3 | Neurons and Neural Codes

The Neuron

The nerve cell, or *neuron*, is the basic anatomical unit of the nervous system; but it is protean in the forms it assumes and we shall see that it may not always be the basic functional unit.

The neuron of the textbooks is divided into three parts that reflect its functions of gathering, collating, and transmitting information (Fig. 3.1): *the dendrites*, which receive signals from other neurons, the *soma*, or cell
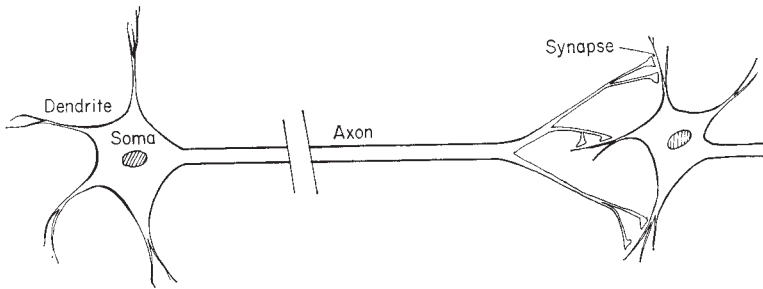

Fig. 3.1 A textbook neuron.

body, and the *axon*, which may be more than a metre in length and along which are carried nerve impulses, or *action potentials*. At its end the axon usually divides into a number of branches, which form junctions on the dendrites and cell bodies of other neurons. At these junctions, which are called *synapses*, the arrival of action potentials causes the release of packages of a *transmitter substance*. A particular synapse is either excitatory or

inhibitory: the transmitter that it releases either increases or decreases the probability that the second neuron will respond with an action potential. In the resting state there is a difference in electrical potential between the inside and the outside of the recipient neuron, the inside being 60–90 millivolts negative relative to the outside, and the transmitter, by changing the permeability of the second cell's membrane to charged particles called *ions*, either reduces or increases this difference in potential. The depolarization, or reduction of the difference in voltage, that is produced at an excitatory synapse is called an *excitatory postsynaptic potential* (EPSP); the *hyperpolarization*, or increase in potential difference, that is produced at an inhibitory synapse, is called an *inhibitory postsynaptic potential* (IPSP). A single neuron may receive hundreds, sometimes tens of thousands, of synapses. It is thought (Eccles, 1973) that excitatory synapses are normally on dendrites and inhibitory synapses normally on cell bodies. At any instant the EPSP's and IPSP's sum algebraically to determine whether the cell will respond: if the net depolarization exceeds a certain threshold an action potential will be initiated near the point where the axon leaves the soma.

The action potential is unlike the graded potentials that gave rise to it: it is very brief, it is of fixed size and it is self-propagating. The membrane of the axon briefly becomes permeable to positively-charged sodium (Na^+) ions: the latter flow inwards and the internal charge typically reverses in sign, passing transiently from its resting value of -70 mv to $+20$ mv. A slightly slower, outward flux of positively-charged potassium ions (K^+), which pass through distinct channels in the membrane, soon restores the original polarization. Some axons are enclosed in an insulating *myelin sheath* which is interrupted regularly by *nodes of Ranvier*: here the depolarization leaps from node to node and the speed of conduction is increased.

Many sensory neurons correspond well with the classical description of the nerve cell, but the reader should be prepared to come across fundamental departures from the received pattern. Let us examine briefly a few of these variations.

(i) Neurons with axons shorter than 1 mm may not respond with action potentials. Of the six main types of nerve cell in the retina of the eye (see Fig. 3.2 and chapter 5 p. 101) the rods and cones, the bipolar cells and the horizontal cells respond only with graded potentials; and only the ganglion cells, the long axons of which form the optic nerve, respond with a train of action potentials. In the case of amacrine cells one or two spikes may be seen superimposed on a transient but graded depolarization.[1] These findings are well established for the retinae of amphibians, but graded potentials have also been recorded intracellularly in horizontal cells in the cat (Steinberg

1. The nature of the signals of amacrine cells is not yet clear. For discussion and references see Werblin (1974).

and Schmidt, 1970). It is an open question how common such neurons are elsewhere in the central nervous system.[2]

(ii) Not all synaptic transmission is chemical. Kaneko (1971) has shown direct electrical coupling of horizontal cells in the retina of the dogfish. Electrical connexions of this kind are thought to be associated with the *gap junctions*, or *tight junctions*, that have been described by anatomists and
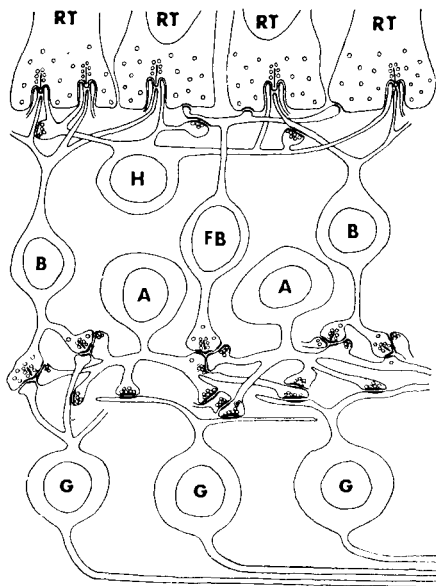
Fig. 3.2 A diagram to show the types of neuron and the synaptic arrangements found in vertebrate retinae. At the top of the figure are the receptor terminals (*RT*) and at the bottom are the ganglion cells (*G*), the long axons of which constitute the optic nerve. The receptors and the ganglion cells are connected, directly or indirectly, by bipolar cells (*B*, *FB*). Notice the laterally extending horizontal cells (*H*) and the axon-less amacrine cells (*A*). (From Dowling, 1970.)

at which the membranes of two cells are separated by as little as two nano-metres.[3] Gap junctions have been found in the primate retina (Dowling and Boycott, 1966).

(iii) Often there is no clear distinction between the receptive ("post-synaptic") and transmissive ("presynaptic") parts of a neuron. An important

2. The discrete and unvarying action potential seems to have evolved as a device for transmitting neural signals over a distance. Since nerves have a very much higher resistance than does, say, copper wire, their signals must be regularly amplified. If information were transmitted by varying the size of the depolarization, any slight error in amplification might be rapidly multiplied. (For discussion, see Rushton, 1961b.)

3. 1 nanometre $= 10^{-9}$ m.

example is found in the phenomenon of *presynaptic inhibition* (Fig. 3.3A). Here the axon of the presynaptic inhibitory fibre (I) forms a synapse on the terminal of a second axon (E) and acts by depressing the output of excitatory transmitter at the second synapse rather than by opposing the post-synaptic action of that transmitter.
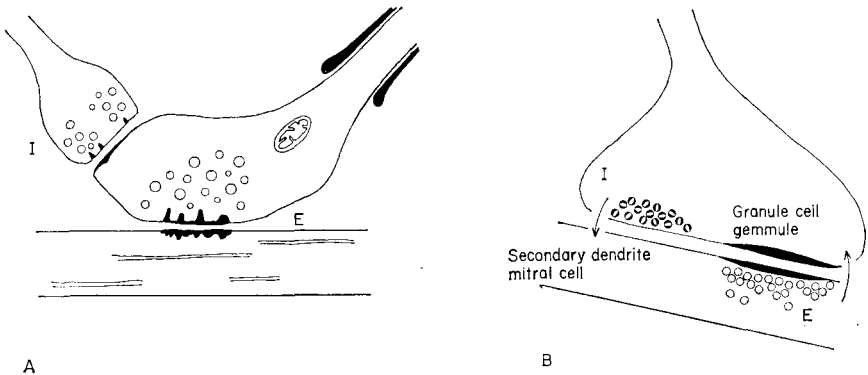

Fig. 3.3 A. Presynaptic inhibition.
         B. A reciprocal synapse in the olfactory lobe.

Impulses in the presynaptic fibre *depolarize* the terminal of the second axon. The size of action potentials in the latter is thereby reduced and the output of transmitter substance is in turn diminished.

A neuron may lack either a clearly-defined axon or clearly-defined dendrites. Thus the *granule* cells of the olfactory bulb[4] and the amacrine cells[5] of the retina are without axons: postsynaptic and presynaptic sites are intermingled on their dendrites.

(iv) It may be necessary to revise more radically the concept of a neuron and to question whether a nerve cell always does act as a single, integrated unit. Between the granule and mitral cells (chapter 5 p. 129) of the olfactory bulb (Shepherd, 1970; 1972; Rall, 1970) and between the amacrine and bipolar cells (chapter 5 pp. 103–106) of the retina (Dowling and Boycott, 1966) are found *reciprocal synapses*: two opposed synapses are found side by side and it is supposed that the granule and amacrine dendrites are providing immediate inhibitory feedback on to the mitral and bipolar cells respectively (Fig. 3.3B). It is possible that such *dendrodendritic* interactions may be quite local and that different parts of the inhibitory neuron may act independently. There may be cases where the cell body

4. The olfactory bulbs lie beneath the frontal lobes of the brain and receive the sensory nerves from the nose. (See chapter 5.)
5. "Amacrine" means literally "lacking a long fibre".

serves primarily a metabolic function and the physiologist who records only from the soma may gain a misleading or incomplete impression of the role of the cell. It is possible that the nervous system can economize by having one nutritive unit sustain more than one functional unit.

An instance where the parts of a neuron almost certainly do not speak to each other is provided by one of the types of horizontal cell found in the mammalian retina (Kolb, 1974). The dendrites of such a cell contact only cones (v. infra) whereas the axon terminals form an elaborately branched structure (the *terminal arborization*) that contacts only rods. These two parts of the cell are connected by a long and extremely slender axon that does not transmit action potentials and is thought to be incapable of transmitting graded potentials. That the cell body and the terminal arborization are indeed physiologically independent is suggested by the finding of Nelson *et al.*, (1975) that the two parts have different spectral sensitivities: when the retina was stimulated with red or blue flashes and electrophysiological recordings were made either from the cell bodies or from the terminal arborization of such cells in the cat, the terminal arborization, which draws its main input from rods, showed a proportionately greater sensitivity to blue light as would be expected. (See chapter 5.)

For a fuller discussion of the modifications that must be made to the neuron doctrine the book by Shepherd (1974) is recommended.

Receptors

To be regarded as specialized types of nerve cells are the *receptor cells* that are found at the first stage of any sensory system. The receptor can be defined as a neuron in which the generator potential is produced not by synaptic action but by particular environmental stimuli such as pressure, heat or light. The production of an electrical potential in response to stimulation is called *transduction*. Since most neurons respond to a chemical stimulus, transduction is not a peculiar property of receptors: an analogy can be drawn between the properties of the membrane of a receptor cell and those of the postsynaptic membrane of other neurons.

Some receptors, such as the hair cells of the ear (see Fig. 3.4A and chapter 5) and the rods of the retina (Fig. 3.4B), lack recognizable dendrites or axons and respond only with graded potentials that act directly upon the synaptic junctions. Other receptors, typically those found in the skin, muscles, joints and viscera of vertebrates (see chapter 5 p. 142), have long axon-like processes and the initial generator-potential gives rise to action potentials. A particularly well-studied example is the *Pacinian corpuscle* (Fig. 3.4C), a large pressure-receptor found throughout the body. Loewenstein and his collaborators have suggested that generator potentials and action potentials

arise at distinct sites within this receptor cell (Loewenstein, 1970). The cell is surrounded by a granular mass called the *core* and the latter is in turn enclosed in concentric layers or lamellae, which rather resemble the coats of an onion. By removing both the lamellae and the core (some 99·9 per cent of

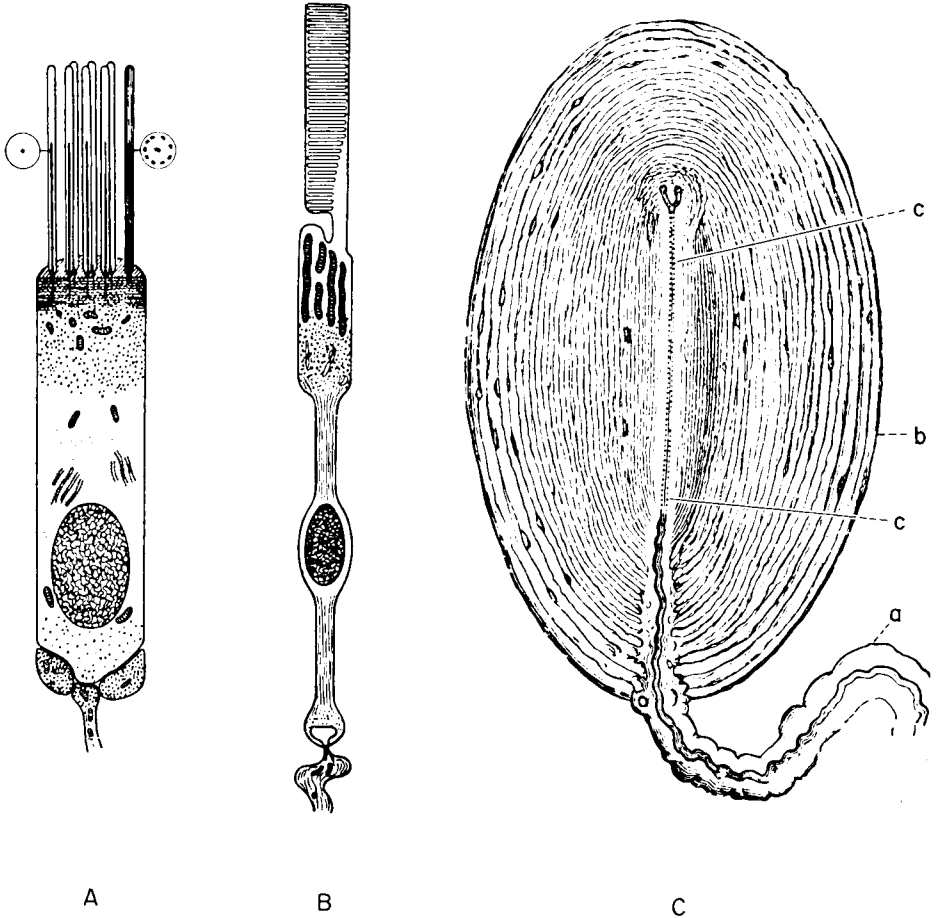A   B   C

Fig. 3.4 Auditory (A), visual (B) and pressure (C) receptors. The Pacinian corpuscle (C) has a long axon-like fibre; the hair cells of the ear (A) and the rods of the retina (B) lack such a fibre.

the entire corpuscle) Loewenstein was able to stimulate, or to damage, selectively different parts of the receptor cell. Local pressure at different points on the exposed ending of the receptor cell produces graded potentials that are independent of one another, whereas action potentials are produced

at the first node of Ranvier when the summed generator-potential exceeds a threshold. Since local distortion of the membrane of the nerve-ending produces only local increases in the conductance of the membrane, the total generator current increases with the area of membrane excited.

The visual receptors of vertebrates, the rods and cones, (Fig. 3.2) are unusual in that they respond to illumination with a hyperpolarization rather than a depolarization: the inside of the cell membrane becomes more negative (cf. chapter 5 pp. 104–106). The hyperpolarization is associated with an increase in the resistance of the membrane (Baylor and Fuortes, 1970) and it has been suggested that a transmitter is continuously released in darkness and is interrupted or decreased in illumination (Fuortes, 1971; Baylor and O'Bryan 1971).

Sensory Codes

Neurons transmit information. They also transmit action potentials. The reader is asked to distinguish carefully these two modes of discourse as we come now to discuss the ways in which the external world is represented in our sensory systems. We should also here anticipate later sections and mention that the chain of neurons that lies between a receptor and the brain is no longer regarded as a passive transmitter of coded information: analysis of the spatial and temporal pattern of stimulation may begin at the earliest stages.

Coding by Frequency

The *all-or-none* principle of nervous conduction, the principle that the action potentials of a particular neuron do not normally vary in size or duration, gained acceptance in the first decade of this century, but perhaps the most persuasive experiment was that reported in 1912 by Adrian: he showed that an impulse that has passed through a region of nerve, where its size is reduced by an anaesthetic or by cooling, will spontaneously regain its full strength when it re-enters normal nerve, provided only that it does succeed in getting through the region of decrement. The subsequent extension of the all-or-nothing principle to sensory nerves quickened the question of how the intensity of a stimulus is neurally represented. Previously it had been easy to postulate more or less of a *vis nervosa* or of an electrical potential. There now seemed two possibilities: as the stimulus increased in intensity either the number of active fibres might increase or the action potentials in a single fibre might become more frequent. It turned out that either or both of these principles might obtain in any particular sensory system. Experimental proof of coding by frequency came in Cambridge in 1925 when Adrian and Zotterman dissected a muscle

of a frog until it probably contained only a single stretch receptor. Recording from the afferent[6] nerve and suspending various weights from a thread attached to the muscle, they found that nerve impulses became more frequent as the weight increased. Instances of frequency coding soon multiplied, especially when the introduction of the microelectrode made it much easier to record from single fibres. In Fig. 3.5 we show two examples,
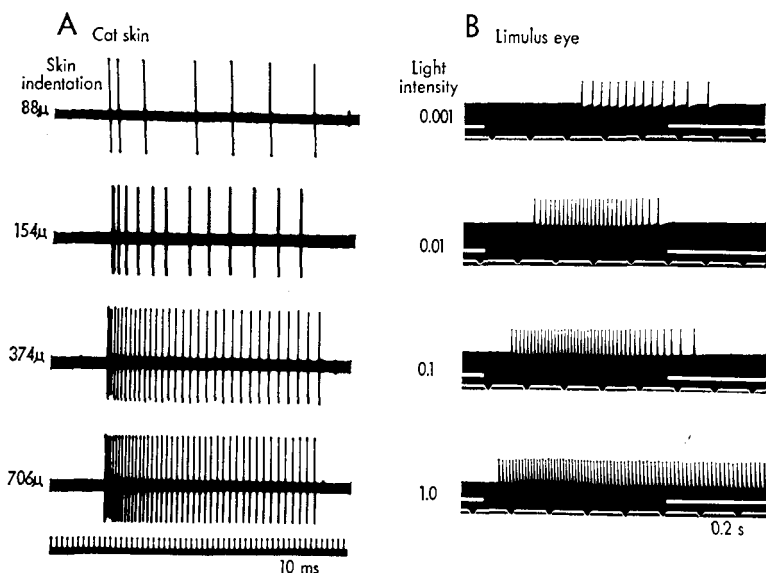

Fig. 3.5 The relation between stimulus intensity and the frequency of action potentials. The left-hand records (A) show the responses of a single afferent fibre in a cat's hairy skin as the indentation of the skin is increased. (From Mountcastle *In*: Eccles 1973.)
   The right-hand panel shows the response of a single optic nerve fibre of *Limulus* to flashes of light of increasing intensity. The duration of the stimulus is shown by the gap in the white bar. (From Hartline, 1934.)

one drawn from the somatosensory system of the cat and one from the visual system of *Limulus*. Two additional features of these records are worthy of the reader's attention. Firstly, *adaptation* occurs: the frequency of action potentials wanes as a steady stimulus is maintained. Secondly, in the records for the *Limulus* eye an inverse relation can be seen between the intensity of the stimulus and the latency of the first action potential.
   A vexed and notorious question is that of the mathematical relation

6. "Afferent" is used of fibres carrying signals to the brain; the antonym is "efferent".

between the intensity of the stimulus and the frequency of action potentials. Can we find in peripheral sensory nerves a basis for either the logarithmic or the power transforms discussed in chapter 2? It turns out that the psychophysiologist may secure almost any answer he wishes by choosing judiciously the modality he studies and the aspect of the response he measures. Thus, in a classic study of the *Limulus* eye, Hartline and Graham (1932) provided support for both logarithmic and power laws (Fig. 3.6).
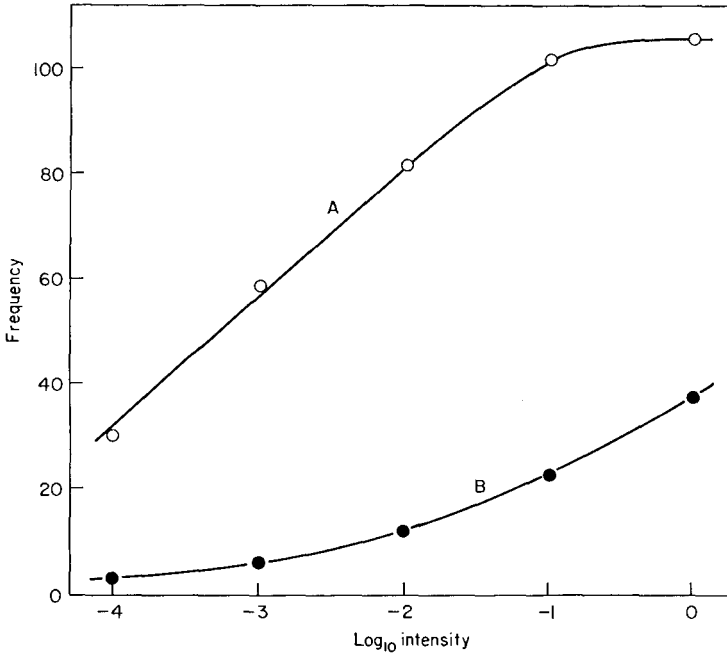

Fig. 3.6 The relation between the logarithm of the intensity of stimulating light and the frequency of action potentials (number per second) in a single optic nerve fibre of *Limulus*. Curve A shows the frequency of the initial maximal discharge. Curve B shows the frequency of discharge 3.5 s after the onset of illumination.

They teased out a single fibre from the optic nerve and recorded the frequency of action potentials produced by a wide range of light intensity. Curve *A* of Fig. 3.6 shows the frequency of impulses in the initial burst that follows the onset of light whereas curve *B* shows the frequency 3·5 seconds later: the former curve supports a logarithmic law, the latter a power law. A very similar choice of functions for the initial and steady states is available in the case of taste: during the first second of stimulation the

frequency of impulses in a single taste fibre of the rat is related to the logarithm of the concentration of a salt solution, but five seconds after the onset of stimulation the relation is better described by a power function (Sato, 1971; Ogawa *et al.* 1974).

However, whether a power function or a logarithmic function proves the better description, we can separately ask how well neural frequency is related to perceived magnitude and here the most remarkable results are those of Zotterman (1971). By a quirk of nature one of the taste nerves, the *chorda tympani*, passes through the cavity of the middle ear (see chapter 5
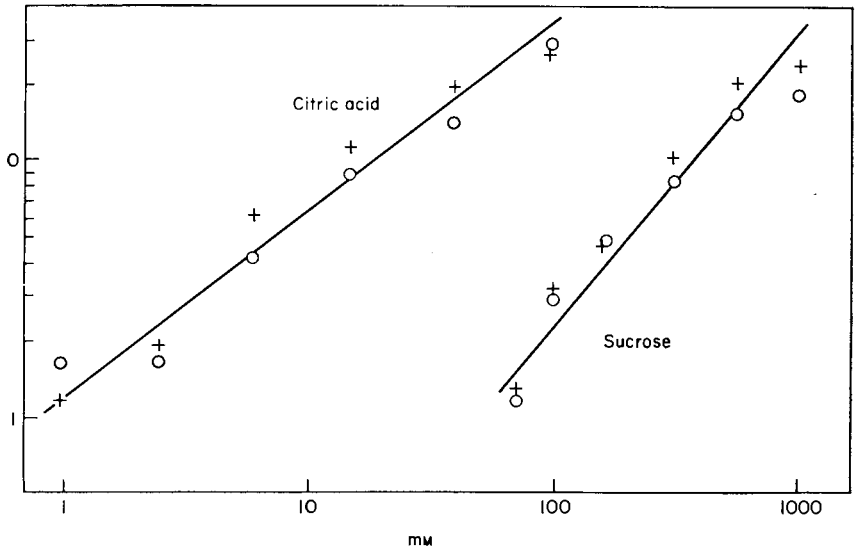

Fig. 3.7 Mean value of neural response (open circles) and of subjective response from two patients plotted against molarity of citric acid and sucrose solution.

p. 115) and during certain surgical operations it is exposed in a way that allows direct recording of the gross neural response to substances that are applied to the anterior part of the tongue. From a small number of patients, Zotterman and his collaborators have been able to obtain both neural recordings and psychophysical magnitude-estimations (see chapter 8) for the same stimulus solutions. Fig. 3.7 shows the intriguing agreement that has been obtained.

Before we leave the coding of intensity, we must be content to mention two complications. Firstly, we cannot predict *a priori* whether a particular physical dimension will or will not be represented by frequency within the nervous system: thus kinesthesis would not normally be classed among the

intensive dimensions, the sensory continua that vary in intensity, and yet the position of a joint appears to be represented by the frequency of action potentials (Mountcastle *et al* 1963, see also chapter 5 p. 154). Secondly, an increase in temperature (Poulos and Lende, 1970) or in visual intensity (Kuffler, 1953; De Valois *et al.* 1965b) may lead to a fall in the activity of some sensory neurons, whereas a decrease in intensity leads to an increase in activity.

Coding by Place

In 1825 in Germany a prominent citizen was attacked and beaten one night by a political enemy. He sued for damages. The plaintiff told the court that the night was so dark he could not see his hand in front of his face and the judge was led to ask how then he had recognised his assailant. "It was very easy", replied the plaintiff, "in the lightning that occurred when he struck me in the eye I easily recognised the evil face of the accused."

It is said that it was this incident, much discussed in the contemporary newspapers, that led Johannes Müller to formulate in 1826 his doctrine of "specific nerve energies": sensations of different quality arise according to which nerve is excited and not according to the stimulus that excites the nerve.[7] Thus, if pressure on the eyeball stimulates the retina, we perceive light rather than pressure; and most of the senses can be excited by electricity, although the resulting sensation varies with the modality stimulated. It is the specialization of the sense-organs that ensures that particular nerves are normally excited only by their proper (or "adequate") stimulus. Müller supposed that the specificity of the sensation associated with each modality had its basis either in the central portion of the nerve or in the termination of the nerve in a sensorium where the soul enjoyed intercourse with the brain.

Müller tended to consider each sensory modality as a whole, postulating just five specific energies, one for each of the senses; but John Elliot (1780),

7. Müller's priority has often been debated, but he himself acknowledged the many scattered anticipations of his doctrine that stretch back to Aristotle (Müller, 1838). Perhaps the most systematic anticipation is to be found in the writings of the obscure, neglected and ill-fated Englishman, John Elliot, whose scientific career was abruptly ended in 1787 when he was committed to Newgate for "wilfully and maliciously discharging two pistols" at the person of the unfaithful Miss Boydell (Elliot, 1780, 1786, 1787). Through a study of the subjective sounds and colours produced by mechanical irritation of the ear and eye the unhappy Elliot became one of the first to appreciate the existence of specific transducers: he argued that physical vibrations were not, as many of his contemporaries supposed, directly conducted along the sensory nerves. This physiological insight in turn led him to the realization that the physical spectrum might extend into the infra-red and the ultra-violet in the same way as there were acoustic stimuli of too high or too low a frequency for us to hear them. Much of the confusion that marked the physical theory of light and colour during the eighteenth century arose because few men were able to grasp that our eyes might be limited in their sensitivity and their discrimination.

Thomas Young (1801) and the mysterious G. Palmer (1786) had already suggested that different nerve fibres mediate the perception of different colours, and Müller himself was prepared to entertain a "place" theory for retinal position (Müller, 1838, Vol. 5, p. 351). It was, however, v. Helmholtz who most notably and most boldly extended the doctrine to individual fibres within a modality: he explicitly suggested that each of several thousand individual fibres in the auditory nerve was specific to a particular pitch. Yet the nature of the neural excitation was in every case the same (v. Helmholtz, 1863).

The representation of a stimulus attribute by which one of a set of neurons is active is now commonly known as *coding by place* (the reader may also come across references to the *labelled line hypothesis*). In Fig. 3.8A are shown modern *tuning curves* obtained by recording with microelectrodes from individual fibres in the cochlea nerve[8] (Evans, 1972): for each of several cells the intensity of a stimulating tone needed to give a detectable increase in activity is plotted against the frequency of the tone. Each fibre has its own *characteristic frequency* and the high-frequency side of the tuning curve is especially steep. How such fine tuning is achieved at so early a stage in the auditory system is an intriguing mystery (Evans, 1974a). In Fig. 3.8B are shown some analogous tuning curves for individual cells in the visual system. Here the abscissa is *spatial frequency*. It has been suggested in recent years, particularly by the Cambridge physiologists F. Campbell and J. Robson, that the visual system analyses the frequencies present in the spatial distribution of light on the retina just as the ear analyses the temporal frequencies present in a complex sound-wave. To the nature and function of this analysis of spatial frequency we shall return in the next chapter; and auditory analysis is further discussed in chapter 7.

In its simplest form the doctrine of specific nerve energies has never been acceptable; and it has seldom been held. As was fully appreciated by Müller himself (Müller, 1838, vol. 5, p. 272, *passim*) and, as has been especially emphasized by Gestaltist and phenomenological psychologists, our immediate perceptual experiences do not depend merely upon which sensory fibres are active, but are markedly influenced by our past experience, by our expectation and by interaction within and between sensory modalities. Many illustrations of this point will be found in later chapters of this book.

Although the doctrine of specific nerve energies needs to be qualified, it is the origin of most of the interesting problems in sensory psychology and we shall see in the next chapter that it is by no means dead: it has undergone a progressive encephalisation and reappears in the doctrine of the "trigger-feature detector" and that of the "grandmother cell". In thinking

8. The *cochlea* is the part of the inner ear that contains the auditory receptors.
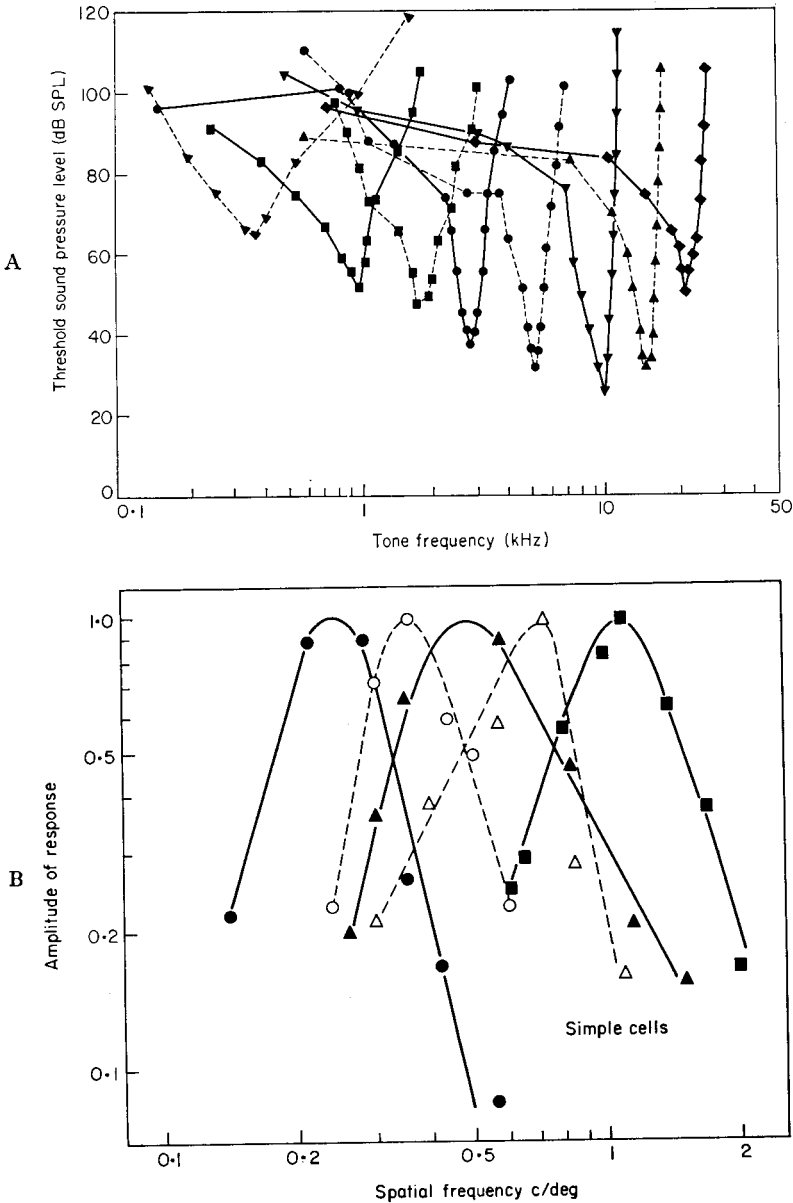
Fig. 3.8 Tuning curves for individual neurons in the cochlea nerve of the guinea pig (A) and in the visual cortex of the cat (B). Notice that in A it is the threshold that is plotted on the ordinate and sensitivity increases downwards, whereas in B the ordinate represents the relative size of the response to a stimulus of fixed contrast and varying frequency. (From Evans, 1972; Maffei and Fiorentini, 1973.)

C

about the doctrine it is well to recall the evidence, mentioned earlier in this chapter (p. 48), that the neuron may not always be the functional unit of a sensory system.

Coding by Spatial Pattern

In an important sense, absolute coding by place seldom occurs. Since no sensory neuron has an infinitely narrow tuning curve (cf. Fig. 3.8), a change in the activity of an individual neuron will always be ambiguous:
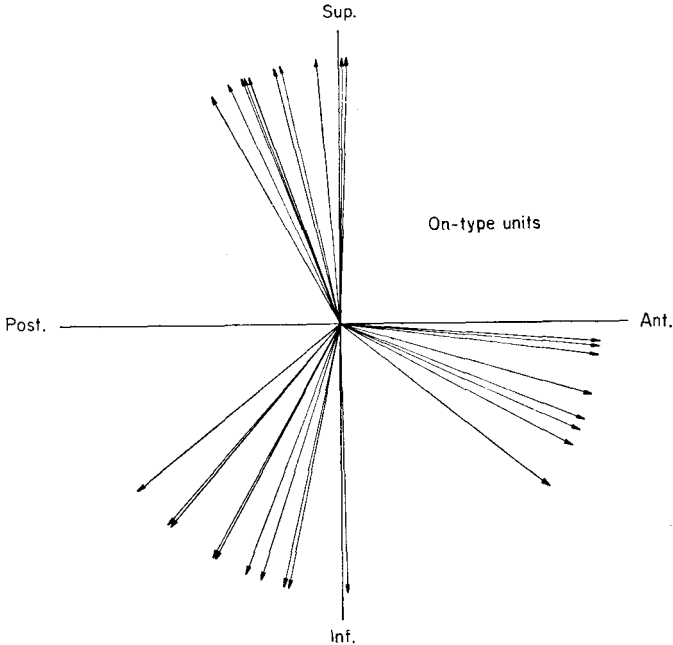

Fig. 3.9 The distribution of the preferred directions of on-type directionally-selective units in the rabbit retina. (From Oyster, 1968.)

a drop in stimulus intensity or a slight qualitative change may lead to exactly the same change in firing rate. A simple distinction between frequency and place is not enough: we must consider the pattern of activity in a population of neurons.[9]

The most celebrated illustration of this principle is to be found in colour vision: at the initial stages of the visual system, information about

9. Helmholtz was quite clear about this; see his "Tonempfindungen," 1863 p. 219: Es wird also schliesslich nur abhängen von der Feinheit, mit welcher die Erregungsstärke der beiden entsprechenden Nervenfasern verglichen werden kann, wie kleine Abstufungen der Tonhöne in dem Intervalle zweier Fasern wir noch werden unterscheiden können.'

wavelength is carried, almost certainly, by only three channels, each with broad sensitivities extending across most of the visible spectrum. Any individual visual receptor, any individual cone, is colour blind. It obeys the *Principle of Univariance* (Rushton, 1972): although its input may vary in wavelength and in intensity, its output varies only in one dimension—is *univariant*. Once a particular photon has been absorbed, all information about its wavelength (its energy-level) is lost. If stimulus intensity is suitably manipulated, different wavelengths can produce the same output from the cone. Thus information about colour is represented by the relative responses of different classes of cone (see chapter 6).

A nice analogy to the coding of colour can be found in the representation of the direction of movement in the rabbit's retina (Fig. 3.9). Some retinal ganglion cells in the rabbit respond maximally when an image moves across the retina in one particular direction, called the *preferred direction*. One class of such cells, those that respond best to relatively slow movement, have preferred directions that fall into just three groups (Oyster and Barlow, 1967). Such a population of units, each maximally sensitive to one of three preferred directions, would be able to represent unambiguously all possible directions of movement. Figure 3.9 is reminiscent of many geometrical representations of colour.

However, in the recent literature on vision only occasional lip-service has been paid to the ambiguity of the response of an individual neuron and the emphasis has been on *trigger features* (see chapter 4). It is in the case of the chemical senses that most has been made of coding by the pattern of activity in a set of neurons (Pfaffman, 1941; Ganchrow and Erickson, 1970; Sato, 1971). Most fibres of the *chorda tympani* seem to be concerned with more than one of the four classical qualities of taste—salt, sour, bitter and sweet. This can be seen in Fig. 3.10, which is taken from Ogawa *et al.* (1968) and which shows the mean responses of fifty fibres that have been ranked according to the strength of their response to salt (NaCl). The distribution among different fibres of sensitivity to each of the basic stimuli is not, however, entirely random; in both rat and hamster, for example, there are positive correlations among responses to hydrochloric acid (HCl), quinine ($C_{20}H_{24}N_2O_2$) and cooling and, in the hamster, sensitivity to sucrose ($C_{12}H_{22}O_{11}$) is negatively correlated with that to NaCl and positively correlated with that to warming. It is suggestive that in behavioural experiments those substances that prove least discriminable are those that produce similar patterns of neural activity in the *chorda tympani* (Marshall, 1968). It is also suggestive that the pattern of activity in a neural population may change as the concentration of a stimulus is increased, in a manner roughly similar to the way in man the reported taste of some substances changes as intensity is increased. Thus the pattern of activity for potassium
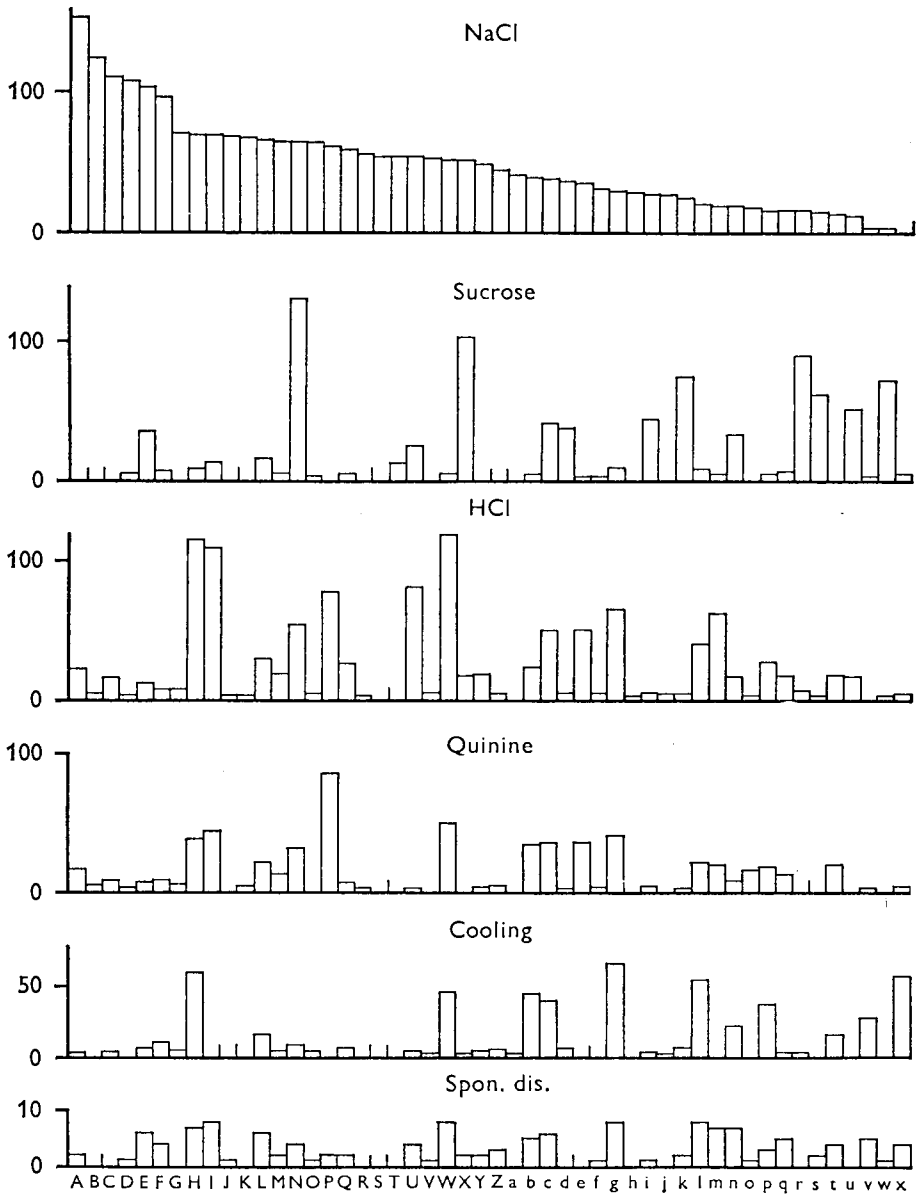
Fig. 3.10 Response profiles of fifty fibres in the chorda tympani of the rat (A, B, . . ., X). The fibres are arranged in order of their responsiveness to sodium chloride. The bottom row shows the spontaneous discharge. (From Ogawa *et al.* 1968.)

chloride (KCl) becomes more like that for salt as intensity increases and becomes less like that for weak sodium saccharine; and whereas at low concentrations the pattern for sodium saccharine (soluble saccharin $C_7H_4NNaO_3 S·2 H_2O$) has the characteristics associated with sweetness, it becomes more similar to those for NaCl and quinine as concentration increases (Ganchrow and Erickson, 1970).

Coding by temporal pattern

In principle, information could be carried by the pattern in time of action potentials within a single fibre or in a population of fibres. Such a hypothesis is most plausible where the stimulus information is itself intrinsically temporal: we could speak then of *temporal isomorphism*. There is indeed both psycho-acoustic and electrophysiological evidence for the *periodicity theory* of pitch perception, the theory that the period of a low-frequency sound-wave is represented directly in the cochlear nerve (see chapter 5 p. 119). Although any particular fibre may have a *best frequency*, a frequency to which it best responds, action potentials are found to be *phase locked*: they are most likely to occur in a fixed relation to the phase of a sinusoidal stimulus (see chapter 6) and thus they recur at integral multiples of the period of the stimulus. This is made clear in the histograms of Fig. 3.11 which are taken from Rose *et al.* (1967): the abscissae correspond to the intervals between successive action potentials and the ordinates to the number of impulses occurring at a particular interval. Notice that an individual fibre does not respond to every cycle of the stimulus even when the frequency is lower that 200 Hz; but we can imagine that in a population of fibres every cycle is represented. In the cat, phase-locking can be clearly seen up to 2500 Hz, but beyond 5000 Hz, if it is present, it cannot be detected in the records. That the human brain actually makes use of phase information is suggested by our capacity to localise low-frequency sounds purely on the basis of temporal differences between the two ears (see chapter 17 p. 463).

There has been a recurrent suggestion (but rather little evidence) that non-temporal qualities may be represented by temporal pattern (MacKay and McCulloch, 1952; Deutsch, 1955) and the hypothesis has most persistently been applied to the coding of wavelength (Troland, 1921; Fry, 1933; Myers, 1965). Thus Fry supposed that brightness was coded by the mean frequency of impulses but that this frequency could be modulated and that either the form or the period of the modulation-wave represented the wavelength of light. Saturation would correspond to the amplitude of the modulation. Most of the electrophysiological evidence now available to us suggests that colour is coded by place (De Valois *et al.* 1966; Zeki, 1973; Gouras 1974) and it is phenomenological evidence that is most often invoked
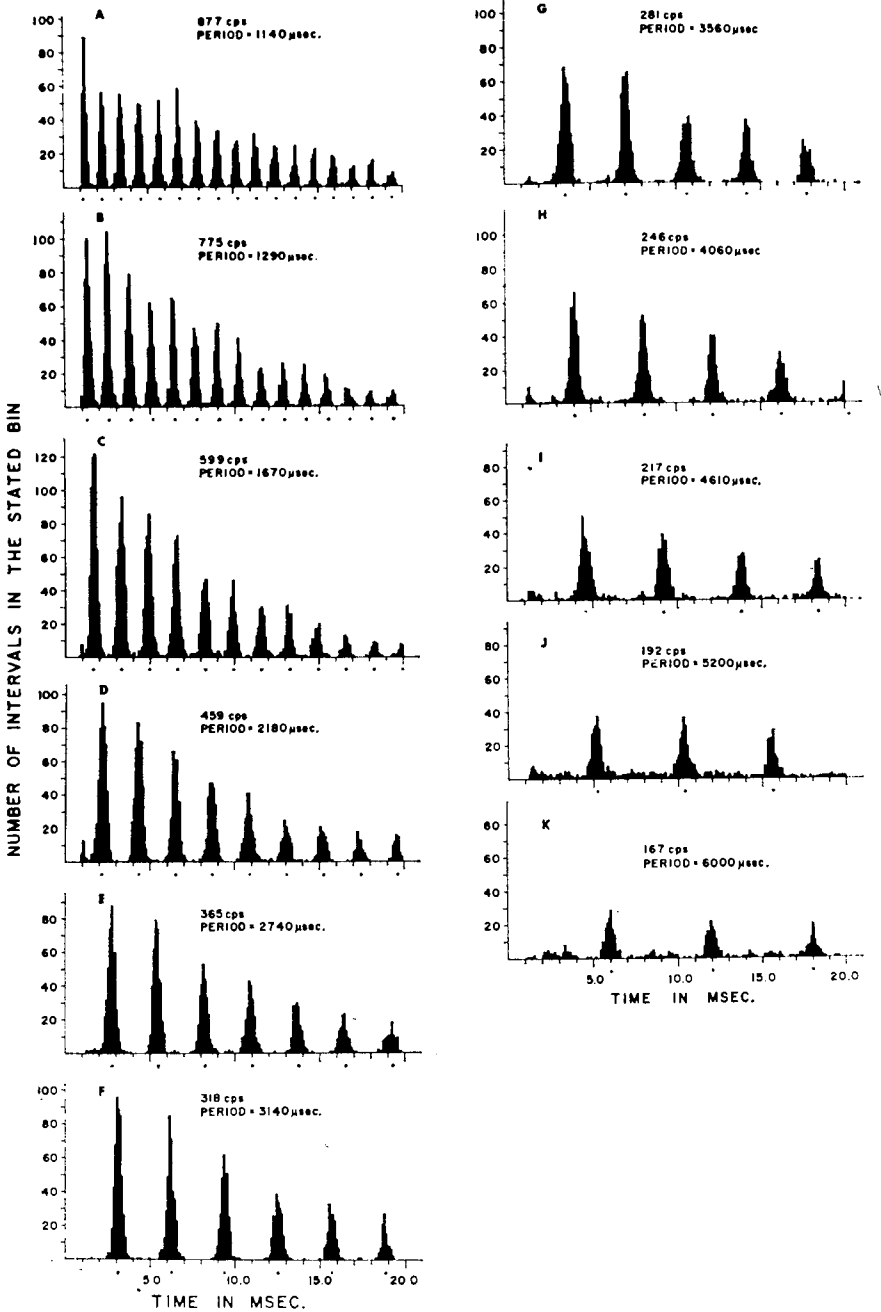
Fig. 3.11 Phase-locking in the responses of single fibres of the auditory nerve of squirrel monkeys. Each graph shows the distribution of interspike intervals for a particular frequency of the stimulating tone. The abscissa is the interval in milliseconds between successive action potentials and the ordinate shows the number of impulses occurring at each interval. Notice that the interspike intervals are clustered around integral multiples of the period of the stimulus. The best frequency for this particular neuron was 600 Hz.

in support of a temporal theory of colour vision. If a black and white disc such as that of Fig. 3.12 is rotated, one sees alternating bands of illusory
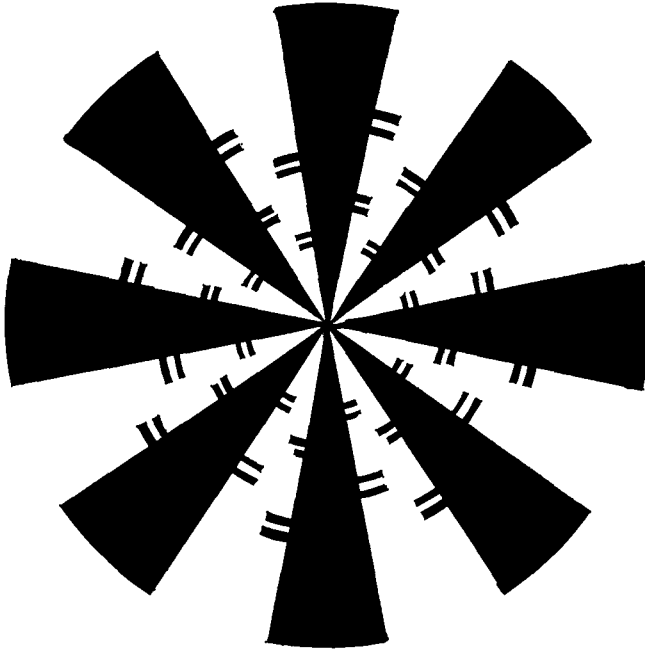
Fig. 3.12 A variant of Benham's top that has been designed to be rotated at 78 rpm. The reader is invited to photocopy it and try it out on his gramophone turntable (if you do not have access to a copying machine that reproduces solid tones, you will need to fill in the black areas; for, like the retina, most Xerox machines emphasize contours). If the disc is rotated clockwise, the innermost ring will be brownish-red and the outermost greenish-blue; if the sense of rotation is reversed the colours will be interchanged. Do not expect the illusory hues to be very rich; they are remarkable not for their saturation but because they occur at all. The best results are often achieved when the disc is lit by a tungsten reading lamp, but the effect can be obtained in daylight. It may be necessary to persevere a little, for the colours may become more salient after a little time. If you have difficulty, try different speeds, different viewing distances and different illuminations. You can also use this disc to examine the after-effect of seen movement. Fixate the centre of the disc as it rotates and then, after thirty seconds or so, switch your gaze to some stationary and textured object: it will appear to rotate in the opposite direction.

colours. These are the celebrated *Fechner-Benham colours* and it has been supposed that the sequence of black and white produces a neural sequence that mimics the code normally used to convey information about colour

(Fry, 1933; Festinger *et al.* 1971).[10] In judging this theory not too much weight should be placed on the dearth of electrophysiological evidence: the electrophysiologist tends not to see what he does not seek and it is only recently that the widespread introduction of small computers has allowed the detailed analysis of the temporal pattern of response.

In the case of stimulus properties that are usually held to be coded by the frequency of action potentials, subtler aspects of the temporal response may have been neglected. Werner and Mountcastle (1963), recording in monkeys from thalamic[11] neurons sensitive to the position of a joint (chapter 5 p. 152), have shown that the standard deviation of the intervals between successive action potentials is inversely and very highly correlated with frequency and thus carries the same information. This was true for both the spontaneous[12] and the driven activity of the cell, but the two types of activity could be distinguished by the slopes of the regression lines that related the frequency of impulses and the standard deviation of inter-spike intervals. Burkhardt and Whittle (1973) have gone further and have suggested that the degree of temporal jitter in the first of several spikes may carry information about stimulus intensity when the frequency of action potentials is unchanging: recording extracellularly from ganglion cells of the frog's retina and presenting brief flashes of different intensities, they showed that the variability of the latency of the first impulse could sometimes change markedly over a range of stimulus intensities where frequency was almost constant. Of course, a single ganglion cell does not have independent knowledge of when an individual flash occurred and thus cannot alone carry information about the latency of the response; but, if several such neurons respond in parallel, a later cell upon which they converge may respond the more strongly the more coincident the individual EPSP's. Burkhardt and Whittle's suggestion is important because it may explain a mysterious discrepancy between retinal physiology and human psychophysics: a dark-adapted man can discriminate the intensities of photopic[13] flashes over a ten-thousand-fold range (Whittle and

10. An alternative and even more venerable theory supposes that the different cone-mechanisms of the eye have different time constants. Mollon and Krauskopf (1973) provide some evidence that this is so. The latter paper and that by Festinger *et al.* provided further references.

11. The *thalamus*, a mass of cells in the centre of the brain (literally, and fancifully, the "couch" upon which each of the great cerebral hemispheres rests), is in part a relay station through which somatic and other sensory pathways reach the cortex and within which some sensory integration occurs.

12. Many sensory neurons are spontaneously active in the absence of an external stimulus. The reader can readily imagine that the synaptic influences upon the cell that produce spontaneous and driven activity are different and thus lend different statistical properties to its discharge.

13. *Photopic* vision is vision that depends on the cones of the retina; rod vision is referred to as scotopic. (See chapter 6, p. 110.)

Swanston, 1974), and yet such recordings as we have from the retinae of vertebrates suggest that single ganglion cells have, at any given level of adaptation, a dynamic range of only about one hundred to one (and the particular range does not vary much from cell to cell). A neural analysis of temporal jitter could perhaps extend this range.

Chung *et al.* (1970) have called attention to other ways in which the temporal pattern of discharge may be changed without a marked change in the average frequency of action potentials. They recorded from those fibres in the frog's optic nerve that discharge when a light is turned off, the "dimming fibres". In the dark the response of one class of dimming fibre is "bursty": groups of impulses are separated by silent intervals. The introduction of dim background illumination abolishes short inter-impulse intervals but leaves the longer intervals unchanged. In the case of another type of fibre a broad spectrum of inter-impulse intervals is recorded in the dark: dim illumination causes the distribution of intervals to become bimodal, so that only very long and very short intervals occur.

In assessing the plausibility of temporal coding the reader may wonder how a temporal pattern of action potentials could be recognized by later neural mechanisms. Two interesting possibilities arise from the fact that most axons end in hundreds or thousands of branches. If a second neuron, B, is to respond to one particular frequency of impulses in a presynaptic axon A, we might suppose that it receives direct excitation from one branch of A while a second branch excites an intermediate neuron that in turn itself excites B. If we further suppose that B responds only if it receives concurrent excitation over the direct and indirect pathways and that an impulse traversing the indirect pathway is subject to a fixed delay, then B will respond if the interval between successive impulses in A is equal to the delay introduced by the indirect pathway.[14] To prevent B responding to frequencies that are integral multiples of its preferred frequency we could add inhibitory circuits to our model or we could appeal to *refractoriness*, to the fact that a neuron remains inexcitable for a brief time after it has been depolarized. Neural refractoriness is indeed the crucial element in a theory of temporal pattern recognition proposed by Chung *et al.* The latter authors note that at each successive bifurcation the branches of an axon become finer, although the two new branches are seldom equal in diameter. It is known that refractory periods depend on axon diameter. Whether or not a particular branch of an axon will transmit a particular impulse will depend on the fibre's diameter and on the time since the last depolarization (as well as on the activity in adjacent fibres). Thus a temporal pattern will be converted into a spatial pattern of activity in the terminal branches of an axon.

14. Cf. the discussion of Exner's model of movement detection in chapter 4.

Thus it is clear that we cannot exclude temporal coding on the grounds that later neural mechanisms could not recognize a temporal pattern. However, we must end this section by mentioning two possible drawbacks of coding by temporal pattern. Firstly, since an impulse that immediately follows another is propagated with reduced velocity, a train of unequally spaced impulses will arrive more evenly spaced at the far end of a fibre (Brindley, 1970, p. 90). Secondly, in so far as a temporal pattern is used to represent non-temporal qualities of the stimulus it probably cannot also represent time itself: there must be a minimum sampling-interval and we must lose temporal resolution. However, our acuity in time is indeed very low and nature may compromise by providing us with specialized subsystems where accurate temporal information is required (Mollon, 1969): if a naive observer is to judge reliably the order of two events he needs an interval of as much as 100 ms*; and yet a difference of only 10μs* in arrival times at the two ears may change the apparent position of a click (Tobias and Zerlin, 1959) and an acuity of a similar order has been demonstrated electrophysiologically in single units of the inferior colliculus[15] (Rose *et al.* 1966). "Die Zeit erstarrt bei der Lokalisationsleistung zu Richtung im Raum" (Katz, 1944 p. 41).

Opponent Processes

Some sensory dimensions, such as brightness-darkness, direction of movement (cf. p. 73) and direction of curvature (cf. p. 74), have been described as *bipolar* or oppositional: the continuum has a central null-point at which neither of the complementary or antagonistic qualities are present.[16] Such dimensions are candidates for coding by *opponent process*. The presence of antagonistic physiological processes is suggested (though not proved) by the phenomenology of *simultaneous contrast* and of *complementary*, or *negative*, after-effects. A grey paper in a blue surround may look yellowish. If one fixates the centre of a disc such as that shown in Fig. 3.12 and allows the disc to rotate, stationary objects will afterwards appear to swirl around in the opposite direction. (On negative after-effects, see also chapters 4 and 6.)

The term *opponent process* has been used indiscriminately. Some who have used it have suggested that the same neuron may respond in two qualitatively distinct and antagonistic ways. In current neurophysiological usage, however, it usually refers to one of two less radical possibilities: (a) a special case of coding by frequency (or by graded potential) where opposite

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* A millisecond (ms) is a thousandth of a second; a microsecond (μs) is a millionth. Thus we are faced here with a remarkable discrepancy of four orders of magnitude.

15. A mid-brain auditory centre ("colliculus" means "hillock").

16. Probably the best discussion of oppositional dimensions is still that by Gibson (1937).

sensory qualities cause the response to depart in opposite directions (increasing or decreasing) from an intermediate level of response that is defined as the null or resting level because it corresponds to either a physical or a phenomenological null-point; (b) a limiting case of coding by place, or by spatial pattern, where stimulus values on an oppositional dimension are represented by the relative activity in pairs (or in paired populations) of neurons, which may be linked by mutual inhibition.

To illustrate the first of these two possibilities we may take the suggestion of Flock (1965) that the hair cells in the lateral line organs[17] of fish may give opposite responses when the sensory hairs are bent in opposite directions, depolarization in one direction and hyperpolarization in the other (Fig. 3.13). Another, and much studied, example of a graded potential that may
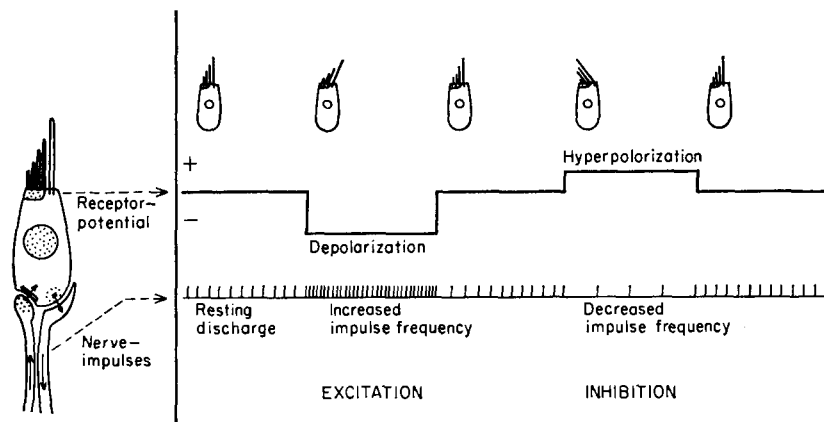

Fig. 3.13 Flock's theory of how hair cells operate, showing how the receptor potential and the frequency of nerve impulses depend on whether the sensory hairs are inclined toward or away from the Kinocilium.

decrease or increase according to the nature of the stimulus is the chromatic *S-potential* found in some vertebrate retinae. These potentials, first discovered by Svaetichin in the fish retina and originally thought to arise from cones, are now known to be the responses of one class of horizontal cells (Kaneko, 1970). The cell hyperpolarizes when the retina is stimulated with light from one part of the spectrum and depolarizes when it is stimulated with other wavelengths (see also chapter 5 and chapter 6, p. 169).

Of those sensory neurons that respond with discrete action potentials, many show a continuous discharge in the absence of any obvious stimulus.

17. The lateral-line canal organs in fishes are located in canals sunk below the skin and they detect movements of the surrounding water. The canals are filled with a viscous fluid that communicates with the outside water through narrow pores (See also chapter 5, p. 116.)

In principal, such a cell can signal by either an increase or a decrease in the frequency of action potentials. An interesting case is found in the afferent nerves from the *otolith organs*[18] of the thornback ray (Lowenstein and Roberts, 1950): tilting the organ in one direction from its normal position may increase the firing rate of a particular fibre and the opposite tilt may decrease it (Fig. 3.14A). Another and famous example is found in the response of some cells in the dorsal *lateral geniculate nucleus*[19] of the macaque monkey (De Valois *et al.* 1966): stimulation of the eye with light from one part of the spectrum will increase the frequency of action potentials; and stimulation with other wavelengths will reduce it (Fig. 3.14B).

However, in few such cases do we know for certain that both an increment and a decrement in firing-rate are treated as signals by later stages in the system. In the case of the so-called *opponent-colour* cells of the visual system, the inhibitory input, which causes the decrement in the spontaneous rate and which is assumed to arise from a distinct class of cones, may really serve to sharpen the spectral tuning of the cell rather than to generate a negative signal (Gouras, 1971). And usually, if neurons are found that respond with an increase to one attribute and with a decrease to its opposite, other cells are found that respond in the contrary fashion. Here we may have a situation akin to (B) above.

Three Final Remarks on Sensory Coding

We must end our discussion of sensory coding with three brief and general caveats.

Firstly, although we can correlate an aspect of the neural response with an attribute of the stimulus, we seldom know whether the aspect of the response that we examine is the one that is critical for later stages of the sensory system. We came across this difficulty in the case of the coding of intensity and again in the case of opponent processes.

Secondly, we may have neglected unduly the role of graded potentials: the transmission of information over long distances by means of discrete impulses may yet prove to be the dullest aspect of sensory analysis.

Thirdly, *coding* and *analysis*, usually confounded, may be worth distinguishing. Consider the two physiological theories of hearing that we briefly examined. When discussing coding by place we saw that auditory frequency could be represented by which neuron was active but we have also seen that low frequencies might be represented rather directly in the

18. The otolith organs are gravity-receptors and are concerned in the maintenance of an animal's equilibrium. (See chapter 5, p. 155.)

19. An extension of the thalamus, the lateral geniculate nucleus receives axons from the retina and projects in turn to the visual cortex of the brain.
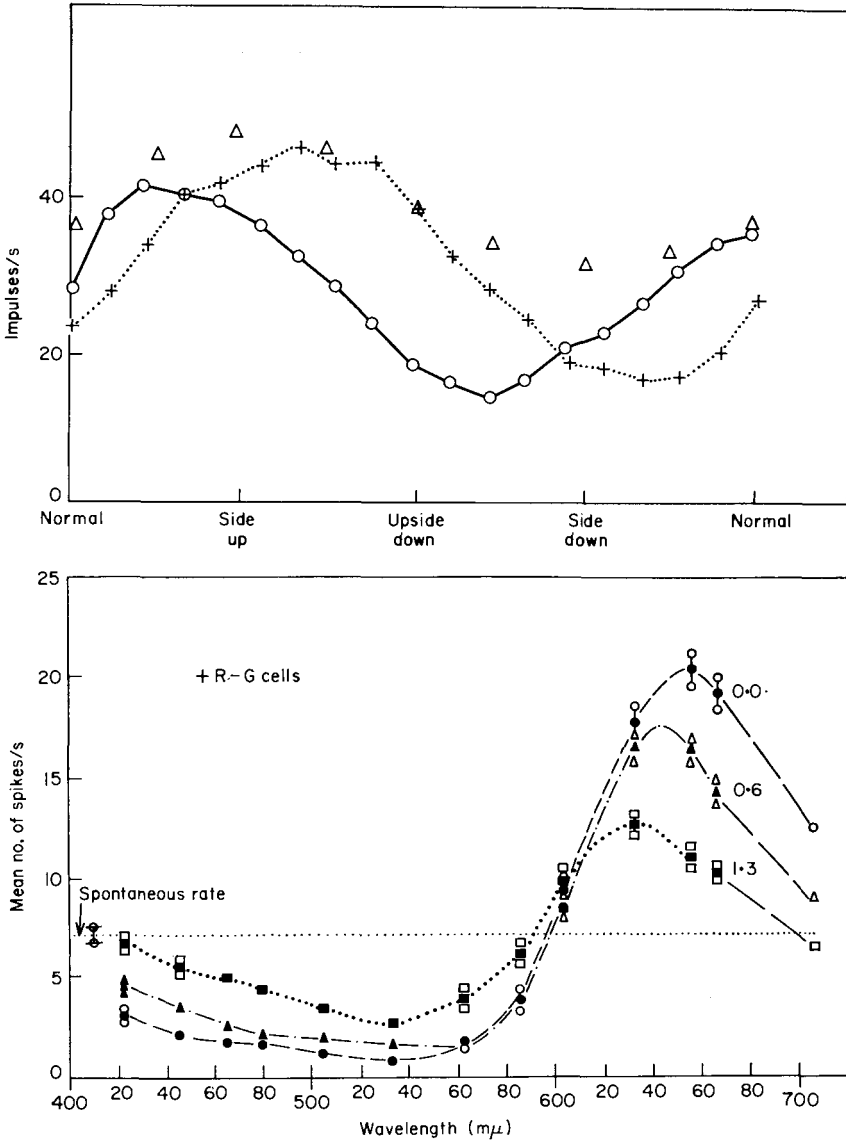
Fig. 3.14 Top. The responses of a single fibre of the utriculus of the thornback ray. The open triangles show the impulse frequencies recorded when the preparation was steady in a particular position. The circles and crosses show the frequencies obtained during continuous tilts in opposite directions. The solid curve is to be read from left to right and the dotted curve from right to left. (From Lowenstein and Roberts, 1950.)

Below. The responses of single cells in the lateral geniculate nucleus of the macaque monkey. All of these particular cells were excited by red light and inhibited by green. The dotted horizontal line in the figure shows the mean firing rate in the absence of stimulation. (From De Valois et al., 1966.)

temporal pattern of impulses. Many psychophysiologists, if pressed, would want to say that the two theories were not of the same kind and that in the former case some analysis, and even recognition, had already occurred, whereas a temporal or a spatial pattern was a mere code and would await recognition by a later neural mechanism. This, perhaps, is why place theories have proved so seductive to so many for so long. In the next chapter we shall return to this aspect of the doctrine of specific nerve energies.