cal/cm}^2\text{/sec} \times \frac{1}{\text{thickness of membrane in cm}} \times t \text{ in sec.)}$$

But this figure must be (1) reduced because not all the energy is absorbed—the visible part is largely transmitted through the translucent membrane and even the long infrared is nearly half transmitted (Bullock & Fox, unpubl.); some is reflected. The value must (2) be further reduced because 0·1 sec is probably an unnecessarily long exposure; this correction may be only a factor of 2 or 3. And (3) the end-point of a clear increase in activity on the oscilloscope is not a sensitive one. While these three factors are difficult to estimate, we doubt whether they would decrease the figure by more than a factor of five to ten. On the other hand, the value may require correction upward owing (1) to the membrane having a lesser heat capacity than water (leather and cellulose have specific heats of 0·3–0·4), and (2) to the heat flow through the membrane being slow enough for the first few μ to be warmed to a higher temperature before conduction distributes the heat. This can be evaluated quantitatively by considering the transmission of effective wave-lengths, the time and thickness available. Calculations by Dr K. Buettner indicate that the correction is likely to be small.

Single units have commonly given weak responses, evidently not far above threshold, to a microscope lamp, whose focused beam has been calibrated in total energy flux, reduced by diaphragm to deliver 10^{-6} cal/mm^2/0·1 sec, or about one-third the intensity used with the whole nerve just mentioned. This represents good agreement at the level of reproductibility of these preparations. The actual effective dose may be considerably less than that calibrated by total energy radiometry, since energy below 1·5 μ is so ineffective.

For comparison we may calculate the flux from a physiological stimulus such as those Noble & Schmidt (1937) found pit vipers would strike at, under conditions presumably assuring that only the pits were responsible. A rat (or a human fist) of 5 cm radius and 50 cm from the pit, with a surface temperature 10° C above that of the snake will emit

$$1{\cdot}3\times10^{-4}\times(T_{\text{rat}}-T_{\text{snake}})\times\left(\frac{\text{radius}}{\text{distance}}\right)^2 \quad \text{or} \quad 1{\cdot}3\times10^{-5}\ \text{cal/cm}^2\text{/sec.}$$

If 0·1 sec is enough to permit this detection and the area of the sensory membrane is 3 mm^2, the stimulating dose is 4×10^{-8} cal for the whole membrane or about 2×10^{-11} cal for the area of branching of a single sensory fibre. This corresponds, on the previous assumptions, to warming the membrane by 0·001° C. This figure is more reliable than the preceding ones because it is subject to fewer corrections (essentially, only the duration of the exposure). The difference may be chiefly in the greater sensitivity of the snake's brain in detecting a small increased discharge in each of many fibres. While we have not tried to check Noble & Schmidt's results, it has been our routine to use the hand as a test stimulus and in the best cases we have been able to get back 40 cm from the organ. The minimum exposure has not been measured but is probably several tenths of a second so that a value not more than ten times the above can be considered as confirmed by our end-point, i.e. change in nerve discharge noticeable in loudspeaker or oscilloscope.

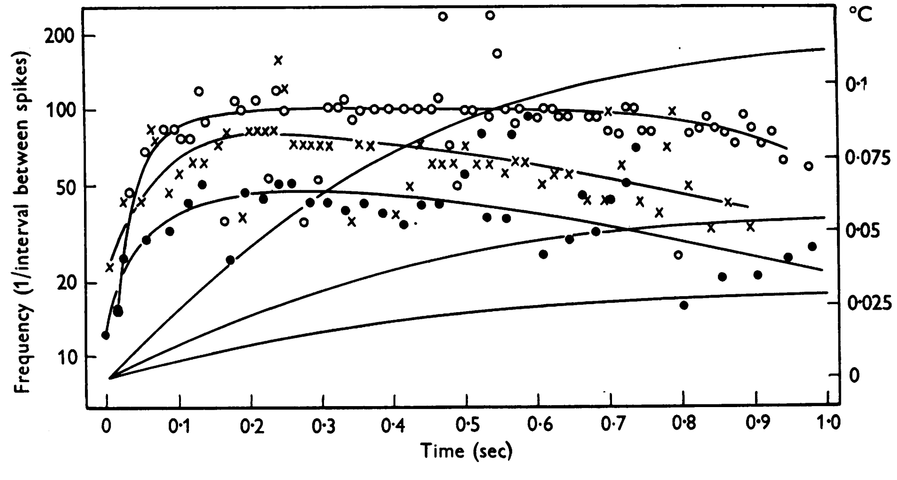
Anticipating the discussion, it may be pointed out that as we approach the threshold, the end-point becomes increasingly unreliable, whether determined by eye on the oscilloscope or by ear using a monitoring loud-speaker (this is more sensitive) or by plotting every spike interval (least sensitive, Text-fig. 4) or integrating over some time. This is owing to the non-rhythmic spontaneous background. The criteria used—by us or by the snake—must be a compromise between reliability, sensitivity and latency or temporal resolution. Hence the figures above and those in the next section, based on minimum responses, are based on 'conservative' criteria, sacrificing the time and sensitivity factors for reliability.

Another experiment was designed to estimate sensitivity in terms of temperature of the sensory membrane. This structure is too small, being 15 μ or less in thickness, to permit direct measurement of its temperature in air without serious heat flow from it into the sensing element. Radiometer measurement of its surface temperature is considered impracticable owing to the small differences expected between its temperature before and during weak stimulation and the small area and recessed location of the surface. The method used was to direct a gentle flow of water into the pit against the membrane and to warm or cool this water. If care is taken to have a moderate and uniform flow no stimulation persists from the mechanical stress. Without altering the flow the water could be heated by a coil, carrying electric current, placed in the stream close to the pit. For the present experiment, estimating threshold, the design was to provide as sharp a front of warm water as possible, with a minimum of mixing in the tube or in the pit. A thermocouple junction was placed in the tube a few millimetres from its end and d.c. amplification used sufficient to display 0·1° C as a 4 cm deflexion on the cathode-ray tube. The time-constant of the thermocouple in water was less than 20 msec, permitting us to follow the temperature, as was required, within the latent period of 0·05–0·2 sec.

The results, illustrated by the experiment of Text-fig. 4, indicate a threshold change in water temperature to be of the order of 0·003° C, measured after the discharge of the single fibre has increased more than 50% above the spontaneous level, which occurred in about 60 msec. These figures cannot be given great reliability because this sensitivity pushes to the limit the usefulness of the available temperature recording system and we are not sure of the form of the initial change in temperature. Because of the short time relative to the flow-rate and the volume of water in the pit, it may well be that the effective stimulus accounting for the observed response is much smaller than 0·003° C. We assume that the temperature of the sensory membrane follows that of the water without appreciable lag, but if this is incorrect the threshold ΔT is smaller still. From the results reported below, it is probable that the rate of change, 0·003° C/0·060 sec, is physiologically a step function, that is, the response occurring in less than several tenths of a second is not slope-determined but determined by the absolute amount of change which has taken place up to that moment minus the latent period.

Another independent method confirms the results just given. It is shown below that at about 100–200 times threshold some characteristic new features of response begin, for example high intensity block. These same features are seen with sharp warm-water fronts of about 0·5° C. Applying the above factor, we should expect threshold to be 0·003–0·005° C. The two figures involved in this method of estimation are not subject to large errors.

The warm-water front experiments therefore agree fairly closely with the calculated sensitivity to the radiation from a rat, by behavioural end-point, when the stimulus in each case is expressed as change in temperature of the membrane. The water estimate (0·003° C) falls in between the behavioural



Text-fig. 4. Sensitivity measured by change in temperature. Water flowing at constant rate over the pit membrane is electrically heated from a certain moment. Three different rates of temperature rise, estimated by reading thermocouple records at 0·3, 1·0 and 2·0 sec. Response measured as interval between successive spikes except at high frequency, when the average interval for two or three successive spikes is plotted. The upper, middle and lower hand drawn curves (circles, crosses and dots, respectively) correspond to the stimulus curves in the same relative positions. There is uncertainty in the position of zero time on the record, owing to the small thermocouple deflexion, of about 0·1 sec. Nevertheless, the response is very abrupt and permits estimation of the ΔT approaching threshold. Ordinate at right in ° C.

(0·001° C) and the figure calculated from the total radiant energy absorption with an incandescent stimulator, by oscilloscopic end-point (something less than 0·02° C).

(2) *The latency.* Since the successive intervals between spontaneous impulses are widely fluctuating, within limits, it is rarely possible to interpret the first interval after application of a stimulus as indicating response, unless it is considerably shorter than the lower of those limits. But response builds up as a progressive shortening of interval over several hundredths or tenths of a second, so that the first interval is rarely very short. Moderately strong stimuli, however, commonly result in a significant departure from spontaneous fluctuation in the second or third interval. This means that latency is commonly as short as 50 msec (sum of first two intervals) and may be as short as 10 msec. It is seldom longer than 150 msec except during experimentally produced depressed states (see below) when values up to 1·0 sec are obtained. Latencies of the cold depression produced by the mild stimulus of cold radiation can ordinarily not be measured because silence supervenes immediately, but this means we can express the latency as less than the average interval in the preceding activity, which may be 20 msec or less.

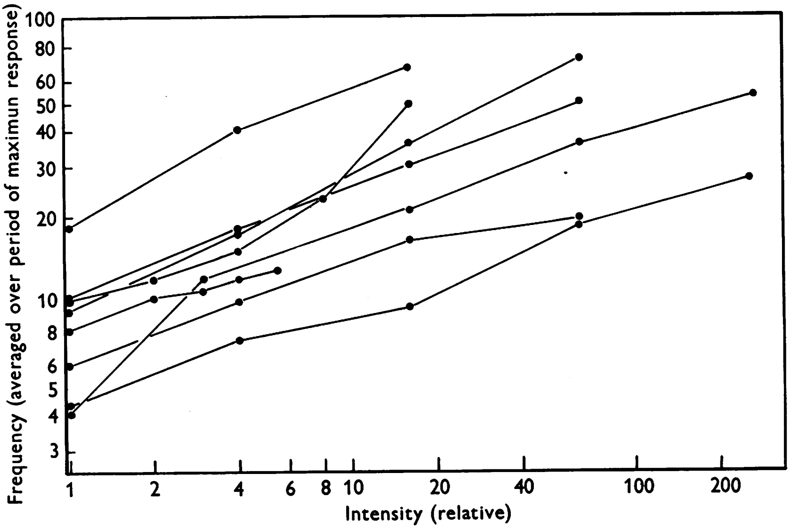
(3) *The first phase of the warm burst and its frequency as a function of intensity.* The initial increase in frequency of impulses rises to a rounded maximum in from 0·2 to 0·5 sec. With the rise in frequency the rhythmicity notably increases (Text-fig. 3). The maximum frequency attained is an almost straight-line function of the intensity of the stimulus, when plotted log-log (Text-fig. 5), but in ten preparations in different animals the slopes have varied from a 2·2 to a 4·5 times increase in frequency for a tenfold increase in intensity.

An important property determined by this slope is the useful range of intensities which the receptor can discriminate. In some units prepared this range was as small as 1:50, while in others no plateau at the high frequency end had become manifest at an intensity 256 times the minimum stimulus used, which was near threshold. The range is limited by the maximum frequency at which the unit will fire and this rarely exceeds 180 impulses/sec.

(4) *Cold inhibition and the importance of contrast.* Objects cooler than some thermoneutral object produce transient inhibition of discharge, either a slight decline in average frequency or complete silence for some seconds, depending on the difference in temperature. The threshold is something less than a 1° C difference for objects which nearly fill the field of view of the pit and appears to be about the same for warm objects. Thin-walled glass vessels filled with water at various temperatures and brought in front of the pit give this result and permit the calculation, on the same formula as that given above, that $1{\cdot}3 \times 10^{-4}$ cal/cm^2/sec is the stimulating flux, or about ten times that from a rat at half a metre. These values should be the same and our data do not exclude the possibility that objects 0·1° C different in temperature can be

detected by their radiation, but the difficulties of maintaining and reproducing surface temperatures at this level have not been overcome.

These tests as well as others demonstrate another fundamental feature of such an organ. The thermoneutral object which causes no response is one whose surface temperature is the same as the average of the other objects in the field of view. In the laboratory, a piece of cardboard, wood or metal which is in equilibrium with the room temperature serves if the latter has not changed appreciably over some time. The thermoneutral object may be warmer or cooler than the animal and its sensory membrane. If the snake is in a cool water-bath but the dry pit is facing the room, an object warmer than the animal's tissues but cooler than the room inhibits nerve activity. There may be some question of the actual temperature of the membrane even though it is well vascularized, so the experiment can be done in the following way. An animal in equilibrium with room temperature faces a large warm plate and after some time a slightly less warm object is brought into the cone of reception. Inhibition results. It does not matter whether this is done promptly or a long time after the warm plate is introduced, except for the magnitude of the effect. The reciprocal is also true—facing a cool background, regardless of air temperature, an object less cool but cooler than the animal will stimulate increased discharge, i.e. a 'warm' response. These relations are of course precisely what is expected of a radiant flux change detector.



Text-fig. 5. The change in frequency with intensity. Each curve is from a different preparation. The frequency is the maximum during the initial burst, averaged over several impulses or 100 msec. The stimulus is an abruptly applied radiant one. The range of intensities over which response is measurable is usually less than 500:1.

These facts emphasize the importance of contrast. The convenient standard test object, the hand, is a very ineffective stimulus on warm days when the laboratory furniture is warm—even if the animal is cooled or for some time after the air is cooled by rapid air conditioning. It is a much more effective stimulus in the cold room, in spite of the somewhat lower skin temperature. Experimentally, in a certain whole nerve preparation the response to a hand at 20 cm in a room equilibrated to 21° C was about threshold. Wheeling the preparation and equipment into a cold room at 15° C nearly doubled this distance, to 37 cm. There was no noticeable difference in threshold between the first moments when the snake's body temperature was still warm and spontaneous activity still high (following adaptation from the initial cold background inhibition) and later when lowered body temperature and lowered spontaneous activity came about.

The response to these tests requires us to modify the formula given in (1), above, to substitute for T_{snake}, $T_{\text{background}}$, meaning the average black body surface temperature of objects or radiant sources (e.g. blue sky) to which the receptors have been exposed even for a few seconds. Thus

$$\text{Cold stimulus intensity} = 1{\cdot}3 \times 10^{-4} \times (T_{\text{background}} - T_{\text{cooler object}}) \times \left(\frac{\text{radius of object}}{\text{distance}}\right)^2$$

and

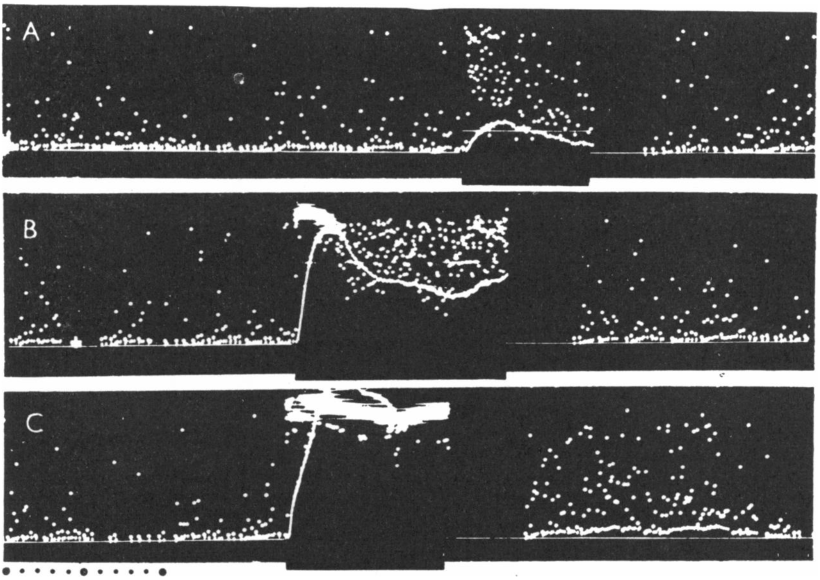
$$\text{Warm stimulus intensity} = 1{\cdot}3 \times 10^{-4} \times (T_{\text{warm object}} - T_{\text{background}}) \times \left(\frac{\text{radius of object}}{\text{distance}}\right)^2.$$

This gives the intensity in cal/cm²/sec if radius and distance are in cm, temperature in ° C. It applies only under given conditions, for example, abrupt introduction of the new stimulating source and 0·5 sec exposure.

(5) *The phases of adaptation, fast and slow.* Weak stimuli result in apparently complete adaptation in a few seconds (Text-fig. 6). It is quite possible that most normal stimuli in the life of the animal are in this category. If so, the range of intensities between threshold and the next category of response-type is hardly more than 1:10.

Stimuli of about 10 to 30 times threshold or higher elicit longer lasting discharge. Here we enter a range of great variation, between preparations and even within a given unit. Typically there are two phases of adaptation (Text-fig. 7). An early one, which involves a fall in frequency of about 20–40%, occurs in a few seconds. But a rhythmic discharge at a high frequency (60–100/sec), relative to the maximum the receptor is capable of initiating, is maintained for many seconds, up to several minutes. Then a second adaptation supervenes, sometimes starting rather abruptly but proceeding much more gradually than the early phase, and requiring 15–30 sec or more.

Whether this adaptation is complete or not is often impossible to say for the frequency falls and the rhythmicity falls, making it difficult to validate differences in average frequency. As will be described more fully below, there are normally slow fluctuations in average frequency with periods of many seconds. In order to compare the adapted level not only with the original spontaneous level of some minutes past but with that following the end of the long maintained stimulus, a further period of minutes must be recorded and all this is a race against death of the unit preparation. While in many cases studied it cannot be decided whether the slow adaptation to strong stimuli was complete, in some it appears virtually so, in others not quite. The significant fact is then clear, that even to strong stimuli adaptation, though delayed and then slow, is almost or quite complete.

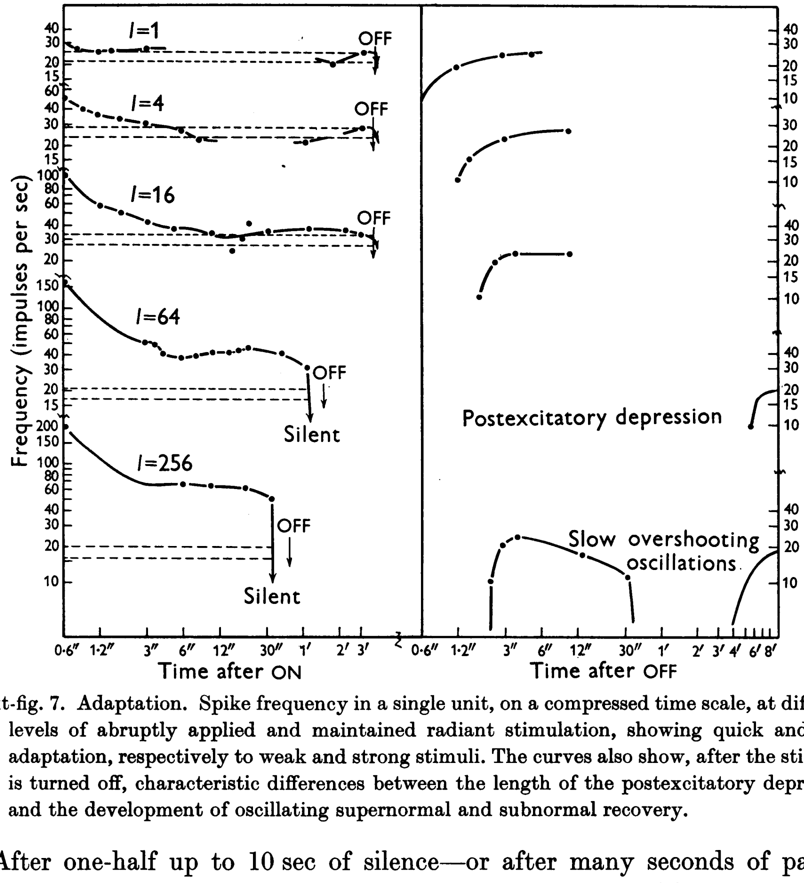


Text-fig. 6. Adaptation. Spike frequency in a single unit, as function of time, at different intensities of radiant stimulation. See Text-fig. 2 for explanation of the record. Stimulation is shown by solid black line below. Integrator time constant, 2·5 sec. Note the early adaptation to a weak stimulus (top), the early partial adaptation and later plateau to stronger stimuli. Note the silent period after OFF and following this for the strongest stimulus, a supernormal activity. For longer maintained stimuli, see Text-fig. 7. Time in seconds.

It is shown by other experiments, e.g. in the cold room and with running water flushing the pit (Text-fig. 8 below) that stimuli strong enough to change the temperature of the membrane several degrees (2–5° C) will usually be associated with an altered level of activity having a positive but low temperature coefficient.

(6) *Special forms of response to high intensity.* Square-fronted radiant stimuli of about 100 to 200 times threshold or strong or sudden increases of about 0·5° C or more in the temperature of water running through the pit elicit a complex pattern of response. There is first a high-frequency burst rising

to nearly 200/sec. This burst is cut short abruptly by a phase of depression which may be partial or complete. The stronger the stimulus the earlier, the deeper and the shorter is this depression (Text-figs. 8, 9). We have seen complete silencing begin as late as 50 sec in some cases and in others so early that no initial burst but an initial silence inaugurates the response. It is in either case extremely abrupt in onset. The partial depressions of less extreme stimuli are gradual. During the silent periods test stimuli superimposed elicit no response (Text-fig. 10).

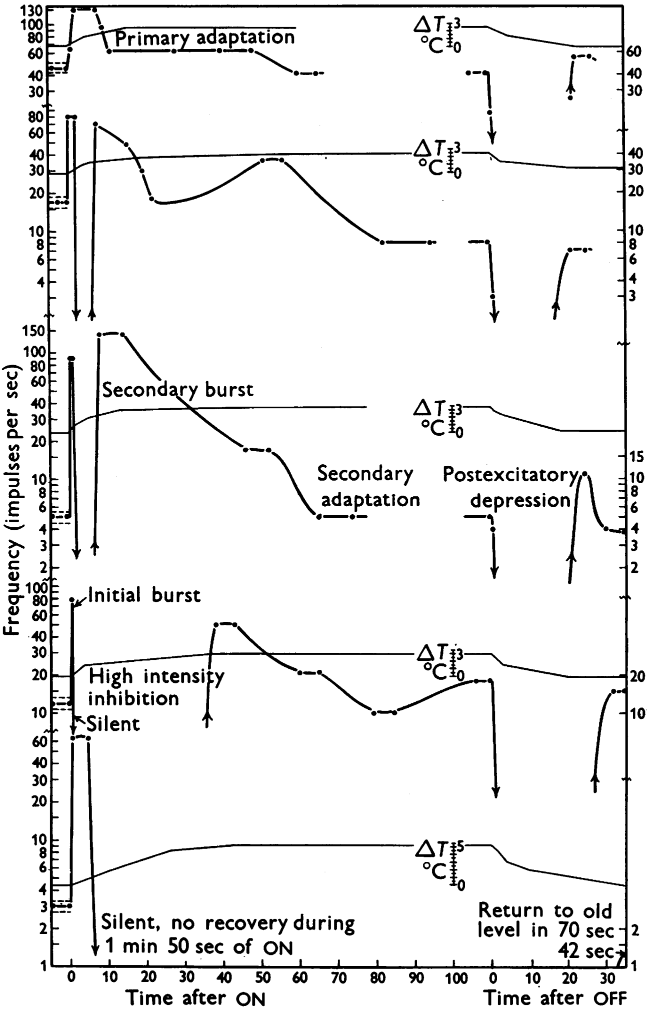


Text-fig. 7. Adaptation. Spike frequency in a single unit, on a compressed time scale, at different levels of abruptly applied and maintained radiant stimulation, showing quick and slow adaptation, respectively to weak and strong stimuli. The curves also show, after the stimulus is turned off, characteristic differences between the length of the postexcitatory depression and the development of oscillating supernormal and subnormal recovery.

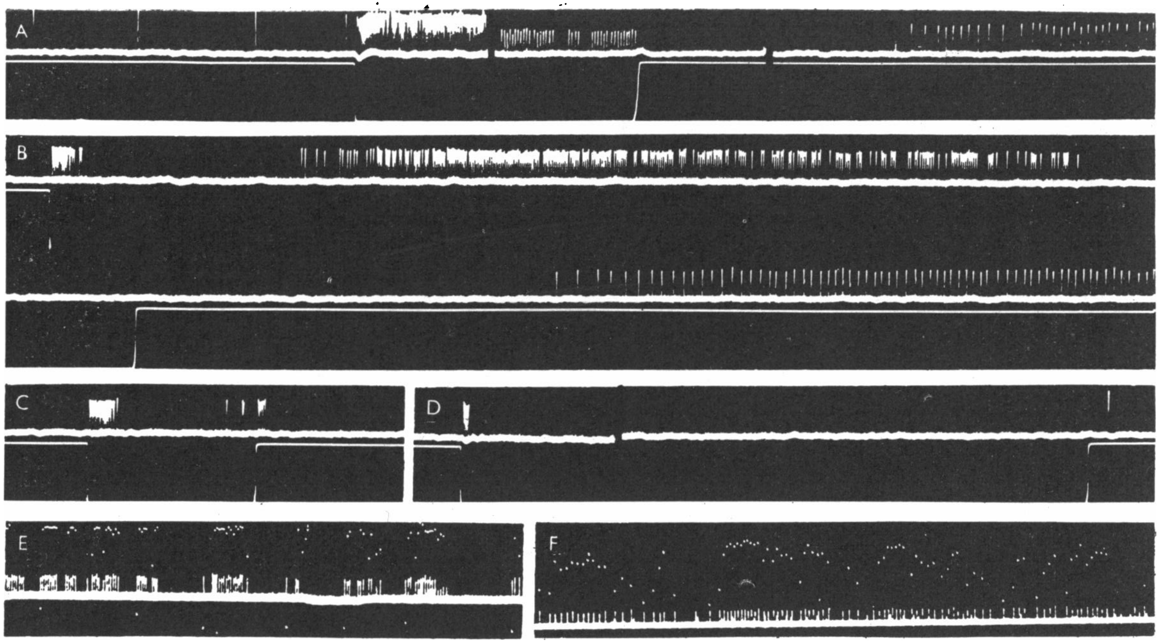
After one-half up to 10 sec of silence—or after many seconds of partial depression—there typically follows a second more prolonged burst. This may come on gradually over a few seconds, rise to an even higher frequency than before and be maintained for many seconds. The stronger stimuli, however, are likely to produce a second silent period lasting this time for several to many minutes. This second heat depression also differs in another way from the first: if the stimulus is terminated during the second silence the latter continues for some minutes without response to the 'off', and activity returns very gradually.

If the end of the stimulus occurs during the first silent period there is a brief, high-frequency 'off' burst, providing it is a silent period which came soon after the 'on' and was not allowed to last more than a second or so before the 'off' took place.

'Off' bursts occur not only when the stimulus ends early in the first silent period but even when it ends during the initial burst (Text-fig. 9). Evidently



Text-fig. 8. The development of non-linear phases of response at increasing intensities of stimulation. Impulse frequency in a single unit, as function of time, at different levels of slowly applied and maintained temperature increase, showing initial, secondary and tertiary high intensity bursts and initial and secondary high intensity depressions and slow adaptation. Flowing water method of stimulation. These phases occur at lower absolute ΔT's when the change is more abrupt (see Text-fig. 10).



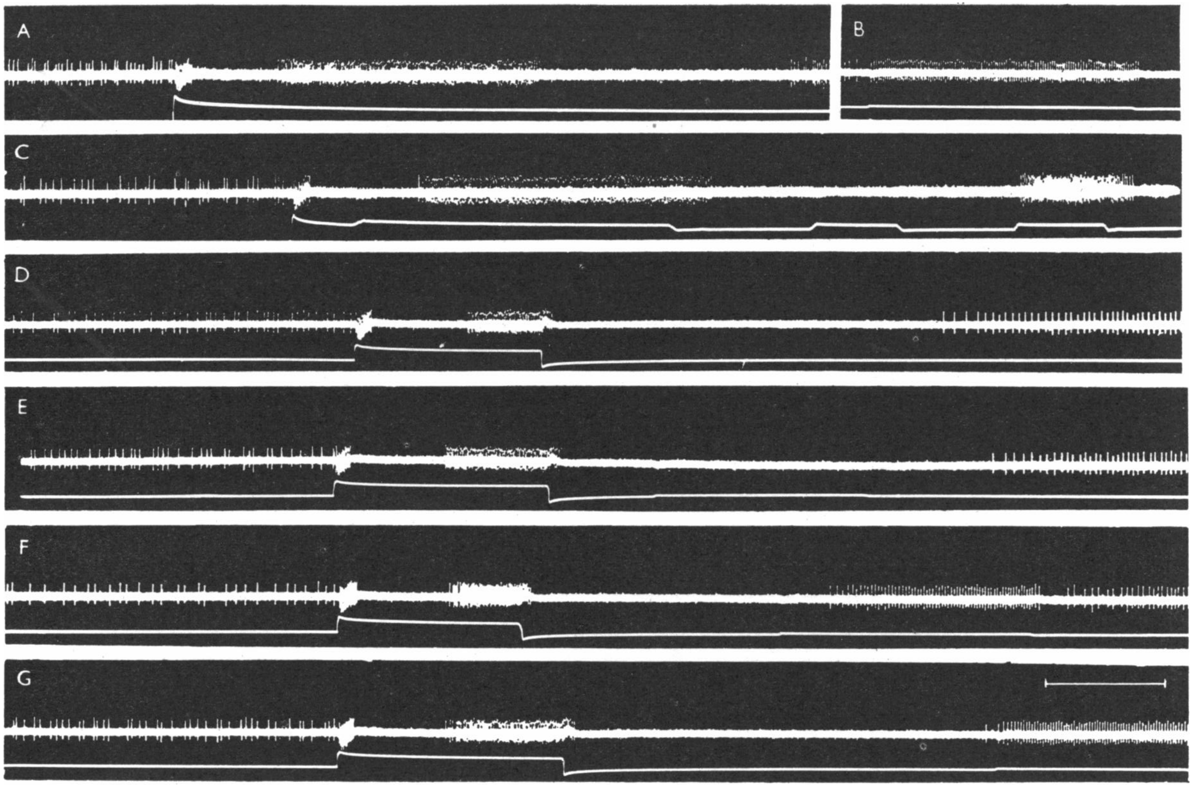
Text-fig. 9. Phases of high intensity response, partial adaptation, initial and secondary high intensity depression, bursts, surges, off response and supernormality. When the signal marker (lower) beam is deflected off scale, the stimulus is on. A: between the first record, of high-frequency response to a strong stimulus, and the second record of a partially adapted level 30 sec of record have been omitted; $2\frac{1}{2}$ sec of the postexcitatory silent period have been omitted; this is followed by a supernormal period when the frequency is well above the original spontaneous level. Reduction in spike height is a common feature of high-frequency response and is probably due to recording close to the injured end of the fibre. B: the same a little later and without omission of any part of the record. Note the initial and later a second silent period during the stimulation; if the stimulus had been maintained the second depression would have gradually yielded to an adapted level of response. The receptor has now altered its characteristic (fatigue, adaptation?) so that the depression phases occur after the same stimulus as in A, just as happens with a stronger stimulus. (The same would be true of a more sensitive unit but this unit is not more sensitive than it was, actually it is less sensitive.) C: an earlier OFF elicits a distinct off-burst. D: a later OFF elicits a minimum off-response, a single spike. $1\frac{1}{2}$ sec of eventless record have been omitted in the middle. E: often during moderately high-intensity response (not so high as to bring on silence, as above), a stuttering or irregular bursting occurs. F: at other times a waxing and waning or surging frequency occurs. Time: each line of the figure is equivalent to 10 sec.

we can infer a depressing process beginning very early and manifest even before it has cut off the initial burst. The depressing process falls rapidly whereas an excitatory process, manifested by the 'off' burst and an unusually long after-discharge, falls slowly. 'Off' bursts are longer the more recently another stimulus took place and the earlier the 'off', i.e. the shorter the stimulus. After the second depression has slowly passed off, if the stimulus is still on, a new plateau of activity considerably above the original spontaneous level typically takes its place. This lasts at least some minutes. Still later stages are described below as steady state temperature effects.

The successive stages of the response to a strong stimulus are themselves variable and suggest simultaneous underlying processes which wax and wane at different rates. But the complexity and the difficulty of describing the typical response in terms of average number of impulses per 0·1 or 1·0 sec or some other period is increased by the common occurrence of intermittency—brief bursts or slower surges alternating with silence or low activity (Text-fig. 9). These are irregular in duration and separation but usually those phases are of a few to several seconds and not greatly different from each other in length. They characteristically come on during the second high-frequency period but may even occur during the third, supposedly fully adapted period of activity. All these phenomena of intense stimulation are moderated or prevented by increasing the intensity slowly (see below).

(7) *Off-phases: after-discharge and flicker fusion.* Following an abrupt 'off' there is typically an after-discharge if there has been rather strong activity up to that moment (Text-fig. 10). Weaker discharges may terminate with the stimulus, without after-discharge. After-discharges of from one to more than a hundred impulses, lasting up to 2 sec, have been recorded, but six to ten impulses over a period of 50–300 msec would be typical of moderately strong stimuli (i.e. not causing high intensity depression). A number of extensive tests have failed to show strong or very consistent effects of stimulus intensity or duration or duration of rest period since the preceding test. The trend is usually for slightly longer after-discharge with strong, longer and more widely separated stimuli; but exceptions occur.

It is chiefly after-discharge which limits the temporal resolution of these receptors. Two flashes of radiation separated by 50 msec can hardly ever be resolved whereas a 75 msec separation generally can, at favourable intensity. Flickering stimuli of 1:1 dark to light ratio produce fused response at high intensity above about 6 or 8 c/s. At maximum flickering frequency, there may be only 1 or 2 spikes per cycle, owing to a prolonged latency. These measurements were made in the first few cycles as there is a lowering of fusion frequency with maintained flicker. Dark to light ratios other than 1:1 give lower fusion frequencies. At 4 c/s or lower there is a specially pronounced response to flicker due to the phenomenon next to be described.



Text-fig. 10. Excitability during phase of high-intensity response in a few-unit preparation. The signal marker (lower) beam is deflected up during a stimulus; the overshoot is an artifact of the photo-cell system, the stimulus is actually square. A: the 'conditioning' stimulus and its response: an initial burst, a silence, secondary burst and silence, and tertiary burst. B: the 'test' stimulus, considerably lower in intensity, and its response. C: the test stimulus is injected first during the initial silent period and appears to be completely ineffective in eliciting response earlier than it would occur anyway. It is then injected during the second silent period with the same result. The third test stimulus elicits an even higher response than it would by itself, occurring as it does when the tertiary burst is due. D: a shorter conditioning stimulus to show the post-excitatory depression period. E: the test stimulus is injected in the middle of this period and elicits no response. F: a little later in the silent period the test stimulus elicits a good response but not as strong a one as the test response above and with a long (400 msec) latency. G: still later, excitability has recovered virtually completely but there is no indication of supernormal excitability although the activity at this time after a conditioning stimulus alone is above normal. Time: the full width of each line is equivalent to 10 sec.

(8) *Off-phases: silence after excitation and vice versa.* Postexcitatory depression and postinhibitory excitation are highly characteristic sequelae of abrupt cessation of warm and cool stimuli respectively (Text-figs. 2 and 6–10). The sudden near-silencing following a very weak warm stimulus is generally a clearer sign that the intensity is above threshold than the initial frequency increase and accordingly is routinely used in testing sensitivity. The percentage change in frequency may of course be much higher for such an inhibition than for an increase of the same absolute number of impulses per second. Moderate and strong warm stimuli produce complete postexcitatory silencing. In general the stronger the stimulus the longer will the postexcitatory depression last. The range is from about $\frac{1}{2}$ sec of only partial inhibition to 30 or more seconds of silence.

Following weak stimuli and complete adaptation, the response and postexcitatory depression look like mirror images, as though a square wave were passing through a condenser. But this analogy breaks down for even moderately strong stimuli. If the 'off' occurs during a maintained higher-than-spontaneous discharge, the depression will be greater than a mirror image of the 'on' response, i.e. will be complete. It may last longer than the 'on' response if the stimulus was only about 1 sec. There may be none even after a strong stimulus if it is less than about half a second in duration. It often lasts longer after longer stimuli, within a range and providing the stimulus is fairly strong, but is then typically cut short by the development of the supernormal period (see below).

Excitability is decreased during postexcitatory depression (Text-fig. 10). The latency of response to a test stimulus is increased by a factor of 2 or less up to 10 or more, which is to say up to about 1 sec. Peak frequency is attained later (e.g. at 300–400 msec instead of 60–160 msec). After-discharge is shorter (e.g. 300–600 msec instead of 900–1000 msec in a certain case). The maximum frequency is lowered appreciably.

When silencing occurs during a strong stimulus (see above), nothing happens at the 'off', unless the 'off' is early enough to result in a brief 'off-burst'. Spontaneous activity may not return for several minutes. Strong test stimuli may show complete refractoriness for a part of this time (many seconds) and subnormal excitability for an additional fraction.

After moderate or strong cold inhibition, a postinhibitory excitation may rise to very intense discharge. We have not seen it last longer than about 5 sec. This overshooting recovery is as conspicuous if the 'off' occurs following complete adaptation as it is when the 'off' occurs during the cold inhibition—just as in the reciprocal case of postexcitatory depression. This description applies to abruptly terminated radiant stimuli; we have not studied these phases after warm- and cold-water stimuli.

(9) *Off-phases: underdamped recovery.* After moderately strong warm stimuli and the subsequent postexcitatory depression it is quite common to see a period of activity distinctly above the original spontaneous level (Text-figs. 6, 7, 9 and 10). This period lasts for from 1 to 15 sec. Identical stimuli to the same single unit sometimes are followed by supernormality and sometimes are not. The factors which correlate with this variation have not been recognized, but may include the duration of the high-frequency response and time of onset of high-intensity depression, for the cases referred to involved strong stimuli and hence these labile phases. Under these conditions also we have seen the supernormal period interrupted by several brief silences, giving the same character to the activity as that we called bursting during high-intensity response. Generally supernormality gives way to a return to the original spontaneous level. However, there seems to be a tendency, manifest after strong stimuli of not too long nor too short duration, for a continued oscillation. Not uncommonly one sees an additional subnormal period which may be brief and slight or deep and prolonged for minutes. Occasionally a still later above-average discharge appears, lasting a number of seconds. These, however, are difficult to be certain of because the amplitude of the oscillation is declining and is now in the same range as spontaneous fluctuations often are.

What is the effect of different steady-state temperatures?

In view of the remarkably sensitive response of the cold and warm receptors of the cat's tongue to steady-state temperatures, discovered by Zotterman and his colleagues (Hensel & Zotterman, 1951*c–e*; Dodt & Zotterman, 1952*a*), and of the ampullae of Lorenzini of the elasomobranch, discovered by Hensel (1955), we have been at some pains to determine the behaviour of the present receptor in this respect. It has proved unexpectedly difficult because (1) adaptation takes many minutes to proceed as far as it is going to, after a change of several degrees C, (2) minute fluctuations in temperature during a supposedly steady state produce a marked effect, i.e. the sensitivity to changing temperature is much higher than to steady states, and (3) variation is great between one preparation and another in the response to apparently equivalent conditions of applying different steady-state temperatures.

The principal result is that many units prepared can be altered five or more degrees on either side of room temperature without evoking a marked change in the level of maintained activity, after adaptation to the change has passed off.

As a simple approximation, and with leads from the whole nerve, a snake can be immersed in ice water with only the head, nerve and recording electrodes in air (18° C). When we gently replace the ice water with water at 25° C, there must be a change of a few degrees in the temperature of the sensory membrane, since the circulation is intact. Yet the integrated activity of the nerve after adaptation is only increased 2–3 db, or about equal to the adapting response to a weak radiant stimulus. The same has been found with cold and warm air baths, changing the rectal temperature between 24 and 18° C.

In one series of measurements the integrated level of activity of the nerve trunk was recorded while the whole preparation was in an air bath and arranged to permit lifting it out into room temperature air without disturbing the relative position of nerve and electrodes. When the air bath was 4–6° C cooler than the room the spontaneous level, after adaptation, was only a few db below that at room temperature. In ten good trials it varied between 0 and 4 db. The time-course of the adaptation could be followed in this case; to be sensibly complete it required 3–8 min. When the air bath was 10–15° C cooler than the room the spontaneous activity was, as before, immediately silenced but now it never returned, at least during the periods of observation, 10–25 min.

Still another method used was that of flushing water through the pit in a continuous stream as described above, changing its temperature slowly. This method permits a better knowledge of the actual temperature of the sensory membrane. The latter must be virtually the same as the water in the pit since its heat capacity is so small. A change of 1° C/min or slower avoids prolonged silencing. An apparently steady-state discharge level is often achieved in 3–5 min after coming to a new temperature equilibrium, judged by the absence of further adaptation in frequency in several additional minutes. This steady-state discharge usually showed a small positive temperature coefficient in the range 18–27° C, i.e. from 6–7° below to 2–3° above the room temperature to which the animals had been acclimated. The difference in adapted level is often so small as to be unreliable when the temperature difference is 1–3° C (a strong stimulus for the adapting fraction of this preparation and quite a reliable one for the maintained fraction in the thermal receptors of the cat's tongue).

Warming the flowing water by several degrees usually resulted in maintained lower frequency than that at room temperature. A strong decline was invariably observed at or above 30° C and higher temperatures depress more, with a steep function, e.g. 1° depressing by a factor of three or more. It seems likely that if the pit or the animals were kept at this temperature or even above 30° C, which silences our preparations, and up to 38° or more after some hours, activity at some considerable level would return, since these are quite normal temperatures for such animals. Our single-fibre preparations were not sufficiently long-lived for us to undertake such experiments; but in one few-unit preparation activity several times returned to nearly room temperature level following a change of 10–11° C (i.e. to 35–36° C) in 10–23 min. Similarly, our preparations, cooled below some point which varied between 17 and 24° C, were depressed. Near-silencing was in one case associated with 18° C, in another unit with 12° C, to give the limits observed.

Between heat depression and cold depression the curve of frequency against temperature may be nearly flat (17–29° C) or may show a peak at or slightly below or slightly above room temperature. Because of the slow fluctuations in frequency and the possibility of small fast fluctuations in water temperature, the single points on these curves cannot be regarded as accurate. However, the fact that impulse frequency does not rise greatly above that near room temperature in one preparation after another, each tested at several points, can hardly be due to any combination of these factors. Likewise it is safe to say that there is not a frequency highly characteristic of each temperature within a range, but only very roughly so, for the slow fluctuations at any given temperature are commonly a factor of two or three.

Sporadic sharp bursts and silent periods or slower surges and ebbs are common with temperatures 1° or more above room temperature. They may persist for many minutes but usually they gradually subside. Occasionally we have encountered bursting or surging during partially depressed low temperature states (e.g. at 15° C). Since the same can happen at any of the higher temperatures, both in those producing depressed and in those producing relatively high-frequency activity, we may conclude that such sporadic intermittency is not the result of firing at close to a limiting frequency. The average frequency over several cycles of burst and silence is not significantly different from that before or following this phase in most cases. This means the frequency during the burst is markedly higher than it is with a more normal distribution of impulses; we are not faced with an intermittent failure alone but a regrouping of impulses. This is not seen at room temperature or in long adapted states, but is common at higher temperatures producing virtually the same adapted frequency. It may be associated with experiments involving more rapidly changed temperatures, the intermittency being elicited by the short stimulus of the change and not passing off as rapidly as the average frequency comes to its adapted level. However, we are not at all satisfied with this as an explanation of the phenomenon and are at a loss for further suggestions.

Long maintained high intensity radiant stimulation of energy sufficient to heat the membrane several degrees gives similar results. Here it is even easier to see the narrow range in which steady-state response occurs, with adaptation times of 5–10 min. In a certain experiment, for example, an intensity of 16 (16 times that which produced a weak but clear adapting response) gave an adapted level of approximately twice the frequency of the spontaneous activity before stimulating; but intensity 8 was not followed by a reliable steady-state change and already at intensity 64 there was silencing for many minutes. Longer adaptation would doubtless extend the intensity range to which steady discharge can respond.

What is the effect of varying the rate of change?

Since the response to different steady-state temperatures and to virtually square-fronted temperature steps is so vastly different, it becomes significant to know the approximate temporal limits separating the two. Accordingly, we have in several experiments estimated the slowest rate of change which is just equal in stimulating efficacy to a square-fronted step of the same height and the fastest rate of change which is physiologically nearly equal to an infinitely slow one. These values would give us the range within which the receptor is influenced by rate of change. The second value is much more difficult to obtain and our results are little more than estimates.

By opening a diaphragm at different rates a certain form of gradually increasing radiant stimulus has been delivered. Our method of doing this has not achieved a simple relation between intensity and time but one which is between a linear and a logarithmic form. In view of the results it seems doubtful whether this seriously influenced the values obtained.

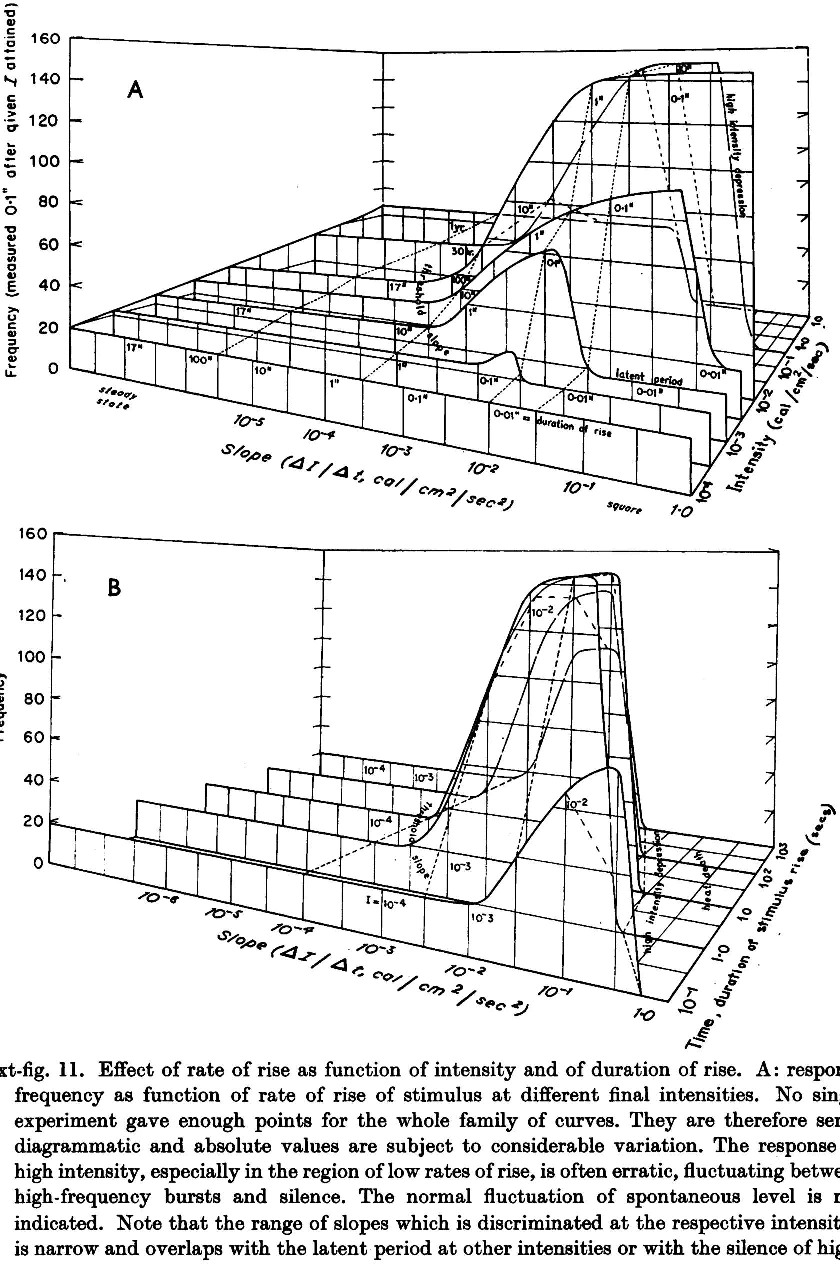
The rise time which is effectively as good as square for moderate intensities is long relative to the latent period, e.g. more than 150 msec but less than 500 msec in a typical case giving 57–70 impulses/sec. For all slopes, therefore, within the range of slope effect, the momentary frequency is 'up to date', i.e. is determined by events virtually up to that moment. However, except for strong stimuli and steep slopes, the poor rhythmicity or scatter of impulse intervals is still so pronounced as to require integration over some time in order to obtain smooth enough curves to compare slopes. This means the smoothed curve is far from up to date and is quite dependent on the form of the slope. This, combined with the variability between unit preparations, the limited life of each unit, the long rest periods demanded after strong response and the unreliability of determinations of weak response owing to spontaneous fluctuations, have prevented the plotting of these relations from a series of strictly comparable points. The curves shown in Text-fig. 11 are constructed from points obtained on different preparations, with some selection in order to avoid inconsistency (e.g. with the rules that higher intensity and higher slope elicit higher frequency). They are thus semidiagrammatic and may be quite distorted relative to a given or even an average unit. It is especially difficult to determine the threshold slope and with our apparatus it has been beyond the range of controlled radiant stimuli. We have used the flowing water stimulus, with slow heating. But we are not able to equate this with the radiation intensity within a factor of several times at low rates of rise.

Text-fig. 11A shows the slope-response curve as a function of intensity. Along the left side of the figure the gently rising line expresses the low sensitivity to steady-state temperature. The rising response to steeper slopes and higher intensities is cut off by the high intensity depression.

From the same data we can plot Text-fig. 11B to show the change in the frequency-slope curve as a function of duration of stimulus up to the moment when the frequency is read. At short durations the whole curve lies to the right because only low intensities have been reached. At longer durations the steeper slopes pass the point of depression and then of heat death progressively sooner and the cut-off point moves to the left. For the first few tenths of a second it rises to higher maximum frequencies and thereafter tends to maintain these at progressively smaller slopes but with disproportionally long durations.

These curves show that the receptor is not acting as a rate of change detector but as an intensity detector with adaptation and that the adaptation, or the two or more separate kinds and rates of adaptation, embrace a time scale from seconds to minutes. If the receptor were a rate of rise detector, Text-fig. 11 would not show rising maximum frequencies for a given slope as the intensity increases and as duration increases, short of the depression point. However, the receptor signals information adequate to measure slope if the receiver can integrate the time-course of frequency change and knows the relation built into the receptor between frequency and intensity and the time-course of adaptation. Because of the fluctuation in response to a given condition and the requirement of averaging widely varying impulse intervals, each additional computation increases the crudeness of the measurement so that we may suggest that this organ is not important in—or at least is not well adapted for—estimation of rate of change of stimuli.

The rate of change does nevertheless determine several features of response. Sensitivity is at least several hundred times greater for a rapidly changing than for a slowly changing temperature, the ΔT necessary for a 50 % increase in frequency being approximately 0·003° C (in 0·05–0·1 sec) and 3° C (in many minutes) in the two cases. These figures expressed in Q_{10} values are approximately 4 and 10^{30}, respectively. Variation among our experiments in both cases



Text-fig. 11. Effect of rate of rise as function of intensity and of duration of rise. A: response frequency as function of rate of rise of stimulus at different final intensities. No single experiment gave enough points for the whole family of curves. They are therefore semidiagrammatic and absolute values are subject to considerable variation. The response at high intensity, especially in the region of low rates of rise, is often erratic, fluctuating between high-frequency bursts and silence. The normal fluctuation of spontaneous level is not indicated. Note that the range of slopes which is discriminated at the respective intensities is narrow and overlaps with the latent period at other intensities or with the silence of high-intensity depression. This means the organ is a poor transducer for rate of change. Frequency bears a complex relation to the intensity. The small numbers inside the graph give the duration of the slowly rising stimulus at that slope and intensity. The frequency plotted is that 0·1 sec after the given intensity was attained and maintained because, if frequency had been plotted at the moment the given intensity was reached, much of the graph would be missing, owing to latency. B: response frequency as function of rate of rise of stimulus at different durations of rise. Semidiagrammatic, as in A. Note the decrease in the critical slope for high intensity depression as longer durations are employed and the similar decrease in threshold slope, at least for the shorter durations. The just effectively square stimulus at each given duration appears to recede to smaller slopes at higher durations. The limits of the slower forms of adaptation are shown in these two graphs by the points of inflexion on the left and the declining maximum frequencies at the higher intensities and durations.

is great but would hardly alter this great difference at all. In contrast to threshold sensitivity the discrimination, defined as sensitivity to change above threshold ($F_2 \div F_1/\Delta T_2 \div \Delta T_1$) is not noticeably different and is small in both cases, values commonly being between 0·3 and 0·7. Rate of rise of stimulus determines a large difference in the useful range defined as the change in temperature producing the maximum response: this is small for sudden changes, even 0·5° C being likely to block, while for slow enough changes it is our presumption (not tested) that the organ is functional at least over the 20° range from 18 to 38° C. Resolution, defined as range divided by threshold to change, is a few hundred for steep and ten or thereabouts for slow stimuli. The receptor is capable of four or five times higher maximum frequency of discharge for sudden changes than for steady states. Finally, we may recognize symmetry or skewness in the curve of response against stimulus intensity; steady states depress at high and at low temperatures without pronounced asymmetry but abrupt stimuli sharply cut off response at some intensity which lies just above that for maximum response.

The fluctuations in frequency under given conditions

The so-called spontaneous activity, as well as that adapted for some minutes to a maintained stimulus, is characterized not only by non-rhythmic discharge of units but by fluctuations in average frequency even when integrated over fifty or a hundred impulses, i.e. several seconds. Single unit activity recorded with an integrator of about 3 sec time-constant shows slow shifts in level with durations exceeding 20 sec and excursions representing twofold changes in average frequency. Shorter term fluctuations are, of course, smoothed by such an integrator, but they show nevertheless because their amplitude is so great. Faithful recording of every interval reveals a range of from 10:1 to 25:1 at room temperature. The range of 2:1 for 3 sec smoothing is often exceeded; high intensity stimulation frequently brings on a state of 'surging' or slow alternation between high and low average frequency. Records of activity in whole nerve trunks also show these fluctuations even though the large number of units contributing to the record are presumably not synchronized and therefore should tend to smooth out individual fluctuation. The amplitude of fluctuation in whole trunks is notably less, so that the assumption of non-synchrony, even of slow fluctuations, is probably correct. Records from small bundles with two or three active fibres directly confirm that the slow fluctuations in average frequency are not in phase in separate units. The fluctuations are probably not attributable to environmental stimulation; they occur when the pit is screened from the room or filled with standing water. The room temperature is not changing sufficiently in magnitude or rate to produce such frequency changes. The animal is typically lying quietly, although capable of some tail and peristaltic movements, breathing regularly, with circulation intact, a minor skin wound and no stimulation via eyes or other channels which would cause an uncurarized crotalid of these species to struggle. Presumably, then, the fluctuating activity inheres in the receptor.

DISCUSSION

We have here initiation of nerve impulses in free endings strongly reminiscent of dendrites (Bullock & Fox, unpublished; Bullock, 1953). It has not been possible to record prepotentials with steel needles in the sensory membrane and fine glass micropipettes have not been successfully inserted. We have nothing therefore to say on the intimate mechanism of the resting discharge. This is unusually non-rhythmic and strongly suggests independent loci of initiation of activity in the terminal expansions. Further speculation must be deferred.

It is of course tantalizing to consider the mechanism of such extremely high sensitivity. We will discuss one aspect of this, narrowing the problem but without any suggestions on cellular mechanism. Then some comment will be directed to the central consequences of the irregular background discharge. Finally, an evaluation of the facial pit organ and its function, first for its owner and then in comparison with some other receptors, will be attempted.

Is the reception wave-length specific or proportional to heating?

The question cannot yet be answered unequivocally whether the receptors of the pit organ are normally stimulated, like the eye, by certain wave-lengths of all those absorbed, or, like temperature receptors, by all wave-lengths in the proportion with which they heat the tissue. The former, amounting to photochemistry in the long infrared region, is very unlikely since there are apparently no known photochemical reactions and each photon is of very low energy in the region of principal emission of physiological stimuli (10–20 μ wave-length). Photoelectric and photoconductive effects are unlikely on the basis of present knowledge of their requirements.

In order to permit the first alternative it would be necessary to show that the action spectrum agrees with, or is contained in, the absorption spectrum of the receptor. We have the transmission spectrum of the whole membrane and some approximation of the action spectrum. However, these are inadequate for decisive comparison because of the probability of a difference between the absorption spectrum of the receptor and that of the whole membrane and because of the difference between the absorption spectrum of the membrane and a transmission spectrum. Reflexion from the shiny, undulating surface of the cuticle may be a significant loss. The only considerable disagreement between our response and transmission measurements is in the visible light region where there is a large (50 %) apparent absorption but little or no sensitivity. This discrepancy may be due to reflexion and scatter.

Temperature reception is not only more likely for these reasons but also because of the agreement between the calculated temperature rise with threshold infra-red stimulation, assuming all the flux is absorbed and effective, and the observed threshold under stimulation with water at known temperature. Such agreement could not be expected if the effective wave-lengths were the short infrared wave-lengths known to be photochemically active, for these constitute a small fraction of the flux from a low temperature emitter. Tentatively we conclude that the pit organ receptors are specialized for responding to temperature change of the tissue of the pit membrane.

The problem of fluctuating spontaneity and central recognition of real signals

Spontaneous activity may be advantageous in providing for high sensitivity and also for signalling in one line both positive and negative changes in the stimulating parameter. But it raises a serious problem in any case like the present one where rhythmicity is not perfect. This is: what change in the output of the sensory nerve fibre constitutes a signal of environmental change? The frequency of nerve impulses in each fibre varies widely under steady-state conditions even when smoothed by averaging several dozen successive intervals. These spontaneous fluctuations must decrease sensitivity, since that is determined by the smallest significant alteration in the output, and also must decrease the temporal resolution of the central nervous system since that organ has to integrate activity over some period in order to gain any reasonable sensitivity. Bullock (1956) has discussed this problem and formulated some of the alternative ways of analysing the signals from a single receptor unit to obtain the most information. He concludes that the central nervous system could analyse signals such as reported here in any of several ways, but that there will not be the maximum combination of sensitivity and temporal resolution (reaction time, flicker resolution, brief stimulus detection) unless the analysis incorporates the following features. It must do something equivalent to integrating the frequency over some short time just past, subtracting some fixed value of optimal magnitude, comparing the result with a similar value obtained with integration over a longer time (background frequency), then multiplying this ratio by an averaged rate of change of this ratio over some intermediate time just past. The value so obtained will be very low for spontaneous fluctuations in background frequency and high for true signals of stimulation. A less processed analysis will give a poorer discrimination, sacrificing one of the parameters listed.

Possibly still more important as a mechanism for gaining reliability from noisy signals like these is the summing of activity in independent input channels, i.e. afferent fibres. This probably occurs as an important normal mechanism and permits the central nervous system to demand a very high level of significance. Hardy & Oppel (1938), for example, plot a curve for warm sensation in man, showing that the threshold stimulus decreases up to threefold for a tenfold increase in the area of skin stimulated and more than 100-fold from minimal to maximal area. Presumably the signals in each afferent fibre were independent of the others and of the areas stimulated beyond its own terminal ramifications, so that only an increased number of channels could account for the effect. The summation effect is curious for it is steep in the range (1 to 40 cm^2 of forehead) estimated to contain tens of warm spots, and, on the ordinate, in a region of stimulus strength which must be eliciting highly reliable signals in each unit. Evidently for the level of conscious sensation a few quite strongly firing receptors are not sufficient to reach threshold (cf. Kondo, 1955). Either an increase in number of units or more intense firing is necessary. Similar results have been reported, among others, by Wright (1951).

It seems likely that something similar happens in the snake. Because of the small size of the sense organ and the fact that the normal stimulus is radiant, most stimuli will impinge upon at least a sizeable fraction of the sensory membrane. Elsewhere, Bullock & Fox (unpublished) have estimated that there are between 500 and 1500 warm fibres ending per square millimetre so that most stimuli will affect a large number of afferent channels at once and thus operate in the range of maximum sensitivity of the central organ. The whole pit organ, with about 3500 endings in 3–4 mm^2 gives more scope for summation than the whole forehead of man, with about 200–400 warm spots in 20,000 mm^2 if we take as an approximation the figures of Bazett (1949). This is the area which Hardy & Oppel (1937) found to have a threshold virtually as low as total body irradiation.

The problem of extracting reliable information from a continuously active background of widely fluctuating impulse intervals may be exaggerated in the present case, but it seems likely that it is quite a general physiological problem. Spontaneous activity has emerged in recent years as a feature of many sense organs as it did 25 years ago in the central nervous system. Even in the best cases of rhythmicity, the constancy of successive intervals is relative and small signals look much like noise.

An evaluation of the facial pit and its function

The facial pit of the pit vipers is remarkably adapted for the reception of heat radiation. In nature there is a dichotomy: most of the radiation emitted is either from a very high temperature source and therefore lies in the visible part of the spectrum or is from ordinary low temperature objects ($<40^\circ$ C) with a peak at 10–20 μ in the long infra-red region; there is little to detect in between. Because of the quantal nature of sensory detection devices (independent receptor units), an adequate stimulus must impinge on the minute area innervated by each afferent fibre, much less than a square millimetre. This means that the normal dose available is a very small quantity of energy (flux is energy/cm^2/sec, threshold dose is energy/physiological unit within a required time shorter than the latent period).

Apparently no mechanism has been found to utilize these low doses in the way the eye does, by specific photochemical reactions, and a perhaps pre-existing temperature sensibility had to be utilized. Looking for such a general cutaneous temperature sensibility, we have recorded from nerves of the belly skin of the same snakes, the nerve homologous to that of the facial pit in non-crotalid snakes (*Pituophis catenifer*, the gopher snake) and in skin nerves of frogs. In no case have we seen any response to warming and only a transient burst to strong cooling (several degrees) which could be coming from tactile fibres (Hensel & Zotterman, 1951*a*). This is contrary to the report of Maruhashi, Mizuguchi & Tasaki (1952) for the frog where they did describe some fibres as temperature-specialized.

Besides increasing the temperature sensitivity of some pre-existing receptor, the pit organ has enormously increased the sensitivity to radiant heat by several secondary features. (1) The superficial position of the endings. These are within 5–7 μ of the surface compared to 300 μ or more in man—a depth so great that radiant heat is totally absorbed long before it reaches the endings which therefore must be heated by conduction. (2) The air space behind the sensory surface. Loss of temperature by reradiation backwards into the inner wall of the inner chamber is much less than conduction loss would be were tissues and blood vessels of the sensory membrane in immediate contact with the depths. (3) The thinness of the membrane. A given amount of absorbed energy has a minimal volume of tissue to warm. Dr Konrad Buettner has kindly calculated the following comparison with man. The rise in temperature of the snake membrane for a given flux and time is given by the following expressions for short periods assuming no loss to the blood or to the air

$$\Delta T = \text{flux} \times \frac{1}{\text{thickness}} \times t.$$

The rise in temperature of the nerve endings in man where conduction is continuous to and beyond them is

$$\Delta T = \text{flux} \times \frac{1}{\text{depth of endings}} \times \sqrt{t}.$$

At 1 sec., given 15 and 300 μ respectively, the snake membrane will change 22 times as much in temperature; at 0·1 sec only 7 times as much.

The sensory membrane is, in the species of *Crotalus* examined, usually not pigmented although the skin of the walls of the pit and of the face is. For the longer infra-red rays pigment does not absorb better than unpigmented tissue, so that this is no handicap. It may indeed be regarded as evidence of the specialization for the longer wave-lengths emitted by ordinary low temperature objects. *Agkistrodon piscivorus*, on the other hand, has a heavily pigmented membrane; no disadvantage or advantage would seem to accrue thereby.

Besides the adaptedness of the membrane we are faced with two other features: the dense innervation and the depressed position. The former, as argued above, may greatly contribute to sensitivity because of the possible central requirement of spatial summation. But it may also have a meaning, along with the depressed position, in conferring a directional sensibility. Radiating objects in the environment are bound to cast sharp shadows of one side or another of the slightly constricted mouth of the pit (Pl. 1, fig. 1) in any position except a very restricted one close to the axis of the cone of visibility. Slight relative movements of the object and the head will assure shadows and will move their margins. It is thus possible, with the structure and the richness of supply, to analyse the shadows and obtain information about direction, distance (by change in position of the shadow with known head turning), and movement of small objects. In a small cone directly in front an object can be 'seen' by both pits; this could facilitate the analysis and add estimation of size. Noble & Schmidt (1937) showed that blindfolded snakes of this group strike correctly at warm moving objects if the pits are not covered. The ability not only to detect warmth by radiation but to estimate its direction and whether the source is moving may be very important to the species; the present analysis shows how these may be accomplished.

As against these advantageous specializations we must recognize the crudeness resulting from the non-rhythmic spontaneous discharge: the fluctuations even in average frequency over seconds, the limited range of intensities and of slopes and the poor reproducibility of response to a given stimulus. These receptors cannot be reliably discriminating among stimuli with any considerable degree of refinement. This conclusion does not exclude the possibility that the central analysing mechanism may, by sacrificing one parameter, e.g. spatial resolution, gain redundancy and thereby considerable improvement in reliability of discrimination. But relative to other sense organs this one appears to be a rather undiscriminating, almost presence-or-absence, signalling device.

While it is easy to conclude that this organ admirably equips the snake for detecting both warm and cool objects (relative to their backgrounds, not to the snake) and to suppose that such objects include warm rocks, shady spots, moist frogs and homoiotherms, it is harder to specify what the normal function is. How this organ is used in nature and what behaviour it permits, which is not possible to non-crotalid snakes, we can only guess. The most obvious advantage perhaps is in hunting at night or in burrows, either for warm or cool food or for warm or cool spots.

The only comparable organs described are the labial pits of some boas and pythons (Ros, 1935; Noble & Schmidt, 1937). These lack the inner chamber and thin sensory membrane but have been shown by the authors mentioned to mediate the ability to strike at warm, moving objects in the absence of vision, of the nostrils, the tongue and the general cutaneous sensibilities, much as in the crotalids. Even some other snakes without pit organs show a sensitivity to warm objects, but it appears possible that they do not localize objects at a distance by this sense. We are not aware of field or behaviour studies which have revealed an advantage of crotalids in certain situations which could be attributed to this sense.

Some comparisons with other receptors

The outstanding feature of the temperature receptors most studied, those in the cat's tongue and in the ampullae of Lorenzini of the elasmobranch (Hensel, 1952*a*, *b*, 1955; Hensel & Zotterman, 1951*a–e*; Zotterman, 1953; Dodt & Zotterman, 1952*a*, *b*; Dodt, 1953) is the sensitivity of the maintained, steady-state discharge to temperature. This is lacking or greatly reduced in the present case.

The snake receptors appear to differ from both these other cases in exhibiting a very slow adaptation to stronger stimuli, following an early phase of adaptation. Even the early phase seems to be slower than the adaptation of the initial high-frequency discharge in the mammalian cold and warm fibres, which falls to half maximum frequency in 1 or 2 sec.

In the mammalian cold and warm receptors, sensitivity of the phasic component is higher than that of the static component and can reach values of 20 impulses/sec for a sudden change in temperature of 1° C, 56 for 2° C, in the maximum cases illustrated by Hensel & Zotterman. These figures are for cold fibres; warm fibres have not been as carefully studied and no small steps of temperature are reported; from the records of larger steps, one may guess that they are not as sensitive as cold fibres. The snake receptors are equally stimulated by far smaller temperature steps (0·001–0·005° C), but it is possible that the apparent sensitivity of the mammalian cutaneous structures is lowered by the combination of time (Hensel, 1952*c*) required for heat to flow the several hundred μ of the depth of the endings and the relatively rapid adaptation. The most sensitive fibres reported from the ampullae of Lorenzini of the ray (Hensel, 1955) attained a maximum frequency of 60 for a step of 1° C, and are thus more sensitive than the mammal and less sensitive than the snake. For the purpose of such a comparison, we cannot employ the ratio of maximum response frequency to spontaneous background because in certain ranges of temperature the latter is reduced greatly, even to zero, while the adapting response still has a finite if feeble value.

Hardy & Oppel (1937) have measured the radiant flux required for threshold sensation in man. In stimulating a large area this is minimal but because of the principle of sensory physiology that each receptor fibre must be independently excited, we may believe that this gives a closer approximation to the physiological threshold of the unit than any smaller area. By extrapolation from direct measurements of surface temperature with large known fluxes, they give the threshold temperature change as 0·003° in 3 sec, the time required for minimum threshold. This is in excellent agreement with the present results. The extrapolation may require modification in the light of newer measurements of heat flow and temperature rise in the skin (Buettner, 1951; Hensel, 1952*c*) but at present this appears to involve a change of not more than a factor of three (Buettner, personal communication) and does not therefore greatly affect the comparison. However, it is interesting that now, for the first time, we have evidence that the threshold of the unit receptor is where it should be, i.e. as low as that estimated on a behavioural index of central sensitivity in the snake, which is about the same as that estimated by the index of sensation in man.

Besides the sensitivity to temperature, we may compare that to radiant flux, to evaluate the degree of specialization for infrared detection. The only comparable values we are aware of are those of Oppel & Hardy (1937) and Hardy & Oppel (1937, 1938), measured on man with a subjective end-point. On irradiating a large area, the threshold for warm sensation was $1{\cdot}5 \times 10^{-4}$ cal/cm^2/sec maintained for 3 sec. Taking a behavioural end-point, such as that given by Noble & Schmidt (1937) for the snake, we have calculated the flux from a rat of 10 cm equivalent diameter at half a metre with an assumed 10° C difference between the surface temperature of the rat and that of the background as $1{\cdot}3 \times 10^{-5}$ cal/cm^2/sec, or about one-tenth that of man. As already discussed above, the dose received by the snake in this case (we are not sure it is all required) is about 4×10^{-8} cal because of the small size and short latency of its organ, while that required by man is at least 9×10^{-2} cal. Calculated for the area of terminal ramification of a single sensory fibre in the snake, the dose is about 2×10^{-11} cal.

In contrast to the warm receptors in the cat's tongue (Dodt & Zotterman, 1952*b*; Dodt, 1953), there is no paradoxical discharge of the snake pit fibres upon a sudden cooling of several degrees. Perhaps the most striking difference between these cases, however, is the readiness with which strong stimuli—e.g. a rise in temperature of one degree or less—block or silence the snake pit receptors. This phenomenon and the long-delayed recovery from it have apparently no counterpart in the mammalian temperature receptors. Adrian (1933) saw a somewhat similar break-down of response in inflation-receptors in the vagus. The long-delayed adaptation from slightly less strong stimuli, with the complex sequence of phases of excitation and depression, seems also to be unlike the properties described in other receptors.

The present results do not support the 'thermopile' theory of Lele, Weddell & Williams (1954) and Tyrrell, Taylor & Williams (1954). These authors believe that spontaneous activity, such as that reported by Zotterman, Hensel and Sand, is due to non-isothermal conditions, and that discharge to thermal stimuli requires a difference in temperature between the terminal 'axoplasmic filaments' of free nerve endings and the 'ensheathed axon'. This difference is supposed to generate a potential which determines a discharge. The evidence is theoretical, based on psychological experiments with human subjects. There is no specific refutation of the experiments of Hensel & Zotterman (1951*a–e*) or Hensel, Ström & Zotterman (1951) nor a suggestion as to how non-isothermal conditions could reasonably persist in Sand's (1938) experiments. Many receptors maintain resting discharge in isolated, apparently isothermal, preparations. Similarly here the sensory membrane, the animal and the room—both its air and its solid objects—can be at equilibrium and yet a spontaneous discharge is maintained. Indeed, direct experiments show that, to stop this discharge by slowly altered or steady-state conditions, a change in temperature of 5–10° C must be imposed. There can be no question of a non-isothermal condition of this magnitude. Even the response to sudden stimulation cannot readily be ascribed to a difference in temperature between free endings and ensheathed axon, for both lie in the thin, 10–15 μ membrane, parallel to the surface (Bullock & Fox, unpublished).

Besides the fact of isothermal discharge, it may be pointed out that some of the basic phenomena, upon which Lele, Weddell & Williams construct their argument as to the properties of the peripheral receptor, may be central. Thus the lack of a simple relation between sensation and skin temperature (Lele, 1954) and the fact of subjective thermoneutrality over a wide range of skin temperatures may largely manifest cerebral processes. Without denying the probability of slow peripheral adaptation or claiming that the receptors necessarily or simply function as thermometers, we can question the assumption that thermoneutrality—or any given sensation—at different skin temperatures means that the same signal is ascending the afferent nerves.

Physiologists are accustomed to comparing the sensitivity of receptors to the 'noise level' of the form of stimulus concerned. This is difficult in the present case. The sensitivity to radiant flux is high enough to stimulate every time the snake suddenly faces a background or a large or close object of black body character (soil, rock, plant or almost any usual ordinary outdoor object) with a surface temperature 0·1° C above or below the previous. We do not know the 'noise level' but this is certainly within the range of minor variations in different parts of the same object, especially in or soon after changing microclimate (i.e. as the sun moves during the day, or as evening and morning redistribution of heat progresses). The sensitivity certainly does not approach that of the retina in terms of energy content or of proximity to random events at the photon level. In respect to temperature, apart from that due to absorbed radiation, the conduction from ambient media is the only problem. We need consider only the blood and the air. Certainly in ordinary environments these commonly fluctuate far more than 0·001° C but we may perhaps believe that each such fluctuation has some meaning in terms of environmental change, i.e. is not 'random'.

The receptor would be useless with such high sensitivity if it did not have both fast and slow adaptation to protect it from high intensity depression by faster or slower overstimulation. It is perhaps a tenable idea that the rates of adaptation bear such a relation to the particular range of rates of change of temperature commonly encountered in ordinary environments that these latter only sometimes exceed the adaptation rates and hence stimulate, but often do not. Hence, without silencing the receptor, it can adapt to 5, 10 or 20° C changes and yet maintain a readiness to signal some small, superimposed change of greater abruptness. Certainly we can say that a rattlesnake will not under ordinary conditions be stimulated only by radiant sources, adapting his receptors faster than all changes in air or blood temperature. The facial pit is readily stimulated by commonplace movements of air masses of different temperature, although considerably protected by the cul-de-sac form. It can also be stimulated, though marginally, by blood temperature changes resulting from body heating which reasonably simulates a snake moving on to a much warmer or cooler substratum without altering the field of view of the pit or the air temperature.

SUMMARY

1. Nerve fibres from the facial pit of rattlesnakes (*Crotalus*) usually show a continual non-rhythmic discharge in the absence of environmental change.

2. The adequate stimulus for increasing this activity is a relative increase in the influx or a decrease in efflux of radiant energy in the middle and long infrared regions. Equally effective stimuli, which however inhibit the spontaneous discharge, are relative increases in efflux or decreases in influx.

3. No response is obtained to sound vibration, a number of chemicals or heat-filtered light, but change in temperature by conduction from ambient media and mechanical deformation of the sensory membrane stimulate. It is concluded that these are minor or incidental in ordinary conditions.

4. All the sensory nerve fibres from the pit appear to be warm receptor fibres. The mechanical sensibility resides in the same fibres.

5. An object provides a stimulus if its temperature contrasts with that of the background, independent of the temperature of the snake or of the air, within limits. If the background is warm, regardless of snake or air temperature, an object 0·1° C cooler elicits a 'cold' response and vice versa.

6. The normal sensibility is directional. Different receptor units have different, sharply defined cones of reception.

7. Sensitivity of units by oscilloscopic end-point extends to less than 3×10^{-4} cal/cm^2/sec or a dose of 5×10^{-10} cal in 0·1 sec on the area of terminal

ramification of one fibre. By behavioural end-point (Noble & Schmidt, 1937) these figures would be $1{\cdot}3\times10^{-5}$ and 2×10^{-11}. Calculated as change in temperature of the membrane, these two end-points give 0·02 and 0·001° C. Direct measurement of the change, necessary to elicit a response, in temperature of water flowing over the membrane gave values of 0·003–0·005° C.

8. The initial burst of response to a sudden warm stimulus rises in frequency from 2·2 to 4·5 times higher for each tenfold increase in intensity but never exceeds about 200/sec. The useful range in intensity is usually not above 1:500. Latency is from 10 to 150 msec, depending on intensity.

9. Adaptation to weak stimuli occurs in several seconds and is complete. Stimuli 10 to 30 times threshold produce long-lasting discharge with an early and a late phase of adaptation. The latter may not begin for several minutes and may require many minutes to come to equilibrium, but is then almost or quite complete. Stimuli several hundred times threshold (several tenths of a degree C) elicit a complex sequence of phases: burst, silence, burst, depression and after minutes a plateau slightly above the original spontaneous level. The interrelationship of these and the effect of varying stimulus intensity suggest that high intensity involves several separate intracellular processes of both signs and different time-courses. High intensity intermittency in the form of stuttering bursts and of waxing and waning surges are described.

10. After the abrupt end of a stimulus one of several sequences follows, involving after-discharge, off burst, postexcitatory depression or silence, supernormal or overshooting recovery and even later phases.

11. The sensitivity to different steady-state temperatures or radiant fluxes is very low. Approximate values are given for the slowest rates of change which are physiologically equivalent to a square stimulus at different final intensities and at different durations of rise and similarly for the threshold rate of change. The relation is complex, but the physiologically just square stimulus is at least several tenths of a second in rising and the threshold slope may require several minutes. At any one final intensity, the ratio between these, i.e. the range of slope which can be discriminated, is much narrower than it is comparing high and low final intensities. The receptor cannot properly be called a rate-of-change detector, but must be regarded as an intensity detector with adaptations of varying time-course. The rate of change determines not only sensitivity (Q_{10} about 4 and 10^{30} at threshold and effectively square slopes respectively) but also useful range, resolution, maximum frequency and symmetry of response/temperature curve.

12. The non-rhythmicity and fluctuations in frequency, even when integrated over some seconds, apparently inhere in the unit receptor not in the environment or in synchronized changes in many units.

13. It is concluded that we are dealing with a reception of the temperature of the tissue, not of specific wave-lengths as in the eye. We have failed to find

any similar response in the homologous nerve in non-crotalids and in other nerves of crotalids.

14. In an evaluation of the biological significance of the pit organ, the high specialization of physiological properties and anatomy are pointed out. Not only is the sensitivity thereby increased, in particular to small doses of radiant energy (e.g. from a mouse distant many cm, against common backgrounds) but a directional analysis is possible. The properties, however, suggest a relatively non-discriminating, largely presence-or-absence-signalling sense organ. Presumably crotalids should have an advantage hunting warm-blooded or cool (moist) prey at night or under ground and in locating warm or cool regions of the substratum.

15. This organ presents in exaggerated form the general problem of the central nervous system in recognizing valid signals of environmental change on a background of fluctuating non-rhythmic spontaneity. The central analysing mechanism must sacrifice either sensitivity or temporal resolution or compromise between them, but it can improve its recognition of signals materially if it can perform three integrations with different time-constants and derive a value from them for the unit receptor signal. Additionally, by sacrificing resolution of shadows and hence directionality, it can sum signals in different afferent fibres to improve signal-to-noise ratio.

16. Comparison with the other physiologically studied temperature receptors indicates that this one is far more sensitive to small steps but far less sensitive to maintained temperature. The snake's warm receptors are strikingly different from the others in respect to the block, slow adaptation and complex sequence of phases following strong stimuli.

17. A simple electronic device is described for automatically and continuously plotting on the cathode-ray oscilloscope the intervals between successive nerve impulses in a single unit as a function of time.

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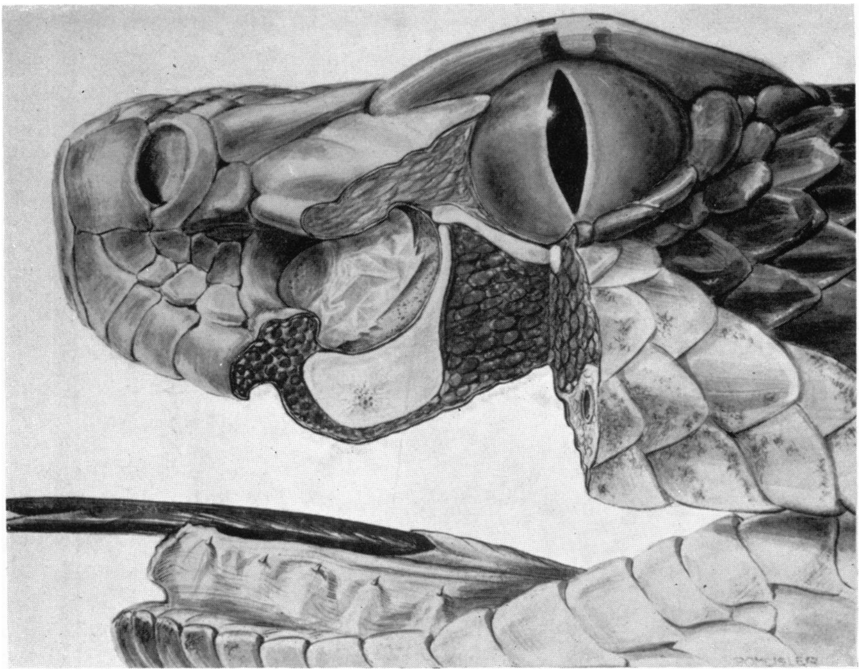

Fig. 1

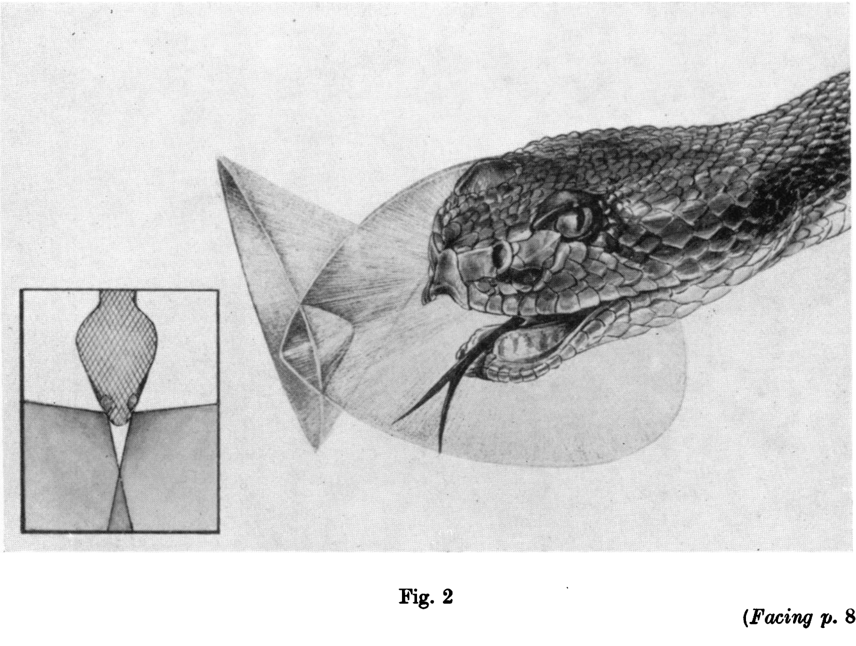

Fig. 2

(*Facing p.* 87)

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EXPLANATION OF PLATE

Fig. 1. Head of *Crotalus viridis* cut away to show the facial pit and its sensory membrane. The membrane is shown as wrinkled to suggest its texture and thinness and to emphasize the air chamber behind it; actually it lies concave outwards, nearly filling the posterior wall of the posterior chamber. Its three nerves, not shown, approach it from above, behind and in front. The preparation chiefly used in this communication involved no surgery in the region of the pit but exposure and dissection of one of the nerves posterior to the eye.

Fig. 2. The cone of reception. The boundaries were determined by recording from the whole nerves (superficial and deep branches of supra-maxillary nerve) while moving a small source across the peripheral field. They are therefore the maximum boundaries, adding the smaller cones of all the individual units.