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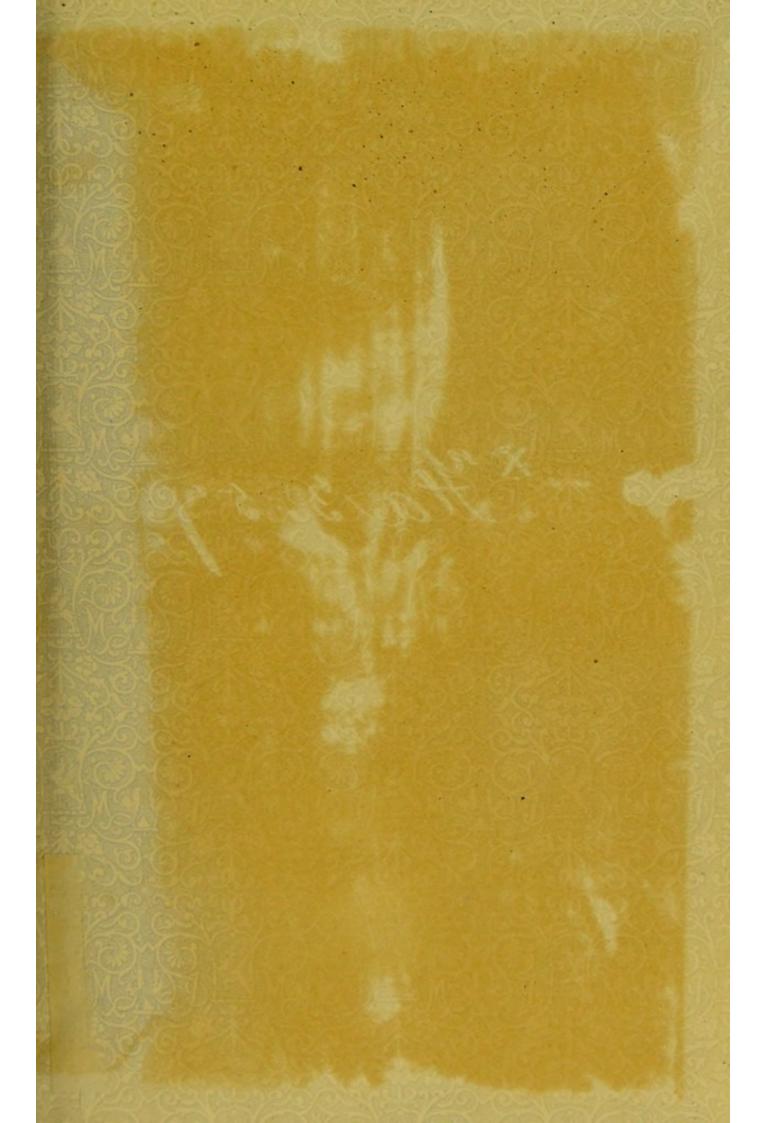
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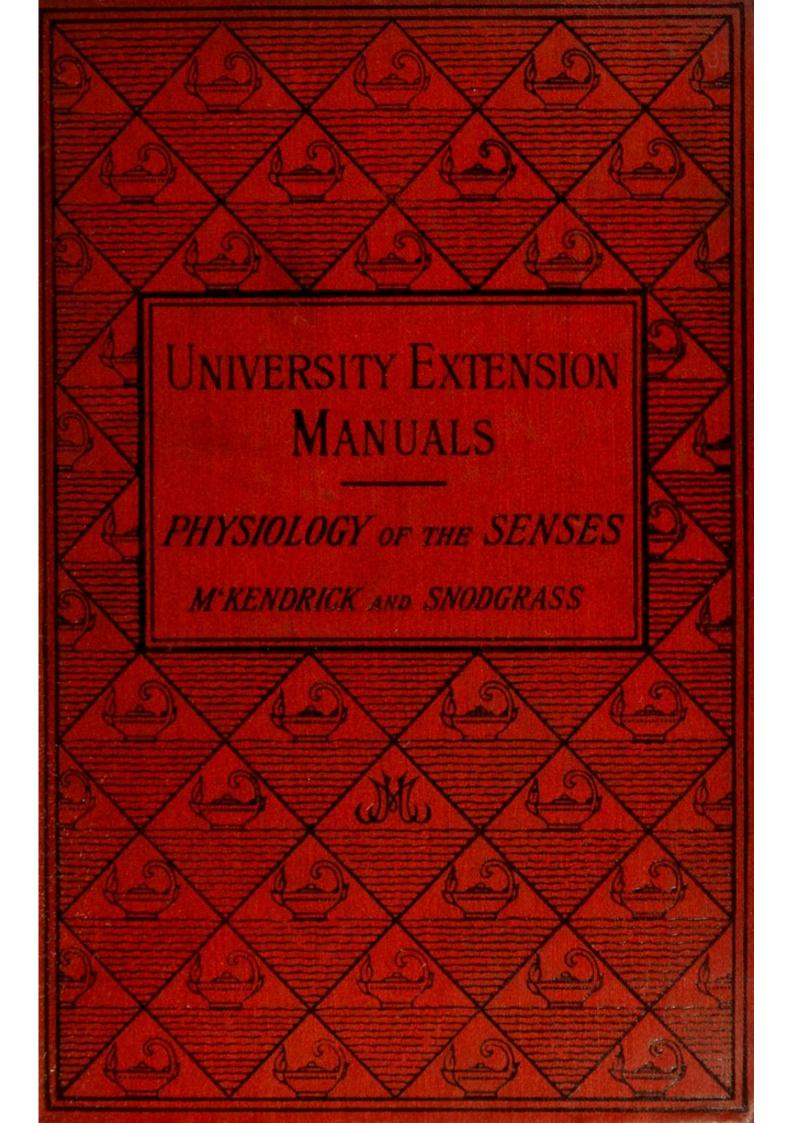Royal College of Physicians Edinburgh

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UNIVERSITY EXTENSION
MANUALS

——

PHYSIOLOGY of the *SENSES*

M‘KENDRICK and SNODGRASS

THE

PHYSIOLOGY OF THE SENSES

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The Manuals are also intended to be contributions to the Literature of the Subjects with which they respectively deal, quite apart from University Extension; and some of them will be found to meet a general rather than a special want.

THE

Physiology of the Senses

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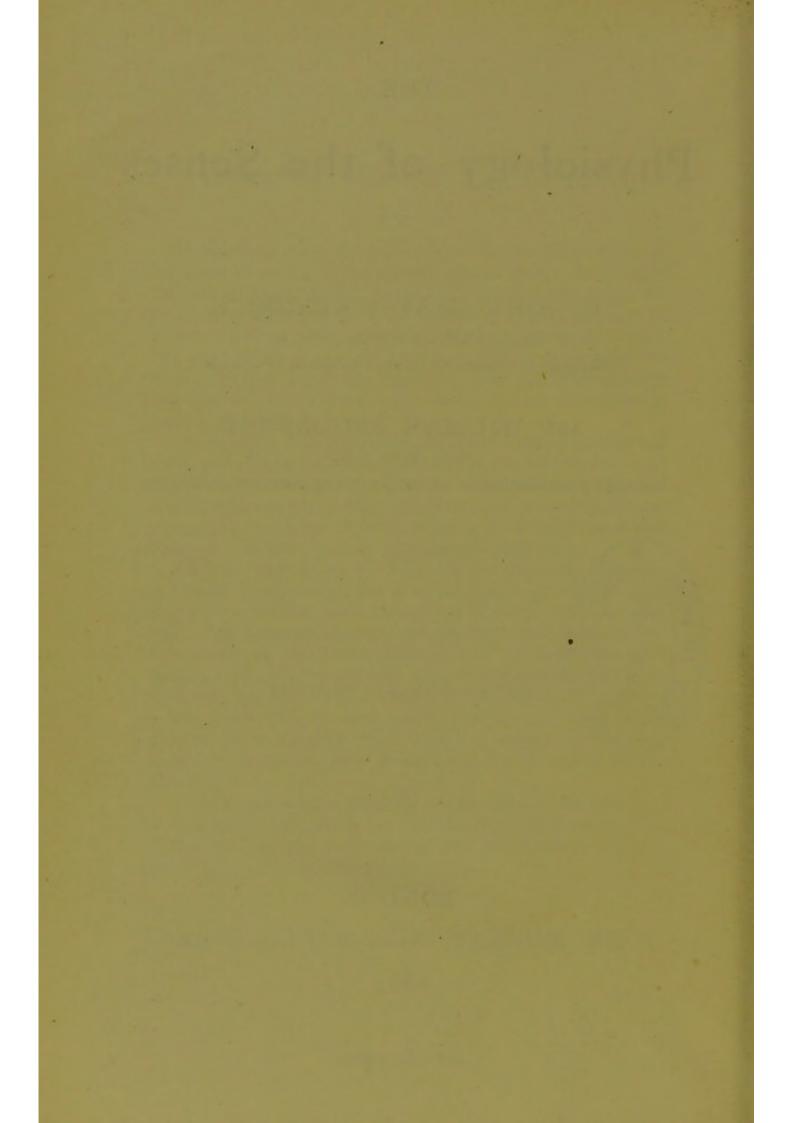
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WITH 127 ILLUSTRATIONS

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JOHN MURRAY, ALBEMARLE STREET

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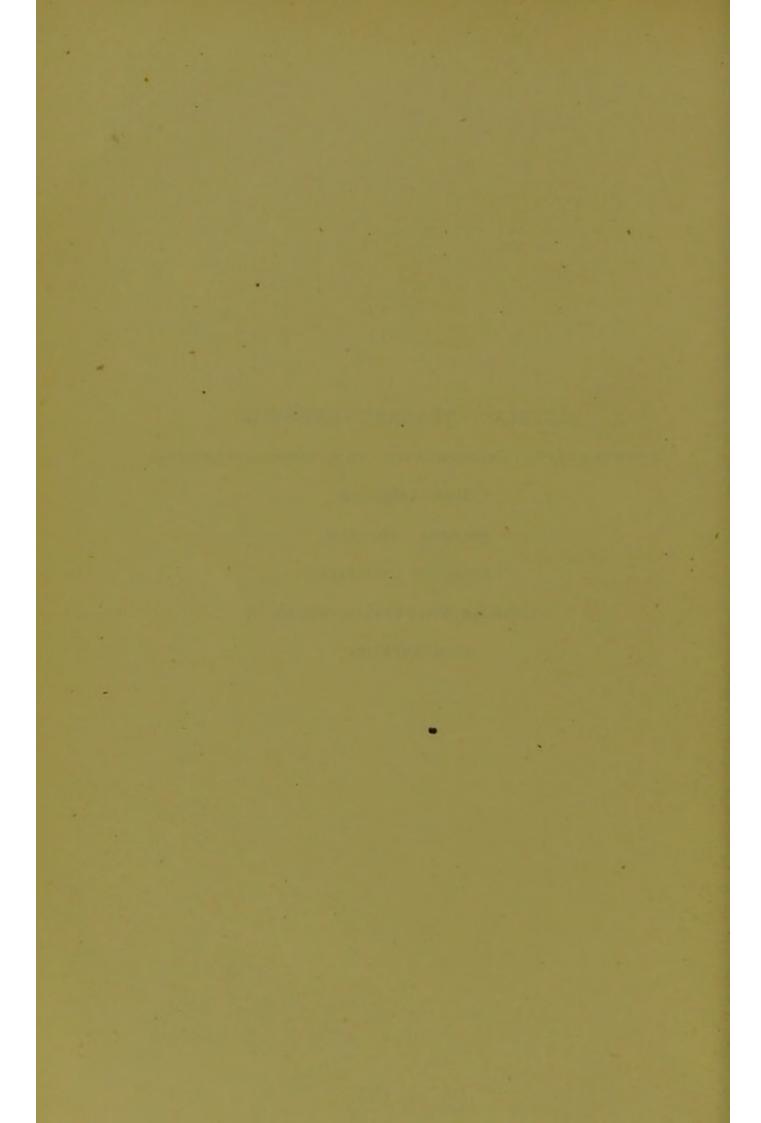
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AUTHORS' PREFACE

IT is the aim of this book to give a succinct account of the functions of the organs of sense as these are found in man and the higher animals. The Authors have refrained from discussing with fulness of detail either the comparative physiology of the senses or the numerous interesting questions of a psychological character that inevitably arise in connection with the study of the mechanism of sensory perceptions. Each of these aspects of the subject would require a volume for itself. On the other hand, a perusal of this volume, which has been written so as to be readily understood even by those who have not made physiology a special subject of study, will be a suitable preparation for entering upon the more recondite questions that underlie physiological psychology. The Authors have endeavoured to treat the physiology of the senses as fully as space would allow, and have also suggested comparatively simple experiments by which any one interested in the subject may test some of the statements for himself. They would also direct attention to the last chapter, in which an attempt is made to elucidate the nature of the physiological basis of sensa-

tion, in the hope that it may be found to be a contribution to speculative thought on this problem.

While every page has been subjected to the careful consideration and revision of both Authors, it may be mentioned that the Introduction and the sections on Sight and Hearing have been mainly written by Dr. Snodgrass.

J. G. M.
W. S.

UNIVERSITY OF GLASGOW,
March 1893.

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GENERAL INTRODUCTION

THE senses are called into play when the condition of the body has been affected to a certain degree by external or internal agencies. A flash of light, a piercing sound, a gentle touch, may so act upon the bodily organism as to be followed by a sensation or mental state, by the consciousness of an alteration that has taken place in the body or in its environment. Sensitiveness is a property of all animals, and possibly of not a few plants. Some animals, indeed, are so low in the scale of organisation as to have no special parts set aside for the reception of sensory impressions, but every part of their body seems alike fitted to recognise variations in its surroundings. As soon, however, as we pass to the higher grades of animal life we find certain parts or organs of sense whose duty is to keep the body in touch with its surroundings, and a nervous system which receives impressions and ensures the co-operation of all the individual elements of the body one with another.

In order that sensations may be felt, we are provided with a central nervous system, or sensorium, from which nerve fibres pass outwards to all parts of the body, and at the ends of the nerve fibres certain structures or terminal organs may be found, which are so formed as to be capable of responding to some special variety of impression. Thus the terminal organ of the nerve of vision is insensitive to

the vibrations which, by acting upon the ear, originate changes leading to the sensation of sound. But, as will be shown in greater detail hereafter, this receptivity is largely conditioned by the special function of each sensory nerve centre. For the sensorium does not act as a whole, but is differentiated so that one part is devoted to one sense, another to another; and when the nerves which lead to these nerve centres have been stimulated, it matters not what the nature of the stimulus to the nerve has been, the sensation experienced is always for each centre of one and the same kind. Thus the optical centre always gives rise to the sensation of seeing something, the auditory centre to that of hearing, the olfactory centre to sensations of smell, the gustatory centre to those of taste, and the tactile centre to touch. But, over and above these special forms of sensation, there are many vague or general sensations, such as those of heat or cold, of pain or fatigue, of pressure, resistance, and the like, which may seem to be felt in almost every part of the body; and although each of these has in all probability its special nerve centre, yet no special terminal organ seems to be necessary.

Special **terminal organs**, then, are developed for the senses of sight, hearing, smell, taste, and touch: their structure will be described when we consider these senses separately.

While we may readily distinguish these organs from one another by examination, either with the naked eye or the microscope, it is quite otherwise when we come to study the nerve fibres or nerve centres. So far as we can as yet determine, the nerve fibres which transmit the various sensory impressions are all of exactly the same composition and structure; and though in recent times it has been found possible to localise with considerable accuracy the centres which are related to special sensations, still it has not been possible to fix upon the exact microscopical

elements concerned ; in other words, physiologists cannot define the particular structure which alone is concerned in a given special sensation. We have no means of observing directly the minute molecular changes which go on in nervous substance ; we know only that this substance is very complex, and that during life it undergoes continual change, and is being constantly built up and broken down ; but neither the microscope nor chemical analysis has hitherto enabled us to determine why one centre should respond to one form of physical change, and another to another ; or why, when one part is stimulated, we have one kind of sensation, and when another part acts we have a different kind.

A brief consideration of the composition and structure of nerve fibres and of nerve centres will enable us, however, to understand better the mechanism required for the transmission and recognition of a sensory impression.

Nerve matter consists mainly of a variety of the substance called *protoplasm*, which is composed of a network of exceedingly fine fibres, the meshes of which are filled up with a fluid or semi-fluid substance. The exact chemical nature of protoplasm cannot be stated, for, in the first place, it is constantly varying during life by taking up nutrient matter of different kinds, and by throwing off certain waste substances, the product of vital action ; and in the second place, whenever we try to subject it to chemical analysis, it dies and is broken up into simpler chemical compounds. The most important chemical elements found in protoplasm are Carbon, Oxygen, Hydrogen, Nitrogen, Sulphur, and Phosphorus, and they are combined in such quantities and proportions as to form molecules of a highly complex nature. Now the more complex a chemical compound is, the more unstable it is ; or, in other words, the more easily may it be broken up, and resolved into simpler substances ; and hence we have in nervous tissues, which are largely com-

posed of protoplasm, a material which may be very readily changed when acted upon by external forces.

That a change does take place in nerve matter, when in action, has been inferred, although we cannot tell what the exact chemical constitution of nervous matter is, nor how it is changed. We know that for the efficient working of the nervous system there must be a full and unrestricted blood supply, bringing fresh nutrient matter to make up for waste, and oxygen, to promote chemical changes. The blood, again, must be free from impurities, or nerve action will be disordered. Surrounding nerve fibres we find a system of fine spaces or channels into which waste products of nerve action are poured, so as to secure their ready removal. When a nerve is acting we can also detect electrical changes corresponding in all probability to chemical transformations of nerve substance, but it must be admitted that no proof has yet been given of chemical changes in a nerve.

Nerves.—When a nerve has been kept in action for some time it apparently becomes fatigued—that is to say, the irritation of the nerve ceases to be followed by the usual result. Thus, if we irritate a nerve passing to a muscle, the muscle at first responds by contracting, but by and by the stimulations of the nerve fail to call forth contraction. We then say the nerve is fatigued, and we may suppose that its vital activity is diminished from lack of time to build up its wasted substance, or from the accumulation of waste products which prevent free action. Of late, however, physiologists are gradually coming to the opinion that there is no direct evidence of fatigue in the nerve itself, and that the phenomena on which fatigue depends really occur in the apparatus or structure at the end of the nerve. From this point of view, nerve fibres may be regarded as not subject to much tear and wear, and they may act more like metallic conductors conveying

currents of electricity, in which the current does not produce what are usually called chemical phenomena.

Nature of Nerve Current.—Structures known as nerve cells maintain the nutrition of nerve fibres. If a fibre is cut off from the cell with which it is connected it soon degenerates, and can no longer transmit a nerve current. But in a healthy nerve fibre a change known as a " nerve current " passes along it in both directions of its length from the point of stimulation. This change may be of a chemical kind, although, as already pointed out, there is no proof of this, and certain facts point the other way. We may imagine, on the chemical hypothesis, the fine nerve fibre as containing very complex and unstable molecules, which are readily broken up when acted upon by some external force. And just as when a match is set to one end of a train of gunpowder, the chemical change in the first granules of powder liberates energy, which gives rise to action in adjoining granules with disintegration of their substance and the formation of simpler compounds, so in nerve the change in one part or molecule may give rise to changes in adjoining molecules, and a so-called current will pass along the fibre. The fact that one current may follow another with great rapidity shows that the nerve substance is altered only in part and is quickly regenerated; but, on the other hand, the too frequent or prolonged application of a stimulus is followed by diminished power of conductivity by a nerve, or of receptivity in the nerve centres. It was at one time supposed that the nerve current might be a *purely* electrical change, and that it travelled with the lightning velocity of the electric current. And no doubt in our ordinary experience this seems to be the case. If the skin be touched with a red-hot iron wire, we seem at the same instant to feel the heat and pain. But by means of apparatus for registering minute intervals of time, and by

stimulating a nerve in different parts of its length, we have ascertained that the rate of the nerve current is much slower than it would be were it purely electric ; and while there may be electric disturbance due to chemical change of the substance of the nerve fibre, that disturbance is probably only a minor part of the phenomenon. The electric flash passes at the rate of thousands of miles, the nerve current never faster than 200 feet, per second.[1]

This rate of transmission of a nerve impulse must however be carefully distinguished from the time occupied by nerve centres in undergoing those changes which may or may not lead to consciousness or the perception of the sensation. Thus if it be arranged that a person shall make a signal as quickly as possible after seeing a flash of light, it is found that the time which elapses between the two events will be greater than would be required for the sensory impulse to pass to the sensory centre, and thence by efferent nerves to the muscles of the limb by which the movement is effected. There is time required for the supervention of the conscious state, and for the generation of the volition which leads to the movement. This interval has been called the *psycho-physical time*, because we have here to do not merely with changes in nerve matter, but also with mental conditions and acts. The psycho-physical time varies considerably under different circumstances. Thus, for example, less time will be required if the observer has merely to make a prearranged signal that he has become conscious of some given sensory stimulus —the so-called *perception time*—than if he be asked to decide between two sensations, as of a low and high sound,

[1] Recently it has been suggested that the nervous impulse is electrical, and that its velocity is slow compared with the velocity of electricity, because great delay occurs at certain points along the fibre, known as the nodes of Ranvier. No positive proof has yet been offered of this somewhat fascinating theory.

or a bright or dull colour. This latter task requires nearly half a second of time. Even longer time is involved when the observer has to make a choice as to which of two stimuli he shall signal—somewhat more than half a second being usually required.

On the other hand, it is possible that a stimulus to a sensory nerve may give rise to movement quite independently of consciousness and volition. In this case the sensory impulse affects certain nerve centres, either in the spinal cord or the base of the brain, which are able so to respond as to cause an efferent current to bring about some
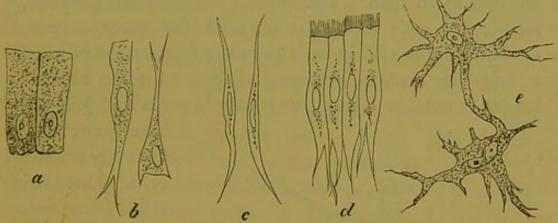
FIG. 1.—Various forms of cells. *a*, cylindrical or columnar; *b*, caudate or tailed; *c*, fusiform or spindle-shaped; *d*, ciliated, having fine filaments projecting from their free surface; *e*, stellate or branched.

muscular action. In this case the time occupied in the nerve centre is less than when volition is involved, but is, however, greater than would be required for the simple passage of the nerve current along a nerve. It amounts to about .05 of a second.

Origin of Nervous System.—We have said that the nerves are largely composed of protoplasm. But this substance exists in all parts of the body, at least in early life. When we examine microscopically the tissues of the body during the earliest periods of its existence, we find that it is composed of minute vital elements to which the name of cells or corpuscles has been given.

These cells are composed of protoplasm, and usually contain an exceedingly minute body, called the nucleus, whose composition is in certain respects different from that of protoplasm, and the cells may, moreover, be surrounded by a cell wall of less actively vital matter. At first the various cells of the body closely resemble one another, but as growth advances they become differentiated in form (Fig. 1) and structure in order to perform special functions, some cells going to build up the skin, some the muscles, some the nervous tissues and the like. In low forms of animal life, however, these cells are often not so highly differentiated as in man. Thus in the sea-anemone (*Actinia*), among the cells which go to form the outer covering or skin, we find certain cells from the free surface of which a hair-like filament projects, while from their attached border a number of processes pass inwards and join with like processes from other similar cells. These hair cells form rudimentary sense organs (Fig. 2).
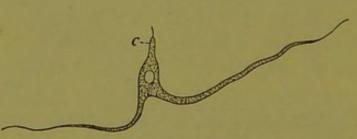
FIG. 2.—Neuro-epithelial cell from the upper nerve ring of *Carmina hastata*. *c*, sense hair passing to the surface; the two long thin processes join a ring of nerve fibres containing ganglion cells. (Hertwig.)

Further, in the network formed by the union of the processes just mentioned may be found cells which seem to have sunk inwards from the surface showing like processes, and regarded by Balfour[1] as an elementary sensory nervous apparatus. In general, it may be said that a study of the facts of development shows us that nerve cells appear at first upon the surface of the body, but that during the growth of the organism the cells become shut off from the surface; and in order to maintain their connection with the

[1] F. M. Balfour, *Comparative Embryology*, vol. ii. p. 332.

periphery, long processes called nerve fibres pass from the cells thus deeply embedded to the surface.

Nerve cells may occur singly, or more commonly they are found gathered together in groups called *ganglia*, the individual cells being known as ganglionic nerve cells. These ganglionic cells are more or less closely connected with one another by means of nerve fibres, and thus community of action is established.

In insects, for example, we find two rows of ganglia, the cells of which are united by nerve fibres both longitudinally and transversely. Sensory impressions pass by nerve fibres to these ganglia, and again, by other fibres passing out from these ganglia and ending in muscular tissue the movements of the body are regulated. In insects, too, it may be noted that the ganglia connected with organs of special sense, such as the eye or ear, are larger than the others. A further development of the nervous system arises through the fusion of ganglia with each other, so that the brain and spinal cord of vertebrate animals may be regarded as a vast number of ganglionic cells and nerve fibres bound into one consistent whole by a fine network of a connective tissue, and by an interlacing of nerve fibres.

The nerve fibres connected with the brain and spinal cord may be divided, according to their function, into two sets—those which transmit sensory impressions inwards, the *afferent* nerves, and those which have to do with the regulation of such changes in the body as lead to motion or secretion, and known as *efferent* nerves. Thus the *sensation* of pain, as, for example, toothache, originates from stimulation of a sensory or afferent nerve ; and the *movements* involved, say, in swallowing, from stimulation of efferent nerves passing outwards from the brain or cord.

Structure of Nerves and Nerve Cells.—The progress of research tends to show that fibres of varying function

always occupy a similar relative position in the central nervous system. As long ago as 1822, Majendie showed that the afferent or sensory fibres always pass into the spinal cord by what is known as the posterior root of a spinal nerve, while efferent or motor fibres emerge from its anterior aspect. See Fig. 3. But it has been found a matter of the greatest difficulty to determine accurately the course of fibres in the cord itself. When we look with the naked eye at a cross section of the spinal cord, we can see at a glance that it is made up apparently of two kinds of material, the outer part being whiter than the inner, which is
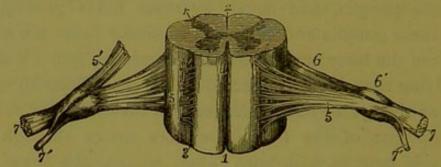
FIG. 3.—Portion of the spinal cord from the region of the neck, with roots of the nerves (slightly enlarged). 1, 1, The anterior median fissure ; 2, the posterior median fissure ; 3, the anterior lateral groove, from which the anterior roots of the nerves are seen emerging ; 4, posterior lateral groove where the posterior nerve roots enter the cord ; 5, anterior roots, to the right passing the ganglion ; 5′, anterior root cut across ; 6, posterior root with ganglion at 6′ : 7, the nerve made up of anterior and posterior fibres ; 7′, the first branches from the compound nerves. (Allen Thomson.)

of a gray colour. This whiteness is due to the fact that the protoplasmic substance of the nerve fibre, the part which conveys the nerve current, the so-called axis cylinder of the nerve, is, in the greater part of its length, surrounded by a sheath of fatty material, known as the white substance of Schwann (Fig. 4), which in bulk gives a creamy white appearance to a group of nerve fibres. This, in turn, is enclosed by a thin transparent covering known as Schwann's sheath, or the primitive sheath. But in the central parts of the cord the white substance is to a large extent absent, and we here find among the fibres great numbers of ganglionic

nerve cells. These cells vary much in shape, but are mostly of the form called multipolar, on account of the large number of poles or nerve fibres which spring from them (Fig. 5), while others, and more especially the cells in the posterior part of the gray matter, are often spindle-shaped or pyramidal (Fig. 6). These cells are in direct connection, for the most part, with efferent motor nerves ; and if they are destroyed by disease or otherwise, the nerve fibres with which they are connected quickly degenerate, and the parts supplied by them are paralysed. These are the cells which may be roused to action by the sensory nerves quite apart from any conscious sensation. If the foot of a person in profound sleep be lightly tickled, it will be drawn away without the sleeper being disturbed. If the middle or upper parts of the spinal cord be destroyed without injury to the lower part of the cord, while sensory impressions can pass to this lower part, and can set up changes in the nerve cells which lead to the movement of the lower part of the body or legs, these movements are performed unconsciously, and therefore cannot be controlled or restrained by an act of will, since the impression is not transmitted to the brain. Man is only conscious when certain parts of his brain have been
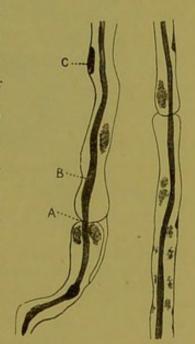
FIG. 4.—Nerve fibres. B, The axis - cylinder surrounded by the white substance of Schwann, which is interrupted at A, a node of Ranvier, and contains a nucleus at C. The external line represents the primitive sheath or neurilemma.

affected. Unless sensory impressions are transmitted to these parts, or unless these parts have been called into action by some variation in their chemical composition, there will be no consciousness. If these parts are ill-

developed and ill-nourished, sensation will be feeble or perverted; and if they are destroyed, the possibility of consciousness will be permanently lost.
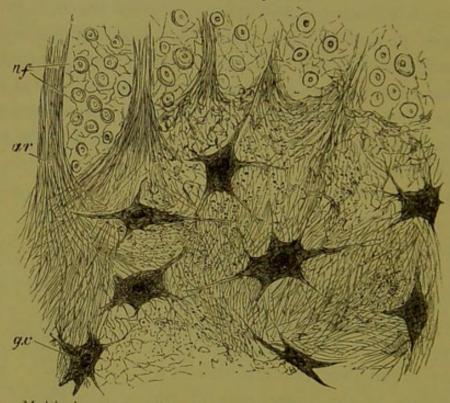
Fig. 5.—Multipolar nerve cells in the anterior part of the gray matter of the spinal cord. *ar*, anterior roots of emergent nerve fibres coming from the nerve cells, *gc*; *nf*, nerve fibres cut across.

PATHS OF NERVOUS IMPULSES

1. **The Spinal Cord.**—When we seek the exact paths, how-
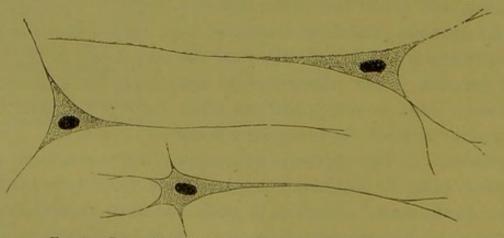
Fig. 6.—Pyramidal nerve cells found principally in the brain.

ever, along which sensory impulses pass up the cord to the brain, we are met by many difficulties. We can only infer that an animal feels some sensation; we cannot enter into its consciousness of it. When the foot of an animal is pinched we believe that it feels pain because of some movement it makes, or some sound it utters, and because we know that a similar pinch to our own feet would cause a sensation of pain in us. But if, by careful and gradual operation, the greater part of the brain has been removed and the animal has survived, we find that the application of the stimulus may still educe movements or cries, while we cannot suppose the animal to be conscious of what it does. Another difficulty in the determination of the sensory path is that of isolating or destroying a certain part of the cord without injury to other parts, and without setting up irritation or shock which may lead to erroneous inferences. It is impossible to reach the deeper parts of the cord without injuring the more superficial, and the individual fibres are so small that it is very much a matter of guess-work whether we have cut the parts we wish or not. We know that sensory fibres enter at the posterior part of the cord, that some of these fibres pass directly into the gray, some into the white, matter; but hitherto it has not been possible to trace these fibres to any extent, on account of their bending away from the plane of section. It has been observed that at different stages of development certain strands of fibres are superposed, as it were, on others; and by examining sections of cords of animals at different ages the connections of special tracts have been traced.

Another method of study which has afforded valuable results is based upon the observation that when nerve fibres have been cut off from the nerve cells with which they are connected, the fibres quickly degenerate; and thus it has been found possible to trace the line of de-

generation for some distance. Similarly, in cases of loss of sensation in disease, it may be possible to discover, by *post-mortem* examination, the part which has suffered; but it will readily be seen that this, and the above-mentioned methods of research, can only afford rough and inaccurate results. One interesting fact we can conclusively settle from cases of disease in the human being is, that different kinds of sensations travel by different paths in the cord. A lesion which may cut off the possibility of feeling pain in a given part of the body, may leave it still susceptible to sensations of heat and cold; or the sensation of touch may be present while the sensation of pain cannot be aroused. From this we see that nerve impulses giving rise to sensations of touch, of pain, of temperature, of the muscular sense, must pass upwards to the sensorium by different paths, one of which may be cut off while the others remain. We may also learn from such cases that the sensory fibres, after passing up the cord, terminate in the opposite side of the brain from that in which we seem to have the sensation.

Where the sensory fibres cross from one side to the other is not known. The experiments of the older physiologists, and more especially those of the French observer, Brown-Sequard, seemed to show that the sensory fibres cross to the other side almost immediately after their entrance into the cord; but later workers in this field of research maintain that the majority of the sensory fibres do not cross at once, but pass up almost to the base of the brain before they change sides. In some parts of the cord, however, the fibres do cross from the right to the left side, and *vice versa*, or decussate, as it is called; so that sensory fibres from the right side of the body pass to the left side of the brain, and from the left side of the body to the right side of the brain. It is probable that they do not extend

continuously, however, as single threads, from the periphery to the sensorium. We have seen that the stimulation of a sensory nerve, say in the right foot, may give rise to changes in the lower part of the cord, and hence to involuntary movements of which we are totally unconscious ; or it may cause a sensation by stimulation of the brain. Now we do not find nerve fibres branching except at their endings. Hence we are led to conjecture that the majority of the sensory fibres pass immediately into the gray matter of the cord and there become connected with nerve cells. From these some fibres may pass to the cells in the cord connected with efferent nerves, while other fibres pass upwards to the brain.

To give a slightly more definite idea of the paths pursued by the different sensory fibres, we may refer to Fig. 7, in which we have a diagrammatic representation of a transverse section of the spinal cord divided into tracts or areas, which are to be understood as indicating bundles or columns of fibres running side by side and communicating freely with one another, but each containing, in the main, fibres of special origin and function. Thus, for example, the nerve fibres which convey *painful* impressions apparently pass into the gray matter of the cord, for if the gray matter be completely divided at any given level of the cord, there will no longer be a sensation of pain when the parts are injured which send nerve fibres to the cord below the level of section. From the gray matter fibres probably pass outward and upward in the anterior root zone (*ar, ar'*, Fig. 7). Suppose the gray matter were divided close above the region where sensory fibres from the legs pass into the cord. Then we might lacerate the foot, and though we might feel that it was being touched, we would have no sensation of pain from the operation. We distinguish, therefore, between *analgesia*, or that condition in which painful sensations cannot be excited, and *anæsthesia*,

or the state in which we are insensitive to tactile sensa-
tions. It will readily be understood that analgesia of any
part of the body might lead to disastrous consequences.
Thus among paralytics we find patients who feel no pain
in, and are unable to move, the lower limbs. They will
allow some part, such as the heel, to remain motionless on
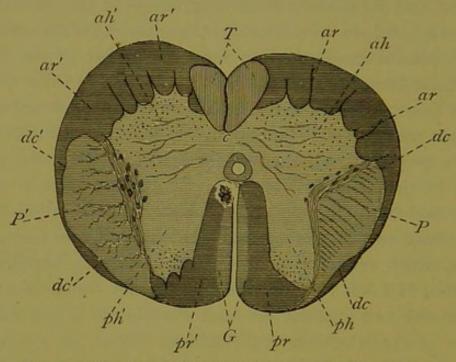
FIG. 7.—Transverse section of human spinal cord. *ah, ah'*, anterior horns of
gray matter; *ph, ph'*, posterior horns of gray matter; *ar, ar'*, anterior root
zones; *pr, pr'*, posterior root zones; P, P', pyramidal fibres of lateral columns
(mainly motor in function); T, columns of Türck (motor in function); G,
columns of Goll; *dc, dc'*, direct cerebellar tract; *c*, anterior commissure;
below *c*, central canal of cord lined with columnar epithelium. (Ross and
Young.)

a couch so long that the circulation of blood in it ceases,
and its vitality may be seriously impaired. Similarly
where the front of the eyeball has become insensitive to
pain, the presence of small foreign bodies in the eye being
no longer felt, such bodies accumulate in the eye, interfere
with its well-being, and give rise to ulceration and de-
struction of the ball. To the healthy body pain is nature's
indicator of danger; the burnt child dreads the fire.

Tactile impressions in man pass upward, for the most part, in those columns of the cord which lie between the posterior roots of the spinal nerves. In this part, besides the paths for the stimuli which give rise to the sense of touch, we have probably also those which excite the sensations of heat and cold, of pressure and resistance, and of tickling. That this is so is most distinctly shown by the study of changes in the cord during the progress of the disease known as *locomotor ataxia*—a disease, one prominent symptom of which is disorder of the power of walking. Patients subject to this disease usually suffer, in the earlier stages, from severe pains shooting apparently into the legs, and due to inflammatory changes in the posterior horns of the gray matter. Then the areas immediately adjoining these (*pr, pr,'* Fig. 7) become diseased, and the muscular sense is impaired, so that there is not the accustomed guide to the muscles as to the amount of force required for movement, and the patient tends to lift his feet too high and to set them down with a stamp. He is not able to judge accurately as to the weight of his limbs, nor of heavy masses attached to them. Then the delicacy of his sense of touch becoming impaired, he has the feeling, even when walking on rough ground, as if he were treading on velvet. No longer receiving the wonted guiding impressions from his feet, he must watch with his eyes his movements in walking, directing his steps by his sense of sight, and if he shuts his eyes he staggers and falls. His muscles act spasmodically, independently of each other, without due co-ordination. At first the motor power remains, but eventually it too may become involved, and the patient is paralysed for motion as well as sensation.

In some animals, such as rabbits, it has been supposed that the tract for tactile sensations is in the lateral columns ; but all experiments on the sensory tracts are very apt to

be deceptive from the difficulty of interpreting the resulting phenomena.

As the sensory tracts pass upward in the spinal cord they are somewhat modified in size and in relative position, owing to intercommunication and the entrance of fresh fibres, but on the whole the strands preserve the same general relationship. But just as the cord enters the cavity of the skull it enlarges, to form a portion about an inch and a quarter long, known as the *bulb* or *medulla oblongata.* Here the arrangement of the white and gray matter is much modified, and mixed with the fibres conducting nerve impulses to and from the brain we find several ganglionic centres which are of vital importance. Here, for example, we find centres which preside over the great functions of respiration and the circulation of the blood, besides such as regulate the acts of mastication and of swallowing, vocal utterance, the secretion of saliva and of sweat. To these centres come efferent impulses from all parts of the body, impulses which may never indeed give rise to conscious sensation, but which, acting on the nerve centres of the medulla, so stimulate and affect them as to keep them constantly ready to respond to the needs of the organism. Under all the ordinary circumstances of life, whether we be sleeping or waking, these centres pursue the even tenor of their way. Influenced by some great emotion, at some great crisis, when all the energy of our being is centred upon one thought or one swift effort, these centres may stand in abeyance for the moment ; nay, the pang may be so great that the vital chain is for ever broken, but as a rule we are unconscious even of the results of their activity. All the great vital functions go on unheeded, unless when some cause arises to interfere with their free and unimpeded action. But their influence over conscious life is none the less potent ; without their

action the great receptive centres of the brain would be powerless. The freedom we have from the necessity of consciously watching over these things alone renders a higher life possible.

2. **The Medulla.**—The difficulties experienced in ascertaining the paths of sensory influences in the cord are great, but they are vastly increased when we come to examine the *medulla*. We have, in fact, to depend mainly upon anatomical and pathological research for what little we know, and it is only possible to separate certain fibres which we can positively affirm to be associated with motor functions.

The upward bound fibres passing through the medulla may either go to the ganglia at the base of the brain, to the cerebellum (Fig. 9, B), or to the cerebral hemispheres. A complete description of the structure and functions even of the parts of the brain devoted in the main to the sensory activities, is beyond the scope of the present work. We can only attempt to give a mere outline of the cerebral mechanism.

3. **The Cerebellum.**—The *cerebellum*, or little brain, is connected by strands of nerve fibres both with the cord and with the brain proper ; and though in all likelihood it acts as a co-ordinating or arranging centre for the nerve currents that induce complicated movements, we have no evidence that it contains any sensory centres. No pain is felt when its substance is injured, nor can we detect any alteration in general or special sensitivity. Some physiologists have advanced the view that it may be connected with the muscular sense. The staggering gait and irregular movements characteristic of an animal whose cerebellum has been destroyed, indicate a loss of a regulating centre which normally is at work. We may understand this if we reflect for a moment upon the complicated nature of the movements we habitually

perform. Walking, for example, involves the consensual action of many groups of muscles, each of which must act exactly at the proper time and with most delicately adjusted force. The acquirement of the power is only gained after many attempts, and the mere preservation of the upright attitude of the body is only possible when the sensory impressions from the feet and limbs are duly transmitted and take their place in the complex sum of afferent impulses. Of the means or methods by which the multifarious peripheral impressions are correlated, and after the nerve centres are excited, the adjustment is carried out and the different muscles set in regulated motion, we know nothing. We do not even think how a movement is to be made. We simply will something to be done, and it is done ; but of the intervening causal chain we are quite unconscious. We think of the end and not of the means. In that sense our movements are automatic ; and it is interesting to note that the more any given movements are practised, the more automatic they become ; and the more purely automatic they are, the more accurately are they adapted to their aim. Illustrations of this are afforded us in all employments where a certain small piece of work is done to the exclusion of all else. The hands will work busily while the thoughts are far away. In such a case we have the same sensory impression travelling to the same centre, giving rise to the same outflow of energy, and along the same efferent channels, and an unconscious memory of what has been required in the past enables us to determine without effort the necessities of the present. But vary the surroundings a little, and new conscious efforts must again be made, and the work requires longer time and conscious effort and attention. It is possible that the necessary fusion of impressions takes place in the ganglia at the base of the brain, and messages to the cerebellum act through its cells and fibres as through

distributing centres to the muscles; but of this we cannot at present speak with certainty.

4. **The Pons.**—The medulla, as we have seen, is con-
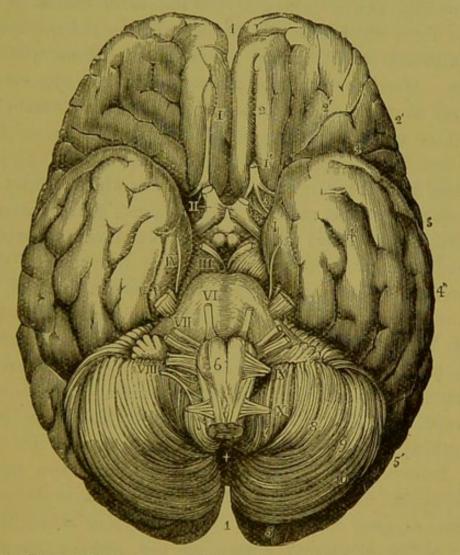
FIG. 8.—Base of the brain. 1, 1, The longitudinal fissure dividing the hemispheres; 2, 2′, 2″, the anterior lobe of the brain; 3, fissure of Sylvius; 4, 4′, 4″, the middle lobe of the brain; 5, 5′, posterior lobe; 6, bulb or medulla oblongata; 7, 8, 9, 10, the inferior surface of the cerebellum. The figures I to IX indicate cerebral nerves: thus I is the olfactory bulb removed on the right side; II is the optic nerve with decussation; V, the sensory nerve of the face and part of the scalp; VII, the auditory nerve; VIII, the glossopharyngeal with sensory fibres from mouth and throat; III is on a crus cerebri; VI and VII are placed on the Pons Varolii; X, the first nerve emergent on the neck.

nected with the cerebellum; the rest of the fibres passing upwards from it enter a structure known as the *pons Varolii*,

or bridge of Varolius (Fig. 8, VI, VII ; Fig. 9, C), so called because numerous fibres pass through it from one side of the cerebellum to the other, and these form a transverse prominence like a bridge across the main course of the nerve fibres which pass up and down. In the pons, as in the medulla, we find many nerve centres mixed with the fibres. Here, for example, among others are situated the centres of origin of the great nerve—the fifth cranial (Fig. 8, V), or main path for general sensory impressions from the face and scalp, of the auditory nerve (Fig. 8, VII) coming from the ear, and of the nerves which control the movements of the muscles of the face. Fibres carrying painful, thermal, and tactile impressions probably pass up through the centre of the pons, where also some of them decussate. The motor fibres are mainly in front of, and the nerve centres behind, these thermal and tactile paths.

5. **The Cerebrum.**—Fibres from the pons and cerebellum pass to the *cerebrum*, or brain proper, by the connecting strands known as the *cerebral peduncles*. These slope upwards and forwards, and the anterior and lower fibres branching outward as they enter each side of the brain are known as the legs of the brain, or *crura cerebri*. The upper and back part of the peduncles is composed mainly of gray matter, and when seen from above shows four slight elevations known as the *corpora quadrigemina*. It is of interest to note that the corpora quadrigemina receive nerve fibres from the eyes through the *optic tracts*, and are concerned in the mechanism of vision. Destruction of one side causes blindness in the eye of the opposite side, with loss of power of accommodation of the pupil of the eye. Whether they are the seat of conscious sensation is, however, very dubious. They are small, and hidden away under the superposed cerebral mass in man, but the corresponding structures

known as the *optic lobes* in birds, reptiles, and fishes are large and important relatively to the rest of the brain. The most attractive hypothesis is that they act in man as centres for the fusion of impressions coming from the eyes by the separate nerve fibres, and for the regulation of bodily or ocular movements dependent upon visual impressions, but
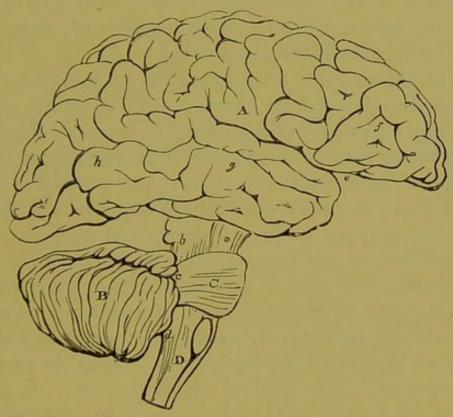
FIG. 9.—Plan in outline of the encephalon, or central nerve system within the skull, as seen from the right side. A, Cerebrum; B, Cerebellum; C, Pons Varolii; D, Medulla oblongata; *a*, crus cerebri or cerebral peduncle; *b* superior, *c* middle, *d* inferior cerebellar peduncles; *b* is placed just in front of the corpora quadrigemina; *e*, fissure of Sylvius; *f* anterior, *g* middle, *h* posterior lobes of cerebrum.

that for conscious vision the gray matter of the cerebrum must be likewise affected.

In front of the *corpora quadrigemina*, and lying at the base of the brain, lie two large ganglionic masses on each side of the middle line—the *thalami optici* and the *corpora striata*—between which passes an important set of fibres from the crura, known as the *internal capsule*. Many

sensory fibres are believed to enter the optic thalami, coming either by way of the corpora quadrigemina, the crura, or the internal capsule, while other fibres join the thalami with the cerebral hemispheres. From their connection with the corpora quadrigemina we find, as might have been expected, that injury to the optic thalami, more especially in their hinder parts, causes visual disturbance, but the thalami are probably connected with many other sensory fibres besides those of vision.

The human brain, when stripped of its investing membranes and viewed from above, is seen to consist of two masses or hemispheres of a grayish colour externally, a deep furrow running between the hemispheres from before backward, at the bottom of which is a broad band of white nerve fibres, the *corpus callosum*, joining the two masses. The surface is not smooth, but thrown into numerous folds, convolutions, or *gyri*, between which lie depressions of varying depth called *sulci*, or fissures. Such convolutions are absent from the brains of many of the lower forms of animals, and even in man, in the earliest periods of life, and they are present in the adult brain in order to allow for increased area of the cerebral surface or *cortex*. At a first glance these ridges and furrows seem to be quite irregular and devoid of arrangement, but a study of the comparative appearances of many human brains leads us to see that though there may be slight divergencies in the number, depth, and regularity of the convolutions, these are largely formed on the same plan. We see that the brain may be regarded as made up of several lobes (Fig. 10), which are named according to the part of the cranium in which they lie, and that each lobe has a definite number of ridges and furrows, the names of which are given in the explanation of Fig. 10. So long as it was supposed that the brain acted as a whole, and that no special function was associated

with any particular area, the relationship of the convolutions was deemed of comparatively little importance. Now,
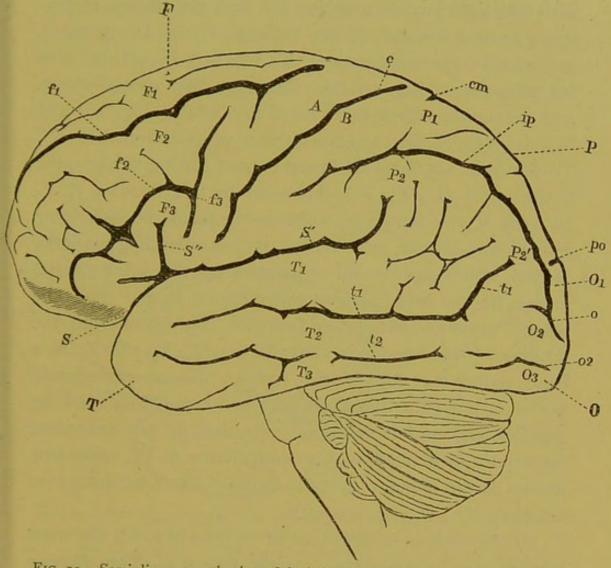
FIG. 10.—Semi-diagrammatic view of the left side of the brain. F, Frontal lobe ; P, Parietal lobe ; O, Occipital lobe ; T, Temporo-sphenoidal lobe ; S, fissure of Sylvius ; S′ horizontal, S″ ascending branch of the same ; c, central sulcus or fissure of Rolando ; A, ascending frontal ; B, ascending parietal convolution ; F_1, F_2, F_3, superior, middle, and inferior frontal convolutions ; f_1, f_2, superior and inferior frontal sulcus ; f_3, præcentral sulcus ; P_1, superior parietal lobule ; P_2 supra-marginal gyrus, and $P_2′$ angular gyrus, parts of inferior parietal lobule ; ip, intra-parietal sulcus ; cm, end of calloso-marginal fissure (see Fig. 11) ; O_1, O_2, O_3, first, second, and third occipital convolutions ; po, parieto-occipital fissure ; o, transverse occipital fissure ; o_2, inferior occipital fissure ; T_1, T_2, T_3, first, second, and third occipital convolutions ; t_1, t_2, first and second temporo-sphenoidal fissures. (Ecker.)

however, it is well to know the names and positions of the various lobes, convolutions, and furrows, so as to be able to

understand descriptions of special areas of the surface. The *lobes* are named from the special bones of the skull with which they come into contact, and are known respectively as the Frontal, F, the Parietal, P, the Occipital, O, and the Temporo-sphenoidal, T, lobes. It will be seen by reference to Fig. 10 that there are two specially deep and well-marked fissures, those of Rolando (*c*, Fig. 10) and of Sylvius (S, S′, Fig. 10), the latter of which is branched, S″. To the front are three well-marked and constant ridges, the frontal gyri (F_1, F_2, F_3), separated by two furrows, f_1, f_2. In front of the fissure of Rolando we have the ascending frontal convolution, and behind it the ascending parietal, behind which again, and separated by the intra-parietal furrow, lie two other parietal convolutions, P_1 and P_2. The second parietal convolution becomes continuous with the superior of three temporal convolutions, T_1, T_2, and T_3, by a bend round the end of the Sylvian fissure immediately below P_2, known as the supra-marginal convolution, and the superior and middle temporal convolutions are connected posteriorly by a small angular convolution at P_2', commonly known as the angular gyrus. Parts of three occipital convolutions, O_1, O_2, O_3, are seen.

Of the various fissures that of Sylvius is much the most marked, the others being merely furrows. The Sylvian fissure really indicates that the posterior part of the hemisphere has in the process of development been bent round and packed away under the frontal and parietal regions. When the Sylvian fissure is opened up there is seen a small pyramidal mass of gray matter—the *island of Reil*—the convolutions of whose surface, being hidden when the brain is in its natural state, are known as the *gyri operti*. The letter S lies external to the spot in which these convolutions are to be found.

When the two hemispheres are separated by an antero-

posterior section in the median plane of the body, each internal surface is seen to present certain fissures and convolutions, the principal of which are—(1) the *marginal gyrus* F$_1$, which is really the internal aspect of the superior and ascending frontal convolutions and ends posteriorly at the fissure of Rolando ; (2) the *gyrus fornicatus*, G*f*,
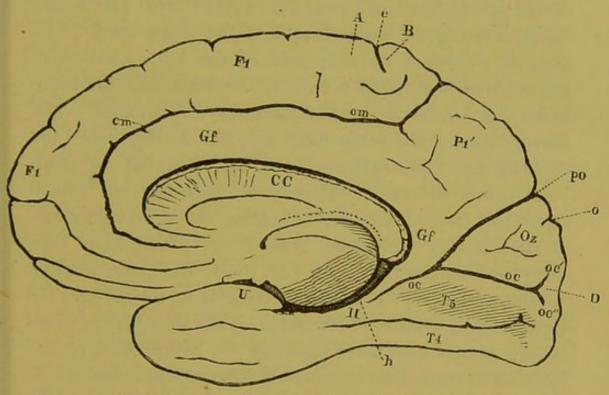
FIG. 11.—Semi-diagrammatic view of the right cerebral hemisphere in its median aspect. CC, corpus callosum divided vertically ; G*f*, gyrus fornicatus ; H, gyrus hippocampi ; *h*, sulcus hippocampi ; U, uncinate gyrus ; *cm*, callosomarginal fissure ; F, first frontal convolution ; *c*, end of central sulcus (fissure of Rolando) ; A, ascending frontal ; B, ascending parietal convolutions ; P$_1'$, præcuneus ; *po*, parieto-occipital fissure ; *o*, transverse occipital sulcus ; Oz, cuneus ; *oc*, calcarine sulcus ; *oc'*, *oc''*, its superior and inferior branches ; D, descending gyrus ; T$_4$, lateral occipito-temporal gyrus ; T$_5$, median occipito-temporal gyrus. (Ecker.)

separated from the marginal convolution by (3) *cm*, the *calloso-marginal fissure*, and continuous posteriorly with (4) H, the *gyrus hippocampus*, so called from the peculiar appearance of the gray matter at this part. It is continued into (5) U, the *uncinate* or hooked-shaped *gyrus*. P$_1$ marks the internal aspect of the parietal convolution, or

præcuneus, and it is separated by *po*, the parieto-occipital fissure, from (6) the *cuneus* or wedge-shaped convolution, whose lower surface is separated by the calcarine fissure, *oc*, from (7) the *temporo-occipital convolutions*, three in number, which lie at the base.

Each cerebral hemisphere has a central cavity or ventricle, which is continuous with a small canal that passes through nearly the entire length of the spinal cord. The internal substance of each side of the brain consists of nerve fibres joining the surface of the brain with the lower nerve centres, or one part of the brain with another. The nerve fibres in the brain have only the axis-cylinder and surrounding white substance of Schwann, but no neurilemma, and hence the difficulty of dissecting out special strands of nerve fibres and of tracing the course they run, is considerably increased. The fibres which have been most definitely traced are (1) those from the internal capsule (p. 23) as they pass outwards to the cortex, the group called the *corona radiata*; (2) the decussating fibres of the corpus callosum; and (3) the longitudinal or collateral fibres connecting different parts of the same side of the brain.

The gray matter of the cortex consists of nerve cells and fibres embedded in a connective tissue material, the *neuroglia*, and well supplied with blood-vessels and lymphatic channels. The cells differ slightly from each other in appearance at different depths from the surface and in different areas, and may be of a pyriform, conical, spindle-shaped, or quite irregular shape, but on the whole they present the form of a pyramid whose apex points towards the surface and from which a long thin pole or fibre, the *apex process*, can be traced outwards for some distance, but whose ultimate destination is unknown. The base of the pyramid is connected with a nerve fibre coming

from the subjacent white matter, and from the angles at the base of the pyramid, or even from the sides, we find numerous branching processes—in some cases as many as fifteen to eighteen—the number of which seems to depend upon the size and age of the cell. These processes are short and quickly break up into a fine plexus of fibres, and it is probable that these act as internuncial fibres bringing the different cells into relationship with each other.

The general arrangement of the structures in the cortex is as follows:—On the surface we find a layer of nerve fibres supported by fine connective tissue and vessels passing straight inwards to reach the deeper layers. Next to this comes a layer of small oval or angular cells with large nuclei and giving off numerous fine processes. Deeper down comes a layer containing more distinctly pyramidal cells, and in the posterior or sensory regions we find many small conical cells packed together. Below these again, we find, more especially in the motor areas (p. 30), very large pyramidal cells of the form described above. Below these again come a set of spindle cells with numerous nerve fibres passing between them to the outer cells.

The more carefully the gray matter is examined the more clearly do we find that each area has its own special groups of cells—a rule that we would expect to hold considering the varying functions of the different areas; nevertheless the transition from one set of forms to another is never very abrupt. That different areas of the brain have different functions, though often conjectured, was not experimentally proved till 1870, when Fritsch and Hitzig performed their celebrated experiments; and this subject has since been carefully studied by many observers, among whom we may mention Ferrier, Horsley, and Hitzig. Thus it has been established that the convolutions adjoin-

ing the fissure of Rolando have to do with the initiation, under due stimulation, of movements throughout the body, and, generally speaking, the broad distinction may be drawn that the frontal and front part of the parietal lobes are associated either with the exercise of the more purely mental powers, or with movement, while the posterior parietal convolutions and the occipital and temporo-sphenoidal lobes have to do with sensation.

The sensory fibres to the occipital and temporo-sphenoidal lobes come in the main from the posterior third of the internal capsule, spreading outward thence in a fan-shaped manner as the radiation of Gratiolet.

The precise position of the different centres cannot be precisely stated, but by localised electrical excitation, or by the destruction of certain areas accidentally, experimentally, or by disease, and by careful observation of the variation in the normal phenomena thus caused, the following tentative conclusions have been arrived at as to the sensory centres of the cortex. Our information as to the centre of vision is more definite than with regard to the other sensory centres, for it will readily be understood that blindness is much more easily detected in an animal than the loss of any other of the senses.

SENSORY CENTRES IN THE CORTEX

1. **The Centre for Vision.**—This is believed to lie in the convex outer surface of the occipital lobe and the angular convolutions (Fig. 10, p. 25, P_2, P_2'). It has been found that electrical stimulation of the angular gyrus causes the animal to turn its eyes to the side opposite to that stimulated, and upwards or downwards according as the front or back part of the gyrus is excited. Further, the eyelids are closed and the pupil contracts. What is the meaning

of these movements? As we shall see in dealing with vision, the distribution of the fibres of the optic nerve is such that we would expect that the occipital lobes of say the left side of the brain would take cognisance of everything visible to the right side of a plane passing fore and aft through the body when the eyes are looking straight forward. The left brain has to do with fibres from the left side of each eye, viz. the part that sees objects to the right. If, then, on stimulating the left occipital or " occipito-angular " area the eyes turn to the right, we may with reason interpret the movement as meaning that the stimulus has given rise to the sensation of something being visible in the right half of the field of vision for the better view of which the head is turned to the right, while the contraction of the pupil may indicate that the sensation is of something near at hand, and the closure of the eyelid that the eye is shut for protection from contact with a near object or the shutting out of a too brilliant flash of light.

Destruction of the central part of the occipito-angular area causes disturbance of vision or blindness of the *same* side of each retina, or, in other words, for the *opposite* side of each visual field. But an important and delicate distinction must be drawn. The blindness is, according to Munk, one of mind—" a psychical blindness or inability to form an intelligent comprehension of the visual impressions received." The eye performs its function correctly; the basal ganglia may fuse the sensations into a coherent whole, the animal may act in a reflex way avoiding obstacles in its path, but the object thus seen awakes no mental activity. An example will illustrate our meaning. It can see and avoid as it walks a plate containing food, but it does not recognise food as such, as something to eat, nor does it show signs of fear when threatened with a whip.

It has been suggested that the removal of the central part of the occipital lobe merely removes that part of the cortex which is associated with the area of *distinct* vision of the retina, that the animal has conscious but not distinct vision. This would be in agreement with the fact that when only injured upon one side the animal within a few days recovers to some extent the sense of sight on the side affected. The improvement might be due to acquisition by practice of powers of vision not usually possessed by the peripheral parts of the retina, but much has still to be learned on this difficult subject. Complete destruction of the occipito-angular areas of both sides, the cuneus (Fig. 11, O_2) being included, causes total and permanent blindness without any other perceptible loss of sensory or motor power.

The power of distinct vision, then, depends in man upon the normal working of a terminal organ, the eye, of the optic nerve partially decussating at the optic commissure, the nerve strands passing thence backwards by the optic tract to the corpora quadrigemina and optic thalami, and thence, by the radiation of Gratiolet, to the cortex of the posterior part of brain. We have seen it to be the law that when a nerve fibre is cut off from its ganglionic nerve cell the fibre degenerates. In the case of the optic mechanism, these ganglionic cells are situated in the retina, which the study of development has shown to be really a part of the brain, and when the retina is destroyed the optic fibres passing from it undergo degeneration.

2. **The centre of hearing** for each ear seems to be situated in the superior temporal convolution (Fig. 10, T_1) of the opposite side. The fibres of the auditory nerve after entering the medulla pass upwards through the pons, decussate there, and thence go through the posterior part

of the internal capsule to the temporal region. Our most valuable evidence as to the auditory centre comes from cases where the brains of deaf or epileptic patients have been examined *post-mortem*. Thus in certain instances the cause of deafness has been found to be disease of the above-mentioned area; and in cases of epilepsy where the fit has been preceded by the sensation of a noise the seat of disease has been in the neighbourhood of this part, and the irritation thus arising has determined the onset first of auditory, and then of motor, disturbance in the adjoining motor areas. The study of peculiar sensory disturbances which often precede a convulsive attack, the *aura*, as it is called, is of great interest in this connection as showing the part of the brain first affected by the disturbing force. Most commonly it is an indescribable sensation seeming to originate in the limbs or body and passing upwards to the head, and that in many cases so slowly as to be capable of being arrested by pressure. In such cases it is most probably due to the disturbance of the muscular sense, but sometimes the aura takes the form of a flash of light, a noise, a disagreeable odour or peculiar taste, in which case the centres of special sense are the parts more directly affected. Fortunately for man, epileptic attacks are seldom directly, and in the earliest stages of the disease, fatal, and our knowledge of the intimate structure of the brain has been so recently acquired, that pathological investigation has not been of so much service as might be supposed. There is undoubtedly reason to believe that this branch of study will yield fruitful results in future.

Electrical stimulation of the corresponding area in the dog causes pricking up of the opposite ear, turning of the eyes and head to the opposite side, with the pupils of the eyes dilated, movements such as the dog would make were

it to hear a sudden sound from the side opposite to that stimulated.

Destruction of the superior temporal convolution causes, according to Ferrier and others, deafness in the opposite ear, but this is denied by Schäfer and Horsley, who urge the difficulty of determining the presence of deafness, and maintain that in one case where both temporal lobes were completely destroyed there was no perceptible loss of the power of hearing. In the case of human beings it is believed that there may be only a partial decussation of the nerves of hearing, just as in the case of sight, so that injury to *one* side of the brain may not cause complete loss of hearing on either side, but where both sides have been affected the loss of hearing is complete. With hearing as with sight Munk believes there may be a psychical as opposed to a complete loss of sensation, and he affirms that destruction of the middle part of the convolution causes psychical deafness.

3 and 4. **The centres for taste and smell** are supposed by Ferrier to be situated in the anterior part of the hippocampal or uncinate gyri (Fig. 11, H, U), as indicated by movements of the nose and lips on stimulation of these areas. The nerves of smell pass upwards from the nose to the olfactory lobes, which lie in man below, and covered completely by, the frontal lobes, though in many of the lower animals they are prominent bodies projecting forward beyond the rest of the brain. Fibres from the olfactory lobes have been traced to the region above indicated, but with regard to their ultimate distribution, and still more to that of the nerves of taste, there is much to be yet learned. A case is recorded of an epileptic patient whose aura was of an olfactory kind, and the seat of disease was found to be in the right uncinate gyrus.

5. **The centre for touch** is believed by Ferrier to be

situated in part at least in the gyrus hippocampus, as shown by loss of tactile sensibility when this area is destroyed.

Schäfer and Horsley found temporary loss of sensation on the opposite side of the body—hemi-anæsthesia—when this part was destroyed, but the loss was more marked and persistent when the greater part of the gyrus fornicatus (Fig. 11, G*f*, p. 27) was destroyed. It has not been possible to find separate centres for painful and tactile impressions, although from considerations advanced when speaking of the sensory tracts in the cord it is quite probable that such do really exist.

It is only of late years that an attempt has been made to distinguish between sensory terminations for the perception of *heat* and *cold*, and no observation has yet been made as to the localisation of corresponding sensory areas in the brain. It has been found that injury to the basal ganglia, and more especially to the corpus striatum, is followed by a prolonged rise in temperature, as if a centre which had normally to do with the regulation of temperature had been affected ; but this is not known to be associated with any sensory effects, and indeed it would be hard to distinguish experimentally, except upon one's self, between sensations of touch, of pain, and of variation in temperature.

In addition to the special forms of sensation we have just considered, there are many sensations of a general kind —common sensations—arising from the internal conditions of the body, such as hunger, thirst, lassitude, the feelings due to distension of the viscera, and many peculiar sensations due to disturbance of the nervous system, such as those felt when a limb is said to be asleep, or formication, the condition in which it seems as if ants were creeping about under the skin. Again these and even vaguer conditions arising from varying general nutrition, such as the feeling of

general well-being, and its opposite, discomfort, general depression, or melancholy, or the restless condition caused in many by the disturbance of the electrical condition of the atmosphere usually preceding a thunderstorm. For all these no special cerebral centres have been found.

The Muscular Sense.—Some at least of these may probably be regarded as special forms of the *muscular sense*, that is to say of that sensation by which we are aware of the position and state of relaxation or contraction of the muscular system of the body, and by which we are guided in our unconscious estimate as to the amount of force necessary for movement. Through it, too, we can estimate the relative weights of bodies.

RELATION OF STIMULUS AND SENSATION

We have now to consider in general terms the effect upon the sensorium which any given change in our environment or in the body itself will bring about. This may be viewed from two aspects, the qualitative and the quantitative.

Qualitatively, the effect will depend upon whether a special or a common sensory mechanism is affected. If the stimulus be one fitted to excite the sense of taste, the sensation it causes is in no way comparable qualitatively to that caused by excitation of the sense of vision. The variation of quality within the limits of any one of the senses varies with the peculiar nature of the excitant. The quality of colour, *e.g.*, varies with the wave-length of light, or, in other words, with its rapidity ; that of sound with the form of wave, or more accurately with the momentum of impact or pressure on the sensory apparatus; that of taste and smell with the molecular constitution of the body, but whether through the rate of motion of the molecule, or the form of the path in which it moves, cannot be said. Special

illustrations of this will be found in the chapters upon the special senses. Quantitatively, the character of the sensation depends upon the receptivity of the organism and the amount or strength of the stimulus. The stimulus may be so feeble that it fails to arouse any sensation whatever, a light may be so small or so far removed from the eye as to be invisible, a sound may be so faint as to be inaudible. But when the energy of the physical disturbance reaches a certain degree, supposing that the receptivity of the sensory organ is always the same, a sensation is felt. Other things being equal, the amount of energy required for the stimulation of any given sense may be regarded as a constant quantity, and the smallest perceptible amount is known as the lower limit of excitation. This excitant acting on the sensory organ brings us, as it were, to the threshold of sensation. In estimating the comparative intensities or strengths of sensations it is commonly assumed that the difference between zero or absence of excitant and the lower limit of excitation may be regarded as the unit of measurement.

We say, for example, that lights from various sources, as a candle, an oil lamp, an electric light, the sun, have different degrees of brilliancy or intensity. We may diminish the brightness till we reach a point beyond which the light is no longer seen, and yet there is a certain amount of energy being exerted of which our senses fail to take cognisance. In stating the relative brilliancies or intensities of the light we would use as a unit of comparison the amount of light just sufficient to give a sense of luminosity. Then so many times this unit would give the measure of the luminosity of the candle, so many more of the lamp-light, so many more of the electric light or of sunlight. We may say that the intensity of one sensation is double, treble, quadruple that of another, and so on ; or, on the

other hand, we may say that a given amount of sensation always bears a certain ratio to the least perceptible difference from it, either in the way of increase or diminution. This ratio, again, corresponds with that between the intensities of the excitant and the sensation. An endeavour has been made to put this latter ratio upon an absolute basis for each of the senses, but this can only be stated as an average of a number of determinations made by different individuals or by the same individual at different times. Thus, for example, it is stated that the least possible difference in the intensity of light which will allow of a sense of different luminosity is $\frac{1}{100}$. Given 100 lights, a difference of luminosity would be noted if one were added or withdrawn; but, given a thousand, no difference would be observed unless at least 10 were added or removed. The least perceptible difference of pressure is caused by the increase or diminution by $\frac{1}{3}$ of the original amount. If a person is holding three pounds in his hand he will not feel any increase or diminution of their original weight unless as much as one pound is added or subtracted. For the pressure sense the ratio 1 : 3 is a constant, whatever be the original unit. Similarly for the other senses, the ratio for the sensation of temperature is 1 : 3, for auditory sensations 1 : 3, for muscular sensation 6 : 100, and for visual sensation 1 : 100.

In the next place, we must note that with variation in the amount of the stimulus there is variation in the intensity of the stimulation, but these do not vary *pari passu* in the same numerical ratio. We have seen, for example, that to have any change at all in the sense pressure there must be an increase or diminution by $\frac{1}{3}$ of the original pressure, but we do not necessarily recognise directly that the pressure is $\frac{1}{3}$ more or less. The law only holds that there will be an equal perceptible varia-

tion when the stimulus varies in constant proportion. There is the same perceptible variation when 3 lbs. are increased to 4 lbs., as when 6 are changed to 8, or 12 to 16. Fechner points out that the strength of a sensation does not increase in the same numerical ratio with the strength of the stimulus, but as the logarithm of the strength of the stimulus, for logarithms of numbers increase by equal increments according to the relative increase of the numbers themselves. Thus 1, 2, 3, etc., are the logarithms of 10, 100, 1000, and similarly, the increase in sensation when the excitant is increased from 10 to 100 will be the same as when the 100 are increased to 1000. Or, putting it in another way, the strength of the sensation increases in numerical progression as the strength of the stimulus increases in geometrical progression. This law, however, only holds within certain limits—between the threshold of sensation on the one hand, and an upper limit on the other. With all sensations there comes a time when an increase in the strength of the stimulus no longer increases the intensity of the sensation, but gives rise to a change in quality. Thus beyond a certain degree of brilliancy the eye will be blinded or rendered insensitive to light, with sounds too loud the ear will be deafened, with too great pressure the tissues will be crushed, and with injury to the sensory organ the sense of pain arises. Fechner's law, again, fails in its applicability to the senses of taste and smell, and, except within narrow limits, to the sense of temperature, while it holds best perhaps in regard to the sensation of light, where, owing to the delicacy of discrimination of the sense of vision, it is possible to judge of differences over a wide range of sensibility.

Sensations and Perceptions.—There is still one point in which we may note a difference in the mental effect of the action of the different senses, viz. the extent to which

they are attended by the idea of externality. With both sight and hearing we very early acquire the power of projecting our sensations outwards, so that objects seen are referred to their relative positions in space, while by the aid of other senses we are able to refer the sound to the sounding body. Similarly we refer odours to the body from which they come, and the senses of touch and taste give us information which we interpret as due to objects in contact with our body, but external to it. The common senses, such as fatigue, pain, etc., give us no impression of an external body in relation to ours, they are purely feelings devoid of a sense of an underlying objective reality. This aspect of the subject will be better understood, however, when we consider the senses in detail.

THE SENSE OF TOUCH

THE sense of touch is located in the skin. The structure of this organ, which acts as a protective covering, and is also concerned in the excretion of sweat, oily or sebaceous matter, and gases, and in the regulation of the heat of the body, will be readily understood by studying the section seen in Fig. 12.

Epi-
dermis. { Horny layer . . . . .
Clear layer . . . . .
Mucous layer . . . . .

True
Skin. { Papillary layer . . . .
Duct of sweat gland . .
Reticulated layer . . .

Sweat gland . . . . .

Subcutaneous tissue . .
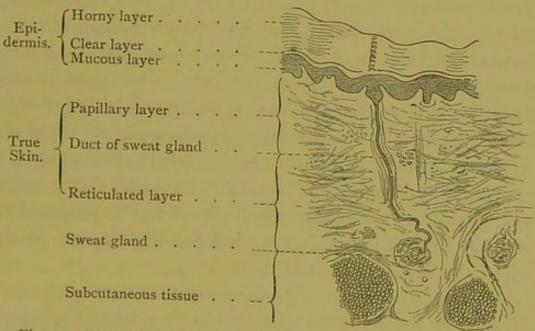
Fig. 12.—Perpendicular section of the skin of the finger of an adult man. Magnified 15 diameters. (Stöhr.)

Structure of the Skin.—It consists of two layers, a deeper, formed of connective tissue, and called the *derma*, *cutis vera* (true skin), or *corium*, and a superficial, known as the *epidermis*, which is composed of epithelium.

(1) *The true skin.*—If we look at the surface of the skin we see it shows delicate furrows or grooves crossing each other, so as to form small lozenge-shaped areas, or the grooves may run parallel for a considerable distance. The lozenge-shaped arrangement is seen on the surface of the skin of the arm, and that with the grooves forms a marked feature on the skin of the palm or covering the tips of the fingers. On the summits of the ridges, on each side of a groove, or enclosing a lozenge-shaped area, we find small prominences termed *papillæ*, the number and size of which vary much in different parts of the skin. They are most numerous, and attain the greatest size (about the $\frac{1}{125}$ of an inch in length), in the palm of the hand and sole of the foot, while they are much smaller and fewer in number on the skin of the cheeks or forehead. The true skin is formed of a felt-work of connective tissue, mixed with elastic fibres, and having also a considerable number of smooth muscular fibres distributed here and there. In the upper layers the connective tissue is condensed so as to form a firm stratum, but in the deeper layers the bands of connective tissue run in all directions so as to form an irregular mesh-work, in the spaces of which we find numerous fat-cells. Thus the skin is tolerably firm in its upper layers, and these may be supposed to rest on an elastic cushion, a condition that favours, as we will find, the mechanism of touch.

(2) *The Epidermis.*—This, the outermost layer, is formed of more or less flattened epithelial cells, arranged in layers or strata. Two such strata are readily seen when we examine a perpendicular section (Fig. 12): a deeper stratum, of soft consistence, filling up the spaces between the papillæ, and termed the *stratum mucosum*, or *stratum of Malpighi* (after the Italian anatomist who first described it), and a superficial and denser stratum, known as the

horny layer or *stratum corneum.* Both strata are built up of epithelial cells, which change in appearance as we pass from below upwards. Those in the mucous stratum are cylindrical, and have a long nucleus ; and above these we find rounded cells, having little spines projecting from their borders, and hence called *prickle cells.* The spines of adjoining cells unite, and thus there is a reticulated space round each cell. Above these the cells become more flattened, and contain bright refractive granules. The cells in the mucous layer of the skin rapidly multiply, the youngest cells being next the papillæ of the true skin, and each layer is gradually pushed towards the surface by a layer of younger cells below it. The horny layer is formed of flat polygonal cells that have lost their nucleus, and the cells of the most superficial layer are gradually being shed by abrasion or rubbing. Thus thousands of hard dry epithelial cells are being rubbed off daily from the surface of the epidermis. In some parts of the skin where the epidermis is very thick, as on the sole of the foot, a clear stripe is seen between the mucous and horny layers. This, called the clear stratum (*stratum lucidum*), is formed of cells that refract light strongly, and hence have a translucent appearance. The colour of the skin depends partly on granules of pigment found in the cells of the mucous layer, and partly on the blood circulating through it, and the thickness of the layer of tissue between the vessels and the surface. Thus when the vessels of the skin are moderately dilated, and when the vessels lie near the surface, there may be the delicate rosy hue of health, while the reverse conditions may produce a pale or swarthy, or even a yellowish tint of skin.

It is foreign to the purpose of this work to describe all the so-called *appendages of the skin,* such as nails, hairs, horn, hoof, quills, feathers, and scales. And yet all

these may be, to some extent, concerned in the sense of touch. They are all modifications of epidermis, and they are all developed or moulded upon papillæ which are similar in character and origin (although often much greater in size) to the papillæ on the surface of the true skin already described. The following general statements regarding these appendages are of physiological interest :—

(1) Each epidermic structure may be regarded as a permanent excretion. They are separated from the blood, and thus modify the constitution of that fluid. Thus the nutrition of other organs of the body may be influenced, and in this way we may establish a physiological connection between the development of hairs, horns, wattles, combs, brilliantly-coloured feathers, etc., and the changes at certain periods of life in the sexual organs.

(2) Each epidermic structure has an individual existence ; it is developed, grows, reaches maturity, declines, dies, and is removed from the body, to be replaced by another of a similar kind. Thus hairs, nails, feathers, etc., have each a limited duration of life.

(3) Epidermic structures, similar in origin, but, in their mature condition, very different in structure, may serve purposes of beauty, as the hairs of the seal or ermine, the feathers of the humming-bird or kingfisher, or the scales of the gold-fish or mackerel ; of warmth, as the hair of the polar bear, the wool of sheep, and the feathers of many birds ; of defence, as the horns of the stag, the spines of the hedgehog, or the quills of the porcupine ; as protective and resistant structures, covering delicate parts of the foot, as the hoofs of the horse, etc. ; and as aids to the sense of touch, as the whiskers of the cat, or the hairs on the ears of many nocturnal mammals. It is remarkable that when epidermis is modified for purposes requiring great powers of resistance, it assumes in structure a concentric arrangement

of epidermic cells, simulating bone, as may be seen by comparing a section of bone with that of hoof, whalebone, or of rhinoceros horn. Lastly, epidermic structures, by containing pigment, confer brilliant colours on many animals, and even where pigment is absent, beautiful iridescent tints may be produced by fine markings on the surfaces of epidermic structures. These markings, or grooves, form diffraction spectra when the light falls on them, and thus we have many humming-birds flashing a variety of tints as the animals flit to and fro in the sunlight.

Structure of Tactile Organs.—As already explained, sensory nerves are those that convey nervous impulses to the brain, and there give rise to sensations. Such sensory nerves abound in the skin, but if one of these be gently touched, the result will not be a sensation of touch in the proper sense of the word, but a more or less painful and disagreeable impression. The direct contact of any foreign body with a naked sensory nerve is too rude a form of stimulation, and hence we find, as a rule, that the fine filaments at the origins of such nerves in the skin are brought into relation with special tactile structures or terminal organs of touch, of which there are several varieties.

(1) *Free nerve-endings.*—In a few situations, single nerve fibres pass up to the under surface of the epidermis, lose their medullary sheaths, and then the axis-cylinder subdivides into fine filaments, which either lose themselves among the cells of the epidermis, or come into contact with cells having branched processes, called the *cells of Langerhans.* This is the simplest form of nerve-ending, and the only form in epidermis. It has been found in the cornea of the eye, the nose of the mole, the nose of the pig, and the skin of the frog and tadpole.

(2) *Nerve-endings in corpuscles.*—The nerve filaments

may terminate in various forms of corpuscles, which, however, are (with one exception) situated in the true skin, or in the subcutaneous tissue. Thus we may have (*a*) simple tactile cells; (*b*) groups of tactile cells; (*c*) touch corpuscles, (*a*) simple, and (*β*) compound; (*d*) end-bulbs; and (*e*) a more complicated structure called a Pacinian corpuscle.

(*a* and *b*) *Simple tactile cells.*—These are oval nucleated cells, about $\frac{1}{1200}$ of an inch in diameter, found in the deeper layers of the epidermis, or in the true skin close to the epidermis. Minute nerve filaments terminate in these by apparently blending with their substance. Sometimes these cells may form a group which takes the form of a little cup, like a wine-glass with the bottom broken off, the nerve ending in the stem of the glass.
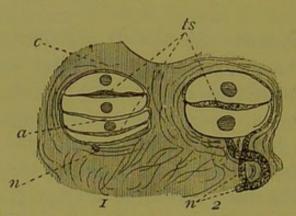
FIG. 13.—Vertical section through the skin covering the attached end of the upper mandible of a goose. Magnified 240 diameters. Shows two touch corpuscles divided transversely to the plane of entrance of the nerves. 1, Tactile corpuscle consisting of four tactile cells; 2, twin tactile cells, *ts*; *a*, tactile disc; *n*, (to the left) nerve filament; *n*, (to the right) medullated nerve fibre; *c*, true skin. (Stöhr.)

(*c*, *a*) *Simple touch corpuscles.*—These, sometimes termed the *corpuscles of Grandry*, or the *corpuscles of Merkel*, are formed of two or more flattened cells, each cell being about $\frac{1}{1700}$ of an inch in length by $\frac{1}{500}$ of an inch in breadth. A medullated nerve fibre, on approaching the corpuscle, first loses the white substance of Schwann, and then the axis-cylinder ends in a flat disc placed between two of the tactile cells. This comparatively simple form of touch corpuscle is found in the skin of the bills, and in the tongues, of birds, especially those of aquatic habits.

(*c*, β) *Compound touch corpuscles.*—These, termed the *corpuscles of Wagner*, or the *corpuscles of Meissner*, are oval bodies, from $\frac{1}{625}$ to $\frac{1}{125}$ of an inch in length, and $\frac{1}{830}$ to $\frac{1}{420}$ of an inch in breadth, found in the papillæ of the true skin, especially in the palm of the hand and sole of the foot. The number of these bodies is very considerable. About fifty in each square millimetre have been counted on the tip of the forefinger. A like area over the second joint contained twenty, and over the first joint seven or eight. About fifteen per square millimetre have been found in the skin of the last joint of the great toe, and three or four in the like area of the sole of the foot. Each tactile corpuscle has one or two medullated nerve fibres twisted spirally round it (Fig. 14), and near the upper pole of the corpuscle the white substance of Schwann disappears, and the axis-cylinder ends in little excrescences or thickenings. The corpuscle is built up of flattened cells, the edges of which, often seen in section, give it a peculiar striated appearance. These bodies are evidently constructed on the same plan as the
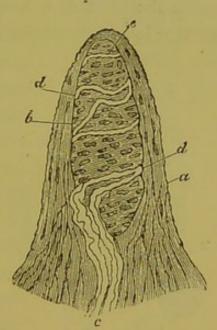
FIG. 14.—Touch corpuscle. *a*, Layers of connective tissue of the true skin ; *b*, body of corpuscle ; *d, d,* nerve fibres twisted spirally round the corpuscle ; *c*, nerve fibres at the lower end of the corpuscle ; *e*, nerve fibre ending in little thickenings near the upper end of the corpuscle. Magnified 50 diameters.

more simple corpuscles in the bills of birds, above described, each consisting of a number of tactile cells.

(*d*) *End-bulbs.*—These, sometimes called the *end-bulbs*, or *end-knobs of Krause*, occur in the conjunctiva of the eye, the mucous membrane of the mouth, in some of the ligaments of joints, occasionally in tendons, and in the sexual

organs. They have also been found on the under surface of the toes of the guinea-pig, in the ear and body of the mouse, and in the wing of the bat. Varying from $\frac{1}{360}$ to $\frac{1}{170}$ of an inch in length, each consists of a delicate wall of connective tissue, sometimes forming a little sac, in the interior of which we find granular matter and nuclei (Fig. 16). Sometimes, also, the granular matter takes the form of a knob. The nerve may apparently end at the lower extremity of the bulb (Fig. 15, 2), or it may
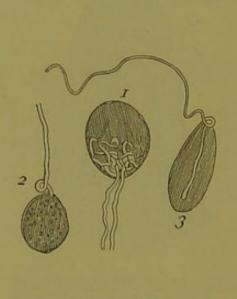
FIG. 15.—Various forms of end-bulbs. (Krause.)
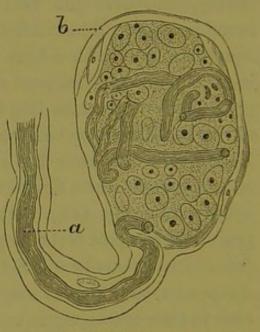
FIG. 16.—End-bulb. *a*, nerve; *b*, connective tissue wall. (Krause.)

penetrate it and form a number of loops (Fig. 15, 1), or it may end in a long ribbon or rod (Fig. 15, 3).

(*e*) *Pacinian bodies.*—These, sometimes termed the *corpuscles of Pacini*, or the *corpuscles of Vater*, from $\frac{1}{25}$ to $\frac{1}{12}$ of an inch in breadth, and from $\frac{1}{12}$ to $\frac{1}{8}$ of an inch in length, are found in the subcutaneous connective tissue of the palm of the hand (including the fingers) and sole of the foot, in the sexual organs, in the deeper layers of connective tissue below the skin near joints, in the mesentery (the fold of peritoneum holding the intestine in position), and in

the connective tissue around the pancreas. They have also been found in the skin of the elephant and of the bat. About 600 exist on the palmar surface of each hand, and as many on each foot. Each Pacinian corpuscle consists of from forty to fifty lamellæ or capsules (Fig. 18) concentrically arranged. The space between each pair of lamellæ is lined by a layer of flattened cells, and is filled with fluid. Each capsule is smaller as we approach the centre, and the capsules are all connected at the pole opposite the entrance of the nerve by a thickening. A small artery enters the corpuscle. The nerve of the medullated variety enters the corpuscle at one pole, and may be regarded as forming its stem or stalk. The fibre perforates the capsules, and the axis-cylinder runs up into the clear mass in the centre of the corpuscle, the medullary sheath and the white substance of Schwann terminating at the entrance of the filament into the clear mass. Near the farthest end the axis-cylinder often divides into two or more branches, and these, in turn, end in a little pear-shaped mass, called the *terminal bud*. Each bud is composed of a dense network of minute fibrils. Surrounding the axis-cylinder we find a transparent or slightly striated substance, with sometimes rows of nuclei, especially near the farther end. Smaller and simpler bodies, but constructed on the same plan, have been found in the bills and
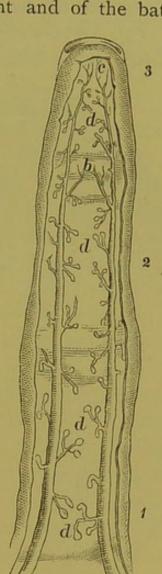
FIG. 17.—Diagrammatic view of the under surface of the index finger with Pacinian corpuscles. *a*, Nerve; *b, c*, lateral and terminal branches of the nerves; *d, d, d*, Pacinian corpuscles; 1 first, 2 second, and 3 third phalanx of the finger. (Schwalbe.)

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tongues of birds (distinct from Grandry's corpuscles), and are termed the *corpuscles of Herbst.*

(3) *Nerve-endings in connection with tactile hairs.*— A hair grows from a follicle or pit in the substance of the true skin. A layer of epidermis dips down into the follicle, lining it, and covering a papilla in the bottom of the follicle. From the surface of the papilla, which is in reality one of the papillæ of the true skin, the hair is developed, and as it passes up to the mouth of the follicle, it is covered by a sheath, composed of layers similar to those of the epidermis. Each papilla on which a hair grows is richly supplied with capillary blood-vessels. The papillæ of the special tactile hairs, like those near the mouth of a cat, are larger and more vascular than those of ordinary hairs. It would appear that each ordinary hair follicle is supplied with fine nerves. Fine medullated nerve fibres form a network in the outer coat of the hair follicle, and they then lose the white substance of Schwann, and run more in a longitudinal direction, parallel to the hair. They then penetrate the wall of the follicle and end in the inner layer of the sheath of the hair, but their exact mode of termination is yet un-

FIG. 18.—A Pacinian corpuscle. N, nerve; V, V, vessel; T, nerve-ending. (Klein and Noble Smith.)

known. The number of nerve filaments brought into close relation with a true *tactile* hair is very great, dense networks being formed both in the inner and the outer sheaths of the hair, and they end in small knob-like swellings between the columnar cells of the outer sheath of the hair. In some cases a special plexus of minute nerve fibrils has been found surrounding, like a ring, the neck of the hair follicle.

It is well known that tactile hairs can be voluntarily caused to stand out stiff and rigid. This is owing to the fact that such hairs possess a special arrangement for so erecting the hairs. Surrounding the neck of the hair follicle we find sinuses and spaces of erectile tissue, controlled by bands of elastic and unstriped muscular fibre. When the spaces are full of blood the hair projects from the centre of a highly elastic cushion, thus, no doubt, giving greater sensitiveness to the apparatus.

The small woolly hairs on the skin of many animals appear to be organs of touch, and experiment has shown that they are more sensitive than the areas of skin between them. In many animals the proper tactile hairs acquire great length, thickness, and stiffness. These *vibrissæ*, or whiskers or mustaches, in marine carnivora, plunging into depths of the sea where there is little or no light, serve, according to Owen, "as a staff, in a way analogous to that held and applied by the hand of a blind man." The night-prowling felines and the nocturnal monkeys, like the aye-aye, have hairs of this kind developed on the eyebrows, lips, and cheeks. Other epidermic appendages serve useful purposes in connection with the sense of touch. The broad massive hoof of the horse is not adapted for delicate discriminations of tactile sensations, but clothing, as it does, highly vascular and sensitive lamellæ, gives broad and massive sensations, which enable the animals to appreciate the solidity of the

ground on which they tread. Animals living in the sea
sometimes have touch organs developed which enable
them to detect pressures or movements, often at a con-
siderable distance from them. Thus whales have large
papillæ in the skin, richly supplied with nerves, and some-
times the skin, bearing these papillæ, is thrown into plaits
or folds, so as to give a greater extent of sensitive surface.
It is said by Owen that this arrangement "is peculiar
to the swifter swimming whales that pursue mackerel
and herring, and may serve to warn them of shoals,
by appreciation of an impulse of the water rebounding
therefrom, and so conveying a sense of the propinquity
of sunken rocks or sand-banks." The nose-leaves and
sensitive ears of some of the bats often show vibratile
movements,—trembling, like the antennæ of insects, as the
animal gathers information as to its environment,—and thus
act as delicate organs of touch. The nose and feet of
burrowers in the earth, like the mole, have always delicate
organs of touch, by which the animals feel their way in
their subterranean galleries.

Nature of the Tactile Mechanism.—Touch is a sensa-
tion of pressure referred to the surface of the body. When
we touch anything there is always a certain amount of
pressure between the sensitive surface and the body
touched. What we call contact is gentle pressure; a
greater amount of force or pressure makes the sensation
of touch more acute; by and by, there is a feeling of
resistance to pressure, still referred to the skin; when a
weight is supported on the palm of the hand there is then a
sensation of muscular resistance, a sensation referred not
only to the skin, but also to the muscles, and by which we
become aware that the muscles are contracted; and,
finally, the pressure may be so great as to cause a sensa-
tion of pain which, however, may be confused with simul-

taneous sensations of contact and of muscular resistance. The force, however, that gives rise to touch, in its various degrees, may not act vertically on a sensory surface, but in the opposite direction, as when we pull a hair. Touch is, therefore, in its essence, the appreciation of mechanical force, and in this way it presents a strong resemblance to hearing, which is a more delicate kind of touch, being due to variations of pressure on the auditory organ. In addition, however, to sensations of touch, contact with a foreign body may give rise to sensations of heat or cold—that is to say, to sensations of temperature. Thus when we place something on the palm of the hand, the resulting sensation may be of a complex character, involving sensations of gentle pressure (contact), of more severe pressure, and of temperature. True tactile impressions are absent from internal mucous and serous surfaces, as has been proved in men having fistulous openings into the stomach, intestine, bladder, or pleural cavities. In such cases pressure does not cause a sensation of touch, but of pain.

A consideration of the structure of the terminal organs of touch, above described, shows that they must serve (1) for protecting the extremities of the sensory nerves from direct pressure; (2) for communicating slight variations of pressure to the nerve-ending; and (3) for so modifying external pressures as to give them more or less of a rhythmic character. Thus if we consider the nerve-ending in an end-bulb, or in a Pacinian corpuscle, lying in a fluid or semi-fluid substance, surrounded by one or more envelopes of connective tissue, we see that most delicate pressures must be communicated to it, and also that a wave-like movement may be set up in the fluid matter, thus subjecting the nerve-ending to a number of intermittent pressures or vibrations. In the case of the touch corpuscles, either simple or compound, the arrange-

ment is evidently that of an elastic cushion against which the nerve filament is pressed, thus again making variable pressures or vibrations possible. In like manner, movements communicated to a hair, the follicle of which is surrounded by elastic structures and nerve-endings, must give rise to impulses in these nerves, probably of an intermittent or vibratory character. No part of the body, when touching anything, can be regarded as absolutely motionless, and the slight oscillations of the sensory surface, and, in many cases, of the body touched, produce those variations of pressure on which touch depends.
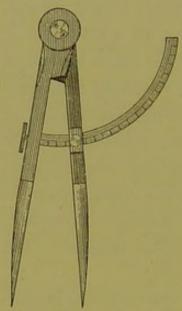
FIG. 19.— Compasses of Weber.

Sensitiveness of the Skin.—It is a familiar observation that all parts of the skin are not equally sensitive. The method of determining the degree of sensitiveness, first employed by Weber, consists in finding the smallest distance at which the two points of a pair of compasses can be felt. Two instruments suitable for such observations are shown in Figs. 19 and 20, and the results in millimetres [1] are given in the following table :—

Tip of tongue. . .	1.1	Centre of palm . .	8-9
Under surface of third		Under surface of third	
phalanx of finger. .	2-2.3	phalanx of great toe .	11.3
Red part of the lip . .	4.5	Upper surface of second	
Under surface of second		phalanx of finger .	11.3
phalanx of finger. .	4-4.5	Back	11.3
Upper surface of third		Eyelid	11.3
phalanx of finger .	6.8	Under surface of lower	
Tip of nose . . .	6.8	third of forearm . .	15.0
Ball of thumb . .	6.5-7	Cheek	15.8

[1] 1 millimetre $=\frac{1}{25}$ of an inch.

Temples	. . . 22.6	Forearm and leg . . 45.1
Forehead	. . . 22.6	Neck 54.1
Back of head .	. . 27.1	Back, opposite fifth dorsal
Back of hand .	. . 31.6	vertebra . . . 54.1
Knee . .	. . 36.1	Upper arm, thigh, centre
Gluteal region	. . 44.6	of back . . . 67.1

Numerous investigations made since the time of Weber have shown considerable variations in different individuals. The method is employed by physicians in the diagnosis of nervous diseases affecting the sensitiveness of the skin. The general result of Weber's method is to show that in a healthy person those parts are most sensitive as regards the power of discriminating two points at a certain
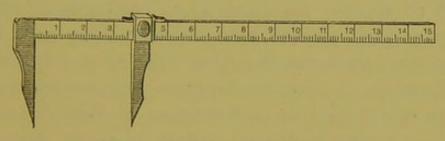
FIG. 20.—Æsthesiometer of Sieveking.

distance from each other, which we use habitually as organs of touch. Thus the tips of the fingers on their under surface, the palms of the hands, the margins of the lips, are more sensitive than the dorsal surfaces of the limbs or the skin covering the back. Sensitiveness is great in parts of the body that are habitually moved, and it increases from the joints towards the extremities. Again, sensitiveness is finer if we proceed a given distance along the transverse axis of a limb than if we pass the same distance along the long axis.

Moistening the skin, stretching it, or taking baths in water containing common salt or carbonic acid, increases sensitiveness, especially as regards the power of discriminating points. An anæmic condition, venous congestion, cold,

and the use of solutions of atropine, daturine, morphine, strychnine, alcohol, bromide of potassium, cannabine, and hydrate of chloral, blunt sensibility. Moistening·the skin with a solution of caffeine is said to increase sensibility.

Sense of Locality.—Not only is the skin sensitive, but one is able, with great precision, to determine the part that has been touched. This power may be termed the sense of locality. The general law is that the greater the number of sensory nerves in a given area of skin, the greater is the degree of accuracy in distinguishing different points, and in determining locality. Contrast, for example, the tip of the finger with the back of the hand.

One would imagine that the habitual use of these parts would so educate the mind as to enable us to identify particular parts touched, even although these parts might not be much more sensitive than other parts. It is doubtful, however, if exercise improves sensitiveness. Thus Galton found that the performances of blind boys, when examined by the Weberian method, were not superior to those of other boys, and he says " that the guidance of the blind mainly depends on the multitude of collateral indications, to which they give much heed, and not their superiority in any of them."

Absolute Sensitiveness.—Hitherto we have been discussing the power of discriminating points, but this is different from the absolute sensitiveness of any part of the skin. What is the smallest pressure that can give rise to a sensation, and what is the smallest difference that can be observed between two sensations? Many attempts have been made to answer these questions. Thus small weights have been allowed to press on the skin, and the smallest weight causing a sensation, and the smallest difference between two weights, have been noted. Again, an ordinary balance has been used, and from the under surface of

one scale-pan a fine needle projected which pressed on the skin, while weights were placed in one scale-pan or the other according to the nature of the experiment. In this way accurate measurements were obtained. To avoid the interfering effects of sudden shocks, the skin has been pressed against a fine tube containing water, so that rhythmic waves, like those of the pulse, were caused to impinge on the skin. The general results of these methods may be briefly summarised thus :—

(1) The greatest acuteness was observed on the forehead, temples, and back of the hand and forearm, which detected a pressure of .002 gramme.[1] The skin of the fingers detected .005 to .015 gramme, and the chin, abdomen, and nose .04 to .05 gramme.

(2) One gramme was placed on the skin, and the least additional weight, in grammes or fractions of a gramme, that could be appreciated was then determined, with the following result :—Third phalanx of finger, .499 ; back of the foot, .5 ; second phalanx, .771 ; first phalanx, .82 ; leg, 1 ; back of hand, 1.156 ; palm, 1.108 ; patella, 1.5 ; forearm, 1.99 ; umbilicus, 3.5 ; back, 3.8. The greatest absolute sensitiveness to a single pressure was on the back of the hand, while the greatest power of discriminating differences of pressure (and also of discriminating points) was on the palmar surface. Eulenberg puts the matter thus : the skin of the forehead, lips, cheeks, and temples appreciated differences of pressure to the extent of from $\frac{1}{40}$ to $\frac{1}{30}$ of the first pressure ; the back of the last phalanx of the fingers, the forearm, hand, first and second phalanges, the palmar surface of the hand, forearm, and upper arm, distinguished differences of $\frac{1}{10}$ to $\frac{1}{20}$; and then follow the back of the foot and toes, the sole of the foot, and the back of the leg and thigh, all of

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[1] A gramme = 15.432 grains.

which require a greater difference than $\frac{1}{10}$ of the original weight.

(3) In passing from light to heavier weights, the acuteness at once increases, a maximum is reached, and then, with still heavier weights, the power of distinguishing differences gradually diminishes and finally disappears.

Fusion of Tactile Impressions.—If the finger is held against a blunt toothed wheel, and the wheel is rapidly rotated, a *smooth* margin is felt when the intervals of time between the contacts of successive teeth are less than $\frac{1}{480}$ to $\frac{1}{600}$ of a second. The same experiment may be made by pressing the finger gently over the holes in one of the outermost circles of a large syren rotating quickly; the sensation of touching individual holes disappears, and there is a feeling of touching a slit. The meaning of these experiments is that the individual impressions, if they follow each other with sufficient rapidity, are fused together in consciousness, so that we experience one continuous sensation. By attaching light bristles to the prongs of rapidly vibrating tuning-forks, and bringing the bristles into gentle contact with the tips of the fingers, and especially with the margins of the lips, curious observations may be made. If the forks are vibrating at rates of from 600 to 1500 vibrations per second, sensations of an acute and almost unbearable character are experienced, but above this limit, sensation, other than that of mere contact, almost or wholly disappears, although the fork is in active vibration.

After-tactile Impressions.—If the weight be considerable, and if it be allowed to press on the skin for a few minutes and be then removed, a faint sensation of pressure may continue for a few seconds. This is termed an *after-effect.* It shows that the influence on the nerves or nerve centres does not disappear the instant the exciting cause is removed. Thus we may compare impressions, and thus

the effect of one impression is more easily fused with the effect of impressions following quickly after it.

Information from Tactile Impressions.—When the skin comes into contact with the surface of any external body, we become aware of the existence of something touching the sensory surface, and from the intensity of the sensation we form a judgment as to the intensity of the pressure. As already pointed out, we, in the first instance, refer the sensation to the skin, but after the pressure has reached a certain intensity, so as to call forth muscular action to resist it, the sensation of touch (pressure) is commingled with that of the so-called muscular sense. The number of points on the surface of the foreign body that individually touch the skin enables us to judge of its smoothness or roughness. Thus, if uniformly smooth it gives rise to a sensation like that of touching a billiard ball, and if we move the hand over a considerable distance of smooth surface there is a sensation of massiveness, as when we touch a marble slab. On the other hand, a body having points irregular in size and number in a given area is rough ; and if the points are very close together, like that of the pile of velvet, a peculiar sensation of roughness may be experienced, almost intolerable to some individuals. If a large area of skin be uniformly pressed upon, the sensation of pressure may disappear after a few minutes, and there will be sensation only when there is a variation of pressure. Again, if one part of the body is subjected to one pressure, and an adjacent part to another pressure, the sensation of pressure may be limited to the line dividing the one area from the other. Thus if we plunge the finger into a dish of mercury, a ring of constriction may be felt just at the junction of the surface of the mercury with the air. The same is experienced when the body is immersed in a bath. No feeling of pressure is felt in

the immersed parts, but if the arm or leg be lifted into the air, a sense of pressure may be experienced on the strip of skin where the limb passes from the water into the air.

The tactile field. As already pointed out, we can determine, with great accuracy, the part touched, and from this the probable position of the touching body. If a point of the skin is touched certain tactile corpuscles are irritated ; these, in turn, set up impulses in sensory nerve fibres, and these impulses are carried by the fibre, first to the spinal cord, and then to the brain, where the fibres end in ganglionic masses in the gray matter on the cerebral cortex. There are thus, projected, as it were, on the cortex of the brain, tactile centres for the hind-leg, fore-leg, neck, eye, ear, trunk, etc., and it follows that each point of the skin has a corresponding point in the cerebral cortex. Thus for each stimulation of a point of the cerebral cortex there is a *local sign*, and thus we localise tactile impressions. There is thus in consciousness, and in the brain, a *tactile field*, to which all points of the skin surface may be referred, point for point. This is comparable to the visual field to which all retinal impressions are related, and which will be afterwards discussed. We have, as it were, a tactile picture of the part touched, and when we pass the hand over any external object (supposing the eyes to be shut) we touch it at various points, and from the differences of pressure, and from a comparison of the positions of the various points in the tactile field, we judge of the configuration of the body. We obtain a number of tactile pictures, and these are fused together so as to give a conception of the whole object. If the object be large, we do not depend, however, on tactile pictures only. It may be necessary to move the limb, or even the body itself, so as to examine the whole of the external object, and the sensations arising from, or connected with, the muscular movement are, in turn, fused with the

tactile pictures. We then judge of the form, size, and nature of surface of the body touched. If there is an abnormal displacement of position of the body touched, or if we touch it with parts of the body that we are not in the habit of using for this purpose, a false conception may arise as to the shape of the body. Thus, in the old experiment of Aristotle, shown in Fig. 21, if a pea be placed between the index and middle finger, so as to touch the outer side of the index finger and the inner side of the middle finger, a sensation of touching *one* round body is experienced ; but

if the fingers be crossed, so that the pea touches the inner side of the index finger and the outer side of the middle finger, there will be a sensation of *two* round bodies, because, in these circumstances, there is added to the feelings of contact a feeling of distortion (or of muscular action) like what would arise if the fingers, for purposes of touch, were placed in that unnatural position.

The knowledge of the tactile field is usually precise and definite. This is illustrated by the well-known fact that when a piece of skin has been transplanted from

Fig. 21.—Experiment of Aristotle.

the forehead to the nose, in the operation for removing a deformity of the nose caused by ulcerative disease, the patient may feel the new nasal part as if it were in his forehead, and he may have a headache in his nose. The mind receives the messages thus transmitted to definite points in the cortex, and assumes that these messages come from the locality from which similar messages have come over and over again. Thus it is that a man may feel pain in the toes of an amputated limb ; and a medical man, who had the misfortune to lose his leg by amputation, told the writer that for years

he sometimes felt pain in a troublesome *corn* that once existed in the amputated member.   There can be no doubt, however, that our knowledge of the tactile field depends largely on the education of the sense, not merely in the individual, but in the race.   Even in the individual much may be done to improve it.   Few, for example, have any knowledge of touching anything with the third toe, because this part of the body is not used in collecting tactile information, but a little practice will soon show any one that sensations may be referred to this part with almost as great ease as to the ball of the great toe, which is in habitual use.

Theories as to Touch.—Various theories have been propounded to explain the phenomena of tactile sensibility, but it cannot be said that any one is wholly satisfactory.   The oldest, first put forth by Weber, and modified by various psychologists, states that while we refer every tactile sensation to a certain position in the tactile field, we do not refer it merely to a point, but to a minute area of skin, which has been termed a *circle of sensibility*.   It is also assumed that we can refer a sensation to each circle, as when we touch the skin with the point of one leg of the compasses in Weber's experiment, above described.   If, however, we bring *both* points within one circle, we still have a sensation of one contact, not of two contacts.   Even if the point of the second leg be placed on another circle immediately adjoining, there is still a sensation of only one contact, and to secure a sensation of two contacts it is necessary, according to this theory, to have always one or more circles intervening, or, to put the matter in another form, there must always be "a non-irritated sensory element" between the two points touched.   It is also supposed that each circle has its own nerve fibre.   There is no proof, however, that this is the case.   The extent of such hypothetical circles can be altered by practice and efforts of attention.

We may therefore assume either that the circles overlap, or that even the same circle may be innervated by several nerve filaments, so that when any part of the circle is touched, various nerve filaments may be excited. One can conceive, however, that the nerve filaments in one circle may not be excited to an equal degree, and that the resulting sensation may thus be variously modified. The suggestion of Krause, that the sensitiveness depends on the number of tactile corpuscles in a given area, is worthy of special notice. He states that the distance of the two points of the compasses at which two points are felt includes, in the mean, twelve tactile corpuscles. It is no doubt true that tactile corpuscles are not absolutely essential to touch. The cornea is sensitive, and yet it contains no such bodies, and when portions of the skin which, by experiment, were found sensitive to touch, were extirpated and microscopically examined, no touch bodies were found. Still, on the other hand, we know that where the sense of touch, and especially the power of discrimination of points, is more acute, there touch corpuscles abound ; so we are entitled to conclude that they act as accessory mechanisms to the sense. Further, it must not be forgotten that processes occur in the nerve centres, and that we must not look to the skin alone for an anatomical explanation. When a nerve cell in the brain receives a nervous impulse by a nerve originating in a given area of skin, the impression may be diffused, by irradiation, to neighbouring nerve cells, which are connected by nerve fibres with adjoining areas of skin. If this be so, then the effect on these cells—in accordance with the law that sensations in nerve centres are referred to the origins, in the periphery, of the sensory nerve fibres reaching them—will be referred to the adjoining areas of skin, or, in other words, to adjoining points in the tactile field.

Sensations of Temperature.—The skin is also the organ by which we appreciate temperature, and it is not improbable that there are thermal nerves and thermal end-organs. Sensations of heat and cold can only be felt by the skin. Direct irritation of a nerve does not give rise to these sensations. Thus if we plunge the elbow into very hot water, or into ice-cold water, we do not experience heat or cold by thus irritating the ulnar nerve, which lies here just below the skin, but there is a painful sensation referred to the extremities of the nerve. The exposed pulp of a diseased tooth, when irritated by hot or cold fluids, gives rise to pain, not to sensations of temperature. Recent observations show that there are minute areas on the skin in which sensations of heat and cold may be more acutely felt than in adjoining areas. Some of these areas are more sensitive to cold, and hence are called *cold spots*, and others, more sensitive to heat, have received the name of *hot spots*, and they appear to be, or to contain, end-organs, arranged in points, subservient to a temperature sense. A topographical view of such spots on the radial half of the dorsal surface of the wrist, as depicted by Goldscheider, is shown in Fig. 22. A simple method of demonstrating this curious phenomenon is to use a solid cylinder of copper, eight inches in length, by $\frac{1}{2}$ inch in thickness, and sharpened at one end to a fine pencil-like point. Dip the pointed end into hot water, close the eyes and touch parts of the skin. When a hot spot is touched there is an acute sensation of burning.

FIG. 22.—C, Cold spots; H, hot spots. (Goldscheider.)

Such a spot is often near a hair. Again, in another set of experiments, dip the copper pencil into ice-cold water and search for the cold spots. When one of these is touched, a curious sensation of cold, as if gathered to a point, is experienced. It will be found, in this way, that in a given area of skin there may be hot spots, cold spots, and tactile spots. Cold spots are more abundant than hot spots. The spots are arranged in curved lines, but the curve uniting a number of cold spots does not coincide with the curve forming a chain of hot spots. Both spots may be perceived as double, by the Weberian method, but we can discriminate cold spots at a shorter distance than hot spots. Thus on the forehead cold spots have a minimum distance of .8 mm. and hot spots 4 mm.; on the skin of the breast, cold spots 2 mm. and hot spots 5 mm.; on the back, cold spots 1.5 mm. and hot spots 4 to 6 mm.; on the back of the hand, cold spots 3 mm. and hot spots 4 mm.; on the palm, cold spots .8 mm. and hot spots 2 mm.; and on the thigh and leg, cold spots 3 mm. and hot spots 3.5 mm. No terminal organ for this sense has yet been found. Electrical and mechanical stimulation of the hot or cold spots call forth the corresponding sensation. This indicates that a special terminal organ probably exists.

It is highly probable that there are nerve filaments specially devoted to conveying to the nerve centres what may be termed thermal impressions, and possibly there may be parts of the brain specially connected with the translation of such impressions into sensations of temperature. A leg sent to "sleep" by pressure on the sciatic nerve will be found to be less sensitive to heat, but distinctly sensitive to cold. In some cases of disease it has been noticed that the skin is sensitive to a temperature above that of the limb, but insensitive to cold.

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Tactile and thermal sensations affect each other. Thus a weight is always felt to be heavier when it is cold than when it is hot, and the minimum distance at which two compass points are felt is diminished when *one* point is warmer than the other. Not unfrequently in diseases of the nervous system tactile sensibility may be diminished or increased without the sense of temperature being affected, and the reverse condition also occurs.

The skin, as an organ for the appreciation of temperature, may be considered from another point of view. In a warm-blooded animal (that is an animal possessing a heat-regulating mechanism by which the mean temperature of its body is maintained fairly constant although the temperature of the surrounding medium may vary within wide limits) the mean temperature of the skin is regulated by the amount of blood passing through it in a given time, and by the degree of activity of the sweat glands. Heat is lost from the skin both by radiation and conduction. If a man stands before a thermal pile connected with a sensitive galvanometer, the radiant heat from his body is at once detected by the movement of the needle of the galvanometer. In this case heat leaves his body by radiation, and also reaches the thermal pile by convection through the air. Again, when he stands before a fire he becomes warm, heat entering the body. When he touches anything it feels hot or cold, according as it conducts heat out of or into the skin. In this way the amount of heat entering or issuing from the skin is constantly varying, and the skin appreciates these variations. When any part of the skin is above its normal mean temperature, warmth is felt; in the opposite case, cold. The following are the chief points that have been ascertained regarding the appreciation of variations of temperature.

(1) With a skin temperature of from 15°.5 C. to 35° C.,

the tips of the fingers can distinguish a difference of .2° C. Temperatures below that of the blood (33° C. to 27° C.) are distinguished by the more sensitive parts even to .05° C.

(2) Parts having the thermal sense acute occur in the following order : Tip of tongue, eyelids, cheeks, lips, neck, belly. The smallest difference of temperature, in degrees centigrade, appreciated by the skin of the breast is .4°; back, .9° ; back of hand, .3° ; palm, .4° ; arm, .2° ; back of foot, .4° ; thigh, .5° ; leg, .6° to .2° ; cheek, .4° ; temple, .3°, giving a mean of about .3°—that is, $\frac{3}{10}$ of a degree centigrade.

(3) Sensations of heat and cold may alternate. Thus, if we dip the hands into water at 10° C. we feel cold ; then transfer them to water the temperature of which is 16° C. and there will be a feeling first of warmth and then of cold.

(4) The extent of the area subjected to heat or cold influences the sensation. For example, the whole hand dipped into water at 29°.5 C. feels warmer than when the finger is dipped into water having a temperature of 32° C.

(5) Great sensibility to differences of temperature is noticed after removal, alteration by vesicants, like cantharides, mustard, or strong acetic acid, or destruction of the epidermis, and in the skin affection (known to be of nervous origin) termed herpes zoster. On the other hand, removal of the epidermis increases tactile sensibility.

Pain.—The sensation termed pain is often referred to the skin, and is due to direct irritation of sensory nerves. Ordinary sensory nerves convey impressions from all parts of the body to the nerve centres, and these impressions give rise to sensations, often of a vague and evanescent character, such as a feeling of general bodily comfort, free or obstructed breathing, hunger, thirst, fatigue, etc. If such nerves are more strongly irritated the sensation becomes one of pain, and, in accordance with the law of the peripheral

reference of sensation, the sensation may be referred to the origin of the nerve in the skin. Sometimes this pain is distinctly located, but in other cases it may be irradiated in the nerve centres, and then referred to areas of skin or regions of the body which are not really the seat of the irritation. The acuteness or intensity of pain depends partly on the intensity of the irritation, and partly on the degree of excitability of the sensory nerves at the time. Sometimes, for example, the excitability of sensory nerves may be so high that a whiff of air may cause acute distress. If only a few nerves are affected the pain is acute and piercing, but if many nerves are involved it may be more massive and diffuse in character. The quality of pain— whether it is piercing, cutting, throbbing, gnawing, dull, or boring—depends on the nature of the irritation, and on whether the irritation is constant or intermittent. Lastly, in many nervous diseases involving the centres of sensation, disordered sensations may be referred to the skin, such as abnormal feelings of heat or cold, 'creeping, itching, burning, or a sensation of insects crawling in the skin, all giving rise to great distress.

The Muscular Sense.—As a rule, we do not judge of the weight of a body by the sense of pressure on the skin alone, but we lift the body and come to a conclusion as to its weight by a sense of the muscular tension necessary to support it against gravity. This is the so-called muscular sense. It depends on sensory nerves originating in the muscles, and carrying impressions from these to the nerve centres. Weber made some ingenious experiments on the delicacy of the muscular sense. Thus he placed certain weights in a cloth, and held it suspended by the four corners, so as thus to remove the effect of pressure or friction, and then he endeavoured to form a judgment as to

the weights by the sensations of muscular resistance referred to the muscles of the forearm. He found that he was unable to form a correct estimate of the amount of the weight either by the muscular sense or by the tactile sense, but he found the muscular sense more discriminating than the tactile sense as to estimation of differences of weight. Thus, by the muscular sense he was able to distinguish weights the ratio of which was as 39 : 40, while by the tactile sense (sense of pressure) he could only distinguish weights the ratio of which was as 29 : 30. There is not so accurate a perception of *locality* in connection with muscular as there is in the case of tactile impressions—that is to say, there is no well-defined muscular field like the tactile field. In actual experience, tactile and muscular impressions are blended so as to give a sharp representation of the position at any time of the parts of the body, as well as of any change in such position brought about even by a *passive* movement. Thus, if we place the arm of a blindfolded person across the chest, he is immediately conscious of the position of the limb, although he has made no muscular effort. Finally, when active movements are made by which the limb is placed in a certain position in space, we have contributing to the mental representation of this position, not only tactile and sensory muscular impressions, but also the sense of *effort* necessary to cause the muscles actively to perform the requisite movement. This sense of effort may be called a *sense of innervation*, and is distinct both from the muscular sense, properly so called, and from the tactile sense.

THE SENSE OF TASTE

THIS sense is located chiefly in the tongue, but sensations of taste may also be referred to the soft palate and even to the region of the fauces. The *tongue* is a muscular organ covered with mucous membrane. By means of its complicated movements it plays an important part in chewing, in swallowing, and in articulate speech. The mucous surface of the organ is covered with minute prominences or *papillæ*, of which there are three kinds. Most abundant are the *filiform papillæ*, small cylindrical bodies, about one-twelfth of an inch in length. Interspersed with these are the *fungiform papillæ*, so called because each consists of a narrow stem supporting a flattened top, something like the shape of a mushroom. They are shorter than the filiform papillæ, varying from one-fiftieth to one-twelfth of an inch in length, and they may often be detected by their bright red colour, caused by their great vascularity. Towards the root of the tongue we find the third kind of papillæ, the *circumvallate*, eight to fifteen in number, arranged in the form of a V, with the apex directed backwards. Each papilla, surrounded by a deep circular furrow—hence the name—consists of connective tissue clothed with epithelial cells, and their height varies from one-twenty-fifth to one-fifth of an inch, and their breadth from one-twenty-fifth to one-eighth of an

inch. It is in connection with the fungiform and circum-vallate papillæ that we find the terminal organs of taste.

Minute Structure of Gustatory Organ.—In many of the fungiform and in all the circumvallate papillæ are the structures called taste buds or taste goblets. They also occur to a small extent on the soft palate, and even on the surface of the epiglottis. They are most conveniently studied in the tongue of the rabbit. Two oval patches — *papillæ foliatæ*—may be seen with the naked eye near the root of the tongue of this animal, one on each side and placed obliquely. Each patch consists of about twenty laminæ or folds of mucous membrane, running parallel, like the leaves of a book, and each fold is composed of three ridges of the derma. Thus a transverse section gives the appearance seen in Fig. 23.

It will be seen that the epithelium is thick over the top and thin at the sides of the fold, and that, in section, the space between two folds has the appearance of a deep groove.
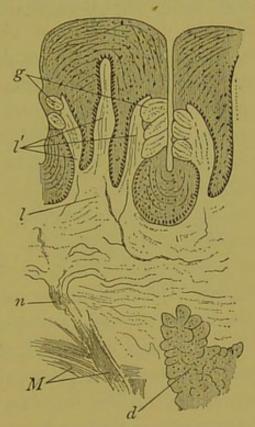
FIG. 23.—Vertical section through a portion of the *papilla foliata* of a rabbit × 80 d. Each fold, *l*, has secondary folds, *l'* ; *g*, taste goblets ; *n*, medullated nerve fibres ; *d*, a serous gland ; *M*, muscular fibres of the tongue. (Stöhr.)

About the middle of the depth of this groove we find a row of minute oval bodies, from three to five in number —these are the *taste buds*, or *taste goblets*. They exist in immense numbers. In the papillæ foliatæ of the rabbit there are from 14,000 to 15,000, while the tongues of the sheep and pig have yielded 9500, and that of the ox 30,000

taste buds. As many as 1760 have been counted on one circumvallate papilla of an ox.

The taste buds are oval bodies, one-three-hundredth of an inch in length by about one-six-hundredth of an inch in breadth, embedded in the epithelial layer. The base rests on the derma, while the other and somewhat narrower end is directed towards the sides of the papilla or folds already described, and shows a minute funnel - shaped opening, called the *taste pore.* Each taste bud is formed of three kinds of epithelial cells : an outer set, of almost uniform breadth throughout, and shaped somewhat like the staves of a cask, and an inner of two varieties, smaller and pointed at each end. The outer cells—*protecting cells*— forming the outer part, are evidently structures that serve the purpose of protecting the more delicate cells in the interior of the little flask. There appear to be two kinds of inner cells. First, we find cells that are narrow and slightly thickened in the middle, where there is a nucleus, surrounded by only a very small amount of cell substance. The outer half of the cell is first cylindrical, then conical, and ends in a fine point, while the inner half runs deeply, sometimes divides into two roots, and is lost in the under- lying tissue. Such cells have been termed *rod cells*, and they probably support the true sensory cells that are found in the middle of the flask. These—the true *taste cells*— are similar in appearance to the rod cells, but more delicate ; and their external portions, in the form of fine threads, converge so as to form a tuft at the taste pore. Both the rod cells and the true taste cells stain with chloride of gold, and behave, to chemical reagents, like sensory cells.

Terminations of Gustatory Nerves.—As to the way in which the nerve fibres terminate there is still consider- able doubt. The fibres of the glosso-pharyngeal nerve ramify in the derma, or tissue underlying the taste buds,

forming plexuses or networks from which minute twigs pass into the taste buds. Many of these fibres are non-medullated. Efforts to trace them into connection with the true taste cells, or with the rod cells, have failed, but there is little doubt that this is their mode of termination. Probably some fibres may not enter the taste buds at all, but may end by fine processes among the epithelium on the top or sides of the papilla.

The proofs that the taste buds are the end organs of taste may be shortly stated as follows: (1) The sense of taste is weakened or absent in those areas of mucous membrane on the tongue from which they are absent or exist only in small numbers; (2) the sense is most acute where they are found in large numbers; (3) section of the glosso-pharyngeal nerve, which is distributed to the area of mucous membrane where taste is present, is followed by degeneration of the rod and taste cells, and ultimately by the entire disappearance of the taste bud.
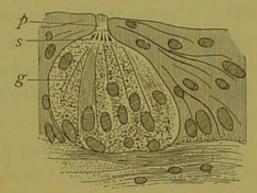
FIG. 24. — Taste bud seen in the papilla foliata of a rabbit × 560 d. *g*, Taste bud, showing outer supporting cells; *s*, fine ends of taste cells; *p*, taste pore. (Stöhr.)

Physical Causes of Taste.—All substances that give rise to taste are soluble in the fluids of the mouth. Insoluble substances are tasteless. Thus, if we touch the surface of a crystal of quartz with the tongue, we have a sensation of smooth contact, or touch, and a sensation of cold, because the crystal conducts heat out of the tongue, but there is no sense of taste. Contrast this with the sensations of saline taste, contact, and coolness experienced when we bring the tongue into contact with the surface of a crystal of rock salt. As solution is a necessary condi-

tion of taste we find near the taste organs numerous small
serous or albuminous glands (see Fig. 23), the secretions
of which assist in dissolving sapid substances. No con-
nection has yet been traced between the chemical composi-
tion of sapid substances and the different kinds of tastes to
which they give rise. Substances of very different chemical
composition may give rise to similar tastes. For example,
sugar, acetate of lead, and chloroform have all a sweetish
taste, although their chemical composition is as diverse as
can well be imagined. Acids are usually sour; alkalies
have a peculiar soapy taste; salts vary much, from the
sweetness of sugar of lead to the bitterness of sulphate of
magnesia; the soluble alkaloids, such as quinine, strych-
nine, etc., are usually bitter; and the higher alcohols are
more or less sweet.

Physiological Conditions of Taste.—The tongue, as
already pointed out, is the seat of sensations that are quite
unlike each other. Thus, there are tactile sensations, as
when we touch the organ with a pin, sensations of pressure,
sensations of heat and of cold, burning or acrid sensations,
peculiar sensations excited by the application to the tongue
of an interrupted electrical current, and, lastly, sensations
of true tastes. We must also distinguish from these, sensa-
tions that are called flavours, experienced when we bring
the tongue into contact with an onion or a savoury bit of
cooked meat or fish. These are in reality sensations
compounded of smells and tastes, and the sensation of
tasting an onion is thus quite changed when we hold the
nose and avoid breathing. True tastes may be classified
as sweet, bitter, salt, sour, alkaline, and, perhaps, metallic.
All of these are specifically distinct sensations, and they
are no doubt due to some kind of action, probably chemical,
which they excite in the taste cells. If we assume that
the taste cells are connected with the ends of the nerves,

then we can imagine that the chemical changes thus excited in the taste cells set up nerve currents which, propagated to specific centres of taste in the brain, give rise there to molecular changes that in turn are related to consciousness.

While, however, chemical action probably lies at the root of the mechanism of taste, it is remarkable that true tastes may be excited by causes that are not strictly chemical. Thus a smart tap on the tongue may excite a taste; and Sülzer demonstrated, so long ago as 1752, that a constant current causes (more especially at the moments of opening and of closing the current) a sensation of acidity at the anode (positive pole) and of alkalinity at the kathode (negative pole). No doubt it is possible that the mechanical irritation, in the one case, and the electrical current, by electrolysis, in the other, may set free chemical stimuli; but of this there is no proof. On the other hand, it has been found that sensations of taste may be excited by rapid induction currents—currents too rapid to produce electrolytic action.

The extent of surface acted on increases the *massiveness* of the sensation of taste, while the *intensity* is influenced by the degree of concentration of the solution of the sapid substance. Suppose we gradually dilute solutions with water, tasting from time to time, until no taste is experienced, some common substances may be classed in the following order: syrup, sugar, common salt, aloes, quinine, sulphuric acid. That is to say, the sweetness of syrup disappears first, and the sourness of sulphuric acid last. Again, it has been found that the taste of quinine continues until diluted with twenty times more water than common salt. It is evident, then, that smaller quantities of some substances, as compared with others, excite taste, or, in other words, the taste cells are more susceptible to the chemical action of some substances than of others. Attempts have been made

to measure the time required to excite tastes. Thus, from the moment of contact with the tongue, saline matters are tasted more rapidly (.17 second) than sweet, acid, and bitter (.258 second)—the difference being probably due to the activity of diffusion of the substance. After a taste has been developed, it appears to last for relatively a long time, but it is not easy to say whether this is due to a persistent change in the taste cells, after removal of the exciting cause, or to the continued action of the exciting substance. It is well known that a temperature of about 40° F. is most favourable to the development of tastes, fluids much above or below this temperature either masking or temporarily paralysing the taste cells. Thus, if the mouth be rinsed with either very hot or very cold water, a solution of sulphate of quinine, distinctly bitter at a temperature of 40° F., will scarcely be perceived.

As one would expect from the anatomical distribution of the taste buds, the surface of the tongue is not uniformly sensitive as regards taste. The sense is most acute in or near the circumvallate papillæ. The middle of the tongue is scarcely sensitive to taste, while the edges and the tip are, as a rule, highly sensitive, although it is said that the sensitiveness of the edges varies much in different individuals. Taste is feebly developed on the soft palate and on the pillars of the fauces, so that after complete extirpation of the tongue, including the part bearing the circumvallate papillæ, feeble sensations may still remain.

Differentiation of Tastes.—Recent observations by Shore[1] have thrown light on the question whether there may be in the tongue different end-organs appropriated to special tastes. If all the taste buds are the same, it is difficult to explain why, in the majority of persons, the back part of the tongue is most sensitive to bitters and the tip to sweets,

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[1] Shore, *Jl. of Physiology,* 1891.

why saline matters are perceived most distinctly at the tip and acid substances at the sides, and why there should be individual variations, as undoubtedly is the case. Assuming that there are different kinds of taste cells, it might be possible to paralyse some without affecting others, and thus different sensations of tastes might be discriminated. This has been done by the use of the leaves of a common Indian plant, *Gymnema sylvestre.* If some of these be chewed, it has been found that bitters and sweets are paralysed, while acids and salines are unaffected. Again, certain strengths of decoctions of the leaves appear to paralyse sweets sooner than bitters. These interesting observations indicate the existence of different taste cells for sweets, bitters, acids, and salines; and it is clear that the region of the tongue most richly supplied with taste cells sensitive to sweets will respond best to sweet substances, while another region, supplied by taste cells sensitive to bitters, will respond best to bitter substances. In like manner the argument may be applied to other tastes. Suppose, again, a set of taste cells sensitive to bitter substances: it is conceivable that in whatever way these were irritated, a bitter taste would result. If so, a substance which applied to one part of the tongue would cause a sweet sensation, might cause a bitter if applied to a part of the tongue richly supplied with taste cells sensitive to bitters. This may explain why sulphate of magnesia excites at the root of the tongue a bitter taste, while applied to the tip it causes a sweet or acid taste. Saccharine, in like manner, is sweet to the tip and bitter to the back of the tongue. Again, it has been found that if the "sweet" and "bitter" taste cells are paralysed by gymnema, electrical irritation of the tip does not give rise to an acid taste mixed with sweet, but to sensations somewhat different, and described as "metallic," or "salt," or "acid."

General Sensibility of the Tongue.—As already said, the tongue is endowed with acute general sensibility. It is evident, then, that a sensation caused by dropping a little vinegar on the tongue is due partly to stimulation of the tactile organs, and partly to stimulation of the true taste cells. Cocaine, the active alkaloid of the coca plant, paralyses tactile sensibility ; and it is said that if the surface of the tongue be painted with a solution of this substance, that acid tastes become more clear and marked. The drug, however, ultimately affects all the end organs, so that lingual sensations disappear in the following order : general sensibility and pain, bitters, sweets, salines, acids, and tactile sensibility.

Subjective Tastes.—Disease of the tongue causing unnatural dryness may affect taste. Substances circulating in the blood sometimes give rise to subjective sensations of taste. Thus santonine, morphia, and biliary products, as in jaundice, cause a bitter sensation, while in diabetes there is often a persistent sweetish taste. The insane occasionally suffer from distressing subjective tastes. In such cases the sensation is caused by irritation of the gustatory nerve, or by changes in the taste centres of the brain. There is, however, no evidence showing that direct irritation of gustatory nerves is followed by sensations of taste.

Nerves of the Tongue.—The distribution of nerves to the tongue is remarkably complicated, and the whole subject presents numerous difficulties. The motor nerve, that is, the nerve that excites and governs the movement of the tongue, is the ninth cranial nerve, known to anatomists as the hypo-glossal. The sensory nerves are usually described as two in number, the anterior two-thirds of the tongue being supplied by the gustatory or lingual branch of the fifth cranial nerve, and the posterior third—the situation of the circumvallate papillæ—by the glosso-pharyngeal nerve.

The lingual branch of the fifth nerve contains both ordinary sensory and gustatory filaments, and the glosso-pharyngeal supplies the circumvallate papillæ and taste buds. Another nerve, however, has to be considered, namely, the chorda tympani, a branch given off by the facial nerve during the passage of the latter through a canal in the petrous portion of the temporal bone known as the aqueduct of Fallopius. Loss of taste on one side of the tongue has been observed in cases of disease of the ear involving the chorda nerve. This, however, is not conclusive evidence that the chorda contains gustatory filaments, as the loss of taste following its injury may be due to the removal of its influence over the nutrition of the mucous membrane of the organ. On the other hand, there are good grounds for the view that the gustatory filaments, both of the lingual branch of the fifth, and of the glosso-pharyngeal itself, come primarily from the roots of the fifth nerve. Disease of this nerve within the cranial cavity causes loss of taste in one lateral half of the tongue, both tip and back, but no case has been recorded of disease of the glosso-pharyngeal being followed by this result.

THE SENSE OF SMELL

THE seat of the structures concerned in the sense of smell is in the *nasal cavities*, situated between the base of the
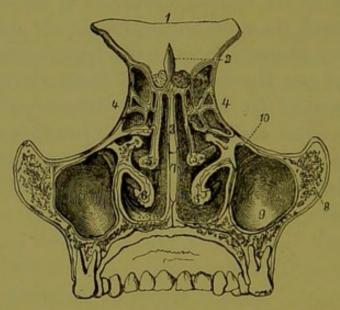
FIG. 25.—Transverse vertical section across the nasal cavities, opposite to the middle of the hard palate; the anterior part of the section seen from behind. 1, Part of inner surface of cranium; 2, projection between the two cribriform plates of the ethmoid bone; 3, median septum or partition in the ethmoid bone; 4, 4, cells in the lateral masses of the ethmoid bone; 5, 5, the middle turbinated portion of the ethmoid bone; 6, 6, the two turbinated bones; 7, the vomer, or bony septum or partition, of the nose; 8, section of the malar or cheek-bone; 9, a large sinus or space in the superior maxillary bone—sometimes called the maxillary sinus, or antrum of Highmore; it communicates with the nasal cavity, at 10, and there is a corresponding space on the other side. (Arnold.)

cranium and the roof of the mouth, at the upper and fore part of the face. The floor, sides, and roof of these cavities

are formed by certain of the bones of the cranium and face (see Fig. 25).

Physiological Anatomy of the Nose.—The *ethmoid bone*, which also forms part of the floor of the cranial cavity, is concerned in the formation of the olfactory region. Thus its cribriform plates form the roof; its sides, which contain numerous cavities or cells formed of bone, constitute the convoluted sides of the upper part of the cavity; and a median plate of bone, forming a septum or partition, assists in dividing the one nasal cavity from the other. The anterior part of the nasal cavities is completed at the sides and in the middle by plates of cartilage or gristle, called the *nasal cartilages*. These cartilages are firmly attached to the margin of the nasal aperture seen in a skull, and they give form and firmness to the visible part of the nose.

The nostrils open anteriorly by apertures called the *anterior nares*, and they are lined by an infolding of skin, bearing short stiff hairs, *vibrissæ*, which, to some extent, prevent the entrance of foreign bodies. Posteriorly, the nostrils open into the pharynx by two apertures, the *posterior nares* (see Fig. 26). The middle wall of each nostril is formed by the septum or partition between the two, and presents a smooth surface. The outer wall, on the other hand, is more or less convoluted from the presence of three delicate scroll-like bones, namely, the upper and middle turbinated parts of the ethmoid, and the lower turbinated bones (see Fig. 25, 5, 6). There are thus three spaces, or recesses, called the *superior*, *middle*, and *inferior* meatus, and these meatuses communicate with cavities, called *sinuses*, in the ethmoid, sphenoid, frontal, and upper jaw-bones. These spaces, along with the cavity of the nose itself, being full of air, act as resonators, and affect the quality of the voice.

The *cavity* of the nose is lined by a membrane, called the *nasal mucous membrane*, or *Schneiderian membrane*,

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which secretes a peculiar kind of mucus known as *pituita.*
The lining membrane is continuous with that of the sinuses
already mentioned, and with the lining of the pharynx and
Eustachian tube, while it is prolonged on each side, through a
small canal, into the lachrymal sac, thus also merging into
the conjunctiva, the mucous membrane of the eye-lids.
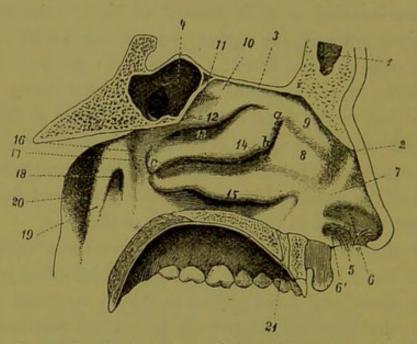
FIG. 26.—Outer side of left naris. 1, Sinus or hollow in the frontal bone; 2,
    free border of the nasal bone; 3, lamina cribrosa or perforated plate of
    ethmoid bone, through which pass the twigs of the olfactory nerve; 4, an-
    trum or hollow of the sphenoid bone; 5, hairs in the vestibule of the nose;
    6, 6′, vestibule of the nose separated by a prominence, 7, from 8, the entrance
    to the middle meatus or passage of the nose; 9, *agger* or mound of the nose,
    the rudiment of a muscle; 10, concha or shell of Santorini; 11, entrance
    to 4; 12, superior spongy bone; 13, upper meatus; 14, middle spongy
    bone; its inferior free border from *b* to *c*; 15, inferior spongy bone; 16,
    naso-pharyngeal fold; 17, naso-pharyngeal duct; 18, pharyngeal opening
    of the Eustachian tube; 19, fold between 18 and pharynx; 20, depression
    of Rosenmüller; 21, the incisor canal. (Schwalbe.)

The *nerves* supplying the nasal mucous membrane come
from three sources. First, it is supplied by the nasal and
anterior dental branches of the fifth pair of cranial nerves;
second, branches are distributed to it from the vidian, naso-
palatine, descending palatine, and spheno-palatine nerves,
in which run fibres of the sympathetic; and, third, we find

in the upper part of the nasal cavities branches of the first pair of cranial nerves, the olfactory nerves. The first two groups of nerves endow the nose with general sensibility, and supply its blood-vessels and glands. The olfactory nerves are the true nerves of smell, and their branches end in the special terminal organs devoted to that sense.

The *olfactory lobes* (see Fig. 8, p. 21) lie within the cranium on the cribriform, or sieve-like, plates of the ethmoid bone, and about twenty small branches, the *olfactory nerves*, issue from their under surface, pass through minute canals in the ethmoid bone, and thus gain the upper part, or roof, of the nasal cavities. There they divide into three groups, one supplying the roof, a second the membrane covering the cellular part of the ethmoid bone, while the third pass as low as the middle turbinated bone. Some fibres also reach and are distributed to the upper third of the nasal septum.

The nasal mucous membrane is richly supplied with blood, a dense capillary network lying below the epithelial layer. The veins converge to the posterior part of the lower meatus, where they form a thick dense plexus. The existence of so many vessels accounts for the nasal hæmorrhage often observed, and as the bleeding not unfrequently proceeds from the venous plexus situated far back in the cavities, it is sometimes staunched with difficulty.

Minute Structure of the Olfactory Organ.—As already mentioned, the membrane lining the movable (anterior) part of the nose is developed from an infolding of the skin, and in structure it resembles skin, showing a layer of stratified squamous epithelium covering papillæ. In it we find numerous sebaceous glands and hair follicles, from which *vibrissæ* spring. This part of the nose, the *vestibular portion*, is at the entrance of the respiratory passage. The *respiratory portion* forms the lower part of the nasal

passage. It is lined by a stratified cylindrical epithelium, the cells of which bear cilia, short vibratile processes, by the movements of which currents are established in the fluid bathing the surface. In this portion, the membrane of which is about one-sixth of an inch in thickness, are numerous minute racemose glands secreting a fluid, thus keeping the surface moist, and it is noticeable that in the sinuses already mentioned the membrane is much thinner, and only very few glands exist.
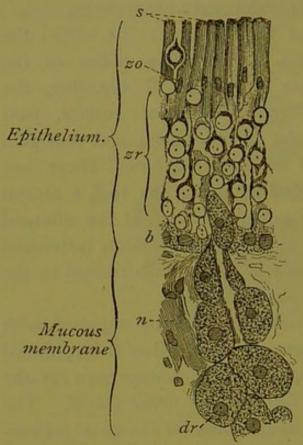
FIG. 27.—Vertical section through the olfactory region of a rabbit, magnified 560 diameters. *s*, Border; *zo*, zone of the oval nuclei; *zr*, zone of the round nuclei; *b*, basal cells; *dr*, portions of Bowman's glands. The lower part of the duct is seen on the right. *n*, branch of olfactory nerve. (Stöhr.)
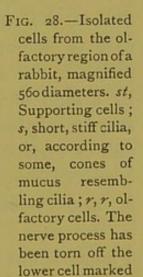
The upper, or *olfactory portion*, is the part specially connected with the sense of smell. It is narrow from side to side, and clothed with a thick mucous membrane, often of a yellowish - brown colour, that contrasts with the reddish hue of that lining the vestibular and respiratory regions. A vertical section of this membrane is seen in Fig. 27. It is formed of an epithelial layer, *olfactory epithelium*, resting on a basement membrane. Two forms of cells are found. The one (Fig. 28, *st*) has the upper half cylindrical, and the free border sometimes shows minute stiff cilia, while the lower half is narrowed, shows indentations, and finally ends in long, sometimes double, processes, which

apparently join with those of adjoining cells. These knife-handle-like cells, called *supporting cells*, show each an oval nucleus, and the rows of such nuclei, seen in a section, as in Fig. 27, form a zone, known as the *zone of oval nuclei*. The second cells have a round nucleus surrounded by only a small quantity of protoplasm, and from this there passes to the surface a narrow round filament, bearing a single cilium on its free end, while another slender filament passes in the oppo-site direction, and terminates in filaments of the olfactory nerve. These are the *olfac-tory cells*. The juxtaposition of the round nuclei forms a zone, called the *zone of round nuclei*. At the boundary of the epithelial layer with the connective tissue, peculiar, somewhat flattened or irregularly cubical cells are found, termed *basal cells* (Fig. 27, *b*). The layer on which the epithelium rests is a loose felt work of connective tissue, con-taining elastic fibres, and the latter may be so close together as to form an elastic layer. Numerous simple or branched glands exist in the olfactory region, named after their discoverer the *glands of Bowman*. They secrete mucus, but their special function is unknown.

FIG. 28.—Isolated cells from the ol-factory region of a rabbit, magnified 560 diameters. *st*, Supporting cells ; *s*, short, stiff cilia, or, according to some, cones of mucus resemb-ling cilia ; *r, r*, ol-factory cells. The nerve process has been torn off the lower cell marked *r*. (Stöhr.)

As to the mode of termination of the olfactory nerves there is still considerable difference of opinion, some holding that they end only in the true olfactory cells (Fig. 28, *r*), while others maintain that they also end in the basal cells (Fig. 27, *b*), and even in the supporting cells (Fig. 27, *s*, and Fig. 28, *st*). The evidence is clear that they end in the olfactory cells, but doubtful as regards the others, and, from the analogy of

other end organs, it is probable that the basal and support-
ing cells have only indirectly to do with the action of odori-
ferous substances on the nerve-endings.

Physical Causes of Smell.—Substances that excite the
sense of smell must exist in the atmosphere in a state of
fine subdivision, and even vapours and gases may be
supposed to consist of minute molecules of matter. If air
conveying an odour be passed through a long glass tube
packed firmly with cotton wool, it will still be odorous,
although this proceeding will remove all particles larger
than the one - hundred - thousandth of an inch. Again,
a grain of musk will for years communicate its odour to
the air of a room, and at the end of the time it will
not have appreciably diminished in weight. Odoriferous
particles will mix with the air either in accordance with
the laws of diffusion of gases or by virtue of their volatility,
that is, the rapidity with which they evaporate. In the
case of odorous gases, no doubt mixture takes place by
diffusion, but an odorous essential oil will give off particles
by a kind of evaporation. The volatility of a substance
may be expressed by the weight that evaporates from a
unit of surface in a unit of time. By means of a specially-
contrived instrument Ch. Henry has measured the volatility
of various odorous substances, and, as might be expected, it
is very great. Thus, taking unity as the one-thousandth of
a milligramme [1] evaporating from one square millimetre in
one second, the following values were obtained : ether, .7 ;
ylang - ylang, .0176 ; rosemary, .0446 ; caraway, .0315 ;
mint, .0354 ; winter-green, .0165 ; bergamot, .0331 ; and
lavender, .0292. These minute quantities are readily
appreciated by the sense of smell, if the nose is held near
the evaporating surface.

[1] The one-thousandth of a milligramme = one twenty-five-millionth
of a grain.

Chemical nature of odorous substances.—Attempts have been made, notably by Ramsay and Haycraft, to discover a relation that might exist between odours and the chemical composition of substances emitting them. Certain gases excite smell, while others are odourless. Thus the following having no smell : hydrogen, oxygen, nitrogen, water gas, marsh gas, olefiant gas, carbon monoxide, hydrochloric acid, formic acid, nitrous oxide, and ammonia. It is necessary, of course, to distinguish between the irritant action of such gases as ammonia and hydrochloric acid, and the true odour. On the other hand, the following gases have an odour : chlorine, bromine, and iodine, the compounds of chlorine and bromine with oxygen and water, peroxide of nitrogen, the vapours of sulphur and phosphorus, arsenic, antimony, sulphurous acid, carbonic acid, some compounds of selenium and tellurium, the compounds of chlorine, bromine, and iodine, with the above-named metals, and many of the volatile compounds of carbon. Substances of low molecular weight either simply irritate the nose, or have no odour. Ramsay states that in the carbon compounds increase of specific gravity as a gas is related (up to a certain point) to smell. Thus, if we take the methane or marsh gas series (the paraffins), the first two have no smell, ethane (fifteen times as heavy as hydrogen) has a faint odour, and it is not till we reach butane (thirty times heavier than hydrogen) that a distinct odour is noticeable. Again, methyl alcohol has no smell ; ethyl, or ordinary alcohol, has a true alcoholic smell, " and the odour rapidly becomes more marked as we rise in the series, till the limit of volatility is reached, and we arrive at solids with such a low vapour tension that they give off no appreciable amount of vapour at the ordinary temperature." [1] Again, acids increase in odour with an increase in density as a

[1] Ramsay, *Nature*, vol. xxvi. p. 187.

gas.   Formic acid, for example, has no smell ; acetic acid
has its well-known odour of vinegar ; and propionic, butyric,
and valerianic acids increase in odour as we ascend the
series.   Groups of chemical substances have sometimes
characteristic smells.   Thus many compounds of chlorine,
sulphur, selenium, tellurium, the paraffins, alcohols, nitrites,
amines, the pyridenes, and the benzene group have each a
characteristic odour.   Again, substances not related, but
similar in chemical structure, may have somewhat similar
odours.   Thus the compounds of hydrogen with sulphur,
selenium, and tellurium, and the compounds of these with
methyl or ethyl, have all a disagreeable odour, something
like that of garlic.   The odours of chloroform and iodoform
are not unlike.

On the other hand, many substances have odours that
are very similar, and yet there is no resemblance in chemical
constitution.   Why, for example, should arsenical com-
pounds have the odour of garlic ?   Why have nitro-benzene,
benzoic aldehyde, and prussic acid almost the same odour ?
Mix sulphuric acid with water, and an odour like that of
musk may be given out.   It is said that emeralds, rubies,
and pearls if triturated for a long time give out an odour like
that of violets.   Again, the disease called favus, ringworm
of the scalp, the body of a patient sick of typhus, and mice
have similar odours.   It is well known that perfumes
from very different sources may be classed under certain
types.   Thus, the rose type includes geranium, eglantine,
and violet-ebony ; the jasmine type, lily of the valley and
ylang-ylang ; the orange type, acacia, seringa, and orange-
flower ; the vanilla type, balsam of Peru, benzoin, storax,
tonka bean, and heliotrope ; the lavender type, thyme and
marjoram ; the mint type, peppermint, balsam, and sage ;
the musk type, musk and amber seed ; and the fruity type,
pear, apple, pine-apple, and quince.

Flowers and odours.—Attempts have also been made to discover a relation between the colours of flowers and the intensity of their perfumes. White flowers manifest the greatest variety of odours, and then follow reds, yellows, greens, and blues. The ratio of the number of odorous species to the number of species in each colour, is as follows : whites, 1 to 6.37 ; reds, 1 to 10.8 ; yellows, 1 to 12.6 ; greens, 1 to 12.7 ; and blues 1 to 19. It is also noticeable that flowers which by their colour emit most heat will volatilise the greatest amount of perfume, and that the more refrangible the rays reflected from the flower the smaller is the amount of perfume. Coloured substances have also different powers of absorbing odours. Whites, yellows, reds, greens, and blues absorb odours on a decreasing scale. The more intense the colour the more likely is it to emit a strong odour, because no doubt the light acts on the essential oil on which the odour depends. Heat more than light favours the volatilisation of perfumes. Hence the odours of a flower-bed in a garden are often most apparent, not in bright sunshine, but in the shade. Some essential oils require a higher temperature than others to bring out their characteristic perfumes. An air of moderately high temperature and the presence of moisture favour the diffusion of the odours of most flowers.

Odours and heat absorption.—Tyndall showed that many odorous vapours have a considerable power of absorbing heat. Taking the absorptive capacity of air as unity, the absorption per cent. for certain odorous matters was as follows : patchouli, 30 ; sandal-wood, 32 ; geranium, 33 ; oil of cloves, 33.5 ; otto of roses, 36.5 ; bergamot, 44 ; neroli, 47 ; lavender, 60 ; lemon, 65 ; portugal, 67 ; thyme, 68 ; rosemary, 74 ; oil of laurel, 80 ; and cassia, 109. In comparison with the air introduced in the experiments the weight of the odours was extremely small. " Still we find

that the least energetic in the list produces thirty times the effect of air, while the most energetic produces one hundred and nine times the same effect." [1]   These results, although interesting, are not of the value they would have possessed if the tensions of the odorous vapours had also at the same time been determined because the tension of the vapour would influence its capacity for absorbing radiant heat.

Odours and ozone.—It is remarkable that on the one hand ozone (condensed, or allotropic oxygen, O_3), as produced by electricity, develops the odours of the essential oils, and on the other, that these oils produce ozone by their action on the oxygen of the air.   Thus, slow oxidation of oil of turpentine, or of one of the essential oils, produces ozone.   Ozone, again, exists in the air of the sea-side when the grassy banks are clothed with wild thyme and other scent-giving plants, and it abounds on the heather-clad hills, more especially when the heather is in bloom.   This suggests that the atmosphere of our cities might be ozonised and made more healthy by the free use of odorous substances like oil of turpentine or the perfumes.

Odours and surface tension.—Some of the physical characters of odorous bodies have been studied by Venturi, Prévost, and Liégeois.   It is well known that if minute fragments of camphor or succinic acid are placed on the surface of pure water, they move with extreme rapidity, owing to changes in the surface tension.   If odorous particles are placed on a glass plate, the surface having been previously moistened with water, the particles at once fly from each other, it may be to a distance of several inches.   This simple method constitutes the *odoroscope* of Prévost.   Liégeois has pointed out that the movements of camphor in water are arrested when an odorous substance is brought into contact with the water.   The odorous oil or essence at

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[1] Tyndall, *Contributions to Molecular Physics*, p. 99.

once forms a pellicle on the surface of the water, and this pellicle consists of minute particles, not broader than from .001 to .003 of a millimetre (that is, from $\frac{1}{25000}$ to $\frac{1}{8330}$ of an inch).[1] This shows how the dissemination of odours is favoured by moist surfaces. Flowers give off odours most powerfully after a shower of rain. No doubt also when the odoriferous substance falls on the moist olfactory membrane it is rapidly disintegrated into extremely minute particles, which are thus more readily brought into close relation with the olfactory nerve endings.

These figures, given by Liégeois, are probably far too high, and consequently the particles are much smaller. Calculation shows that the thickness of the layer of oil which is necessary to stop the movement of small pieces of camphor over a definite area surface of water amounts to only 1.5 millionth of a millimetre [2] (that is, about one-sixteen-millionth of an inch).

Special Physiology of Smell.—The air containing the odour must be driven against the membrane. The nostrils may be filled with an odoriferous substance like eau-de-cologne, or air impregnated with sulphuretted hydrogen, and no smell will be experienced if no inspiration is made. When we make a sniff, the air in the nasal passages is rarefied, and as the odour-bearing air rushes in to equilibrate the pressure, it is forcibly driven against the olfactory surface. Odorous air passing from the posterior nares also gives rise to a sensation of smell, although not so intense as when it passes in the normal direction. An odour may be perceived even although the nostrils are full of fluid. Weber stated that no odour was noticeable if the nostrils were full of water, but Arensohn has shown that this was because the water injured the olfactory surface,

[1] Liégeois, *Archiv. de Physiologie*, 1868.
[2] Lord Rayleigh, *Proc. Roy. Soc.*, 28th March 1890.

and that if the water was replaced by a weak solution of common salt (.07 per cent—an inert fluid), odours were readily perceived. It is well known, also, that fishes possess a sense of smell. Fragments of bait cast into the water soon attract fishes to a fishing-ground, and that at depths into which little or no light can penetrate. The fish must smell the odoriferous morsels.

The *intensity* of an odour depends (1) on the number of olfactive particles, and (2) on the extent of olfactory surface affected, or, in other words, on the number of nerve-endings stimulated. It is remarkable that sensations of odours are very evanescent. Hence to maintain the sensation fresh particles must be brought to act on the olfactory surface, and when we wish to maintain the sensation experienced in sniffing the delicate odour of a flower, we sniff and sniff again.

The *delicacy* of the sense varies much in different individuals and in different animals. It is highly developed both in carnivora and herbivora. The dog, for example, appears to depend on the sense of smell almost to as great an extent as on the sense of sight, and olfactory impressions probably are to him both more vivid and more permanent than to a man.

Attempts have been made to combine odours, but without success. Thus, if we fill each nasal passage with a different odour, we do not experience a mixture of two sensations, but the odours come alternately, and we smell only one at a time. There is usually a difference as regards olfactive sensibility between the two nasal cavities, when they are tested with the same odour.

Beaunis,[1] by noting exactly the moment that an odour is experienced after it has been presented to the nose, has discovered that this time is not the same for all odours.

[1] Beaunis, *Recherches expérim.*, 1884.

Some have greater power of penetration than others, the maximum being reached by ammonia, and the minimum by musk, and odours analogous to it. This power of penetration is in the inverse ratio to the divisibility of the odorous substance. He divides odours into (*a*) *pure odours*, like musk, which he terms scents or perfumes, and (*b*) *mixed odours*, like that of peppermint, in which there is a combination of odour with a vague tactile sensibility referred to the mucous membrane. To these we may add (*c*) substances like acetic acid, that act at the same time on the olfactory nerves and on the tactile nerves of the mucous surface—the latter action being stronger and more irritating than in the case of *b*, the mixed odours, and (*d*) substances that act only on the tactile nerves, like carbonic acid.

Mode of Excitation of the Olfactory Nerves.—No satisfactory theory of smell has yet been offered. Graham suggested that the odorous substance was probably oxidised on the olfactory surface, but this view was founded only on the observation that odorous substances are readily oxidisable. Ramsay has offered the theory that smell may be excited by vibrations—the period of vibration of the lighter molecules being too rapid to affect the sense—then a number of vibrations is reached capable of exciting the sense organ, while beyond an upper limit the vibrations again are not attuned to the sense organ and the odour disappears. All this is merely speculative, and has no foundation on experiment. Schultze was inclined to the view that the action might be mechanical, because he found minute stiff cilia on the olfactory surface, but this mechanism is far too coarse for the appreciation of the almost infinitesimal amount of odorous substances capable of exciting the sense. Stimulation by electricity has thrown no light on the question. The opening and closing of a

continuous current, led to the olfactory surface through a
solution of common salt at a temperature of 38° C., cause
a sensation of an odour like that of phosphorus. The
action of odours is not through the medium of the ether,
the movements of which account for the phenomena of
light. Odours have to do with the grosser forms of matter,
and all the evidence is in favour of some kind of chemical
action, the nature of which, however, is quite unknown.

Loss of the sense of smell is termed *anosmia*. This is a
rare condition, usually congenital. In such cases all tactile
sensations referred to the mucous membrane of the nose, and
all tactile and gustatory sensations referred to the tongue,
may exist. The sense of smell alone is absent. Subjective
sensations of odour are rare, but they have been found in
the insane, and are due to excitation of the part of the
brain connected with the sense of smell.

The sense of odour, termed by Kant *taste at a distance*,
gives us information as to the quality of food and drink,
and more especially as to the quality of the air we breathe.
Hence we find the organ placed at the opening of the respira-
tory passage and in close proximity to the organs devoted
to taste. Taste is at the gateway of the alimentary canal,
just as smell is the sentinel of the respiratory tract, and
just as taste, when combined with smell to give the sensa-
tion we call *flavour*, influences the digestive process, and is
influenced by it, so smell influences the respiratory process.
This has recently been shown by Ch. Henry.[1] He has
recorded the entrance and exit of air by the nose, with
and without odours (the quantity of odoriferous substance
being noted), and he finds that the presence of odours
influences both the amplitude and the number of the

[1] Ch. Henry, *Revue Scientifique*, 1892, p. 73.

respiratory movements. Thus the smell of winter-green notably increased the respiratory work ; next came ylang-ylang ; and last rosemary. The breathing of a fine odour is therefore not only a pleasure, but it increases the amplitude of the respiratory movements. Just as taste and flavour influence nutrition by affecting the digestive process, and as the sight of agreeable or beautiful objects, and the hearing of melodious and harmonious sounds, react on the body and help physiological well-being, so the odours of the country, or even those of the perfumer, play a beneficent rôle in the economy of life.
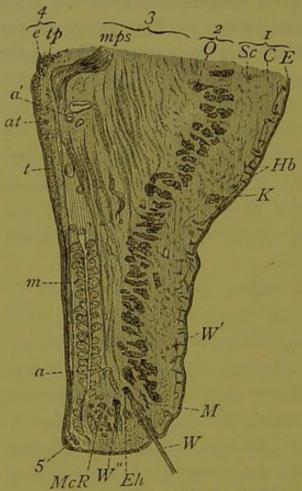
FIG. 29.—Antero-posterior section through upper eyelid, × 7 d. 1, Outer skin—E, epidermis ; C, corium; Sc, subcutaneous tissue; H*b*, fine hairs; K, M, sweat glands ; W, eyelash; W′,W″, roots of eyelashes; E*h*, reserve hair ; 2, muscles for closing eye—O, muscular bundles cut transversely ; McR, ciliary muscle of Riolanus ; 3, tendon of muscle elevating the eyelid, *mps* ; 4, conjunctival region ; *tp*, tunica propria ; *e*, conjunctival epithelium ; *at*, gland ; *t*, tarsus ; *m*, Meibomian gland ; *a*, *a′*, arteries ; 5, corner of eyelid. (Stöhr.)

THE sense of sight differs from the senses of taste and smell in this important particular, that through it we seem to become aware of the existence of things which are entirely apart from us, and have no direct or material link connecting them with our bodies. Yet physicists tell us that in vision the eye must be affected by a something which is as certainly material as a sapid or an odorous substance, and which, permeating the universe, transmits by its vibrations movements that affect the eye, and give rise to the sensation of light, or to the perception of even the most distant objects. This medium for the transmission of light is

called the luminiferous ether, and our eyes are so constituted as to respond to its vibrations ; changes are set up in the optic nerve and in the brain, and we see.

That the eye may be sufficiently sensitive to the ray of light, its sensory surface must be carefully protected from all hurtful influences.   Accordingly, we find that the eyeball, embedded in soft fat, is placed in a socket whose margins are formed of strong bone which can withstand heavy blows ; it is also protected from drying by the action of the lachrymal gland which secretes a watery fluid, and from dust and foreign bodies by the lids with their long eyelashes.   The watery fluid which bathes the eyes passes away by two fine pores at the inner angles of the eyelids into a passage to the nose, and is prevented from overflowing and running down the cheeks by an oily secretion coming from glands in the upper eyelid (Fig. 29, *m*) which anoints the edges of the eyelids (Fig. 29).   Furthermore, the eyebrows protect the eyes from perspiration trickling from the forehead.   The eye may be moved in various directions by muscles which will be described later.

I.—STRUCTURE OF THE EYE

Coats of the Eyeball.—The *eyeball* is nearly spherical in shape, but is slightly elongated from before backwards, for the front part, which is clear and transparent, to allow the entrance of the rays of light, bulges forward somewhat prominently.   The ball is elastic but firm, and is enclosed by a covering which may be divided into three layers, each of which has important functions to discharge.   (For the relative position of the various parts of the eyeball see Fig. 30.)

1. The outermost coating is composed of a layer of firmly

H

felted fibrous tissue, which, being very tough, preserves the form, and prevents rupture of the eyeball. To it the muscles that move the eyeball are attached. It is called the *sclerotic* (Greek, *scleros*, hard), and the part of it seen when the eye is open is known as the "white of the
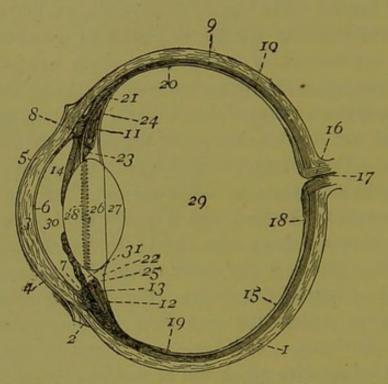

FIG. 30.—Diagrammatic section of the eyeball. 1, Sclerotic; 2, junction of sclerotic and cornea; 3, cornea; 4, 5, conjunctiva; 6, posterior elastic lamina; 7, junction of iris with choroid; 8, canal of Schlemm, a lymph space; 9, pigmented tissue uniting sclerotic to choroid; 10, choroid; 11, 12, 13, ciliary processes; 14, iris touching, but not connected with lens posteriorly; 15, retina lined by hyaloid membrane; 16, optic nerve; 17, central artery of the retina; 18, yellow spot with central groove; 19, 20, anterior portion of retina; 21, junction of choroid and ciliary processes; 23, free border of ciliary process resting on anterior suspensory ligament of lens; 22, canal of Petit; 24, hyaloid membrane; 25, fibres to posterior surface of lens; 26, 27, 28, lens; 29, vitreous humour; 30, anterior chamber containing aqueous humour; 31, posterior chamber communicating with 30.

eye." In early childhood the white of the eye, being thin, appears bluish in tint from the pigment seen through it, while in old age it becomes yellowish by a deposit of fat.

The clear transparent circular disc in the front of the eye, the *cornea*, is a modification of this external coat. The

fibres of the cornea are united by a cement substance into transparent sheets or membranes, which lie parallel to one another like the coats of an onion, but connected together by many intercommunicating fibres (Fig. 31). In the flat spaces between the fibrous sheets lie numerous corpuscles, flattened, transparent, and branching so as to join with one another. The fibrous substance of the cornea is lined in front and behind by a homogeneous elastic layer, that at the back of the cornea being the thicker and called the posterior elastic lamina of Bowman, or the membrane of Descemet. This lamina is itself covered on its posterior aspect by a layer of flattened cells lying side by side as in a tesselated pavement. There are no blood-vessels in the cornea, nutrition being effected through the branching cells.

The whole of the exposed part of the eye is covered with a transparent epithelium or skin called the *conjunctiva*, which is continuous all round with that lining the eyelids, and which, closely adherent to the cornea, and more loosely joined to the sclerotic, forms a sensitive protective covering for the open eye.
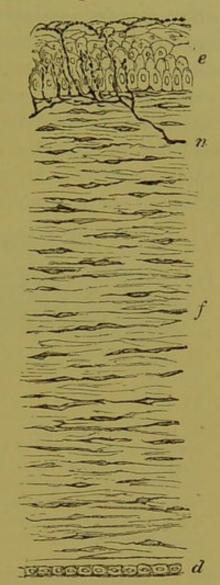
FIG. 31.—Antero-posterior section of cornea. *e*, Conjunctiva; *n*, nerve sending branches to cornea and conjunctiva; *f*, fibres of cornea between which are flattened spaces containing corpuscles; *d*, layer of cells covering posterior surface of cornea, and separated from the fibrous part by the posterior elastic membrane. (Schofield.)

2. The middle coat, the *choroid*, is largely composed of blood-vessels which branch frequently in its outer part,

and form a very fine network of capillaries to the inside. The blood-vessels of the choroid coat are known as the *ciliary* arteries and veins. The veins as they emerge join together in a stellate fashion, forming groups, the *venæ vorticosæ*, from the union of which single veins pass outwards through the sclerotic. The spaces between the vessels are occupied by elastic fibrous tissue, and by cells loaded with granules of very dark brown pigment, the whole being bound together by cement substance. The colouring matter render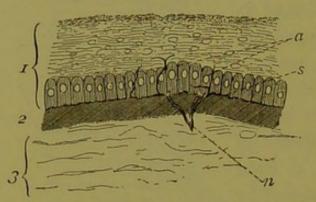s the choroid opaque, and absorbs the rays of light passing into the eye, thus preventing their reflection to and fro in the interior of the eyeball, and the confused vision that would ensue therefrom.

FIG. 32.—Antero-posterior section through conjunctiva and fore part of human cornea, ×240 d. 1, Conjunctiva; *a*, nerve fibres in conjunctiva; *s*, network of nerve fibres between conjunctiva and cornea; 2, anterior elastic membrane; 3, substance of cornea with *n*, a nerve passing through it. (Stöhr.)

The choroid is closely united to the sclerotic by means of connective tissue, but just where the sclerotic merges into the cornea an interesting and important alteration occurs. Were the choroid to line the cornea as it does the sclerotic, light could not enter the eye. Accordingly this coloured layer hangs separate from the cornea as a curtain or ring of variable size called the *iris* (*iris*, a rainbow), and is pierced by an aperture known as the *pupil*, through which light may enter. The space between the iris and the cornea, the *anterior chamber*, is filled with a watery fluid, the *aqueous humour*. The back of the iris is lined with dark pigment, and according as the substance of the iris contains less or more pigment, the eye has a blue, gray, or

brown colour. The central aperture is usually black, from the pigment absorbing most of the light that enters the eye, so that almost none is reflected out again ; but sometimes, as in albinos, the pigment is awanting, and then the pupil is pink, as may be seen in white rabbits. In many of the lower animals the pupil is often seen of a greenish lustre owing to partial reflection of light from the back of the eye. In herbivora this iridescent gleam is due to the arrangement of the fibres to the outside of the capillary layer in a
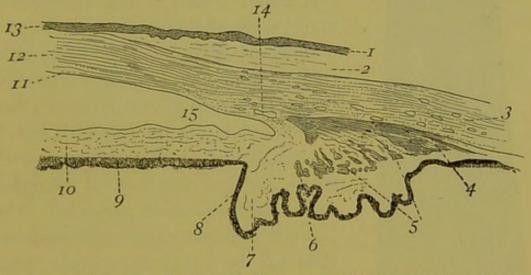
FIG. 33.—Meridional section through ciliary region of human eye, × 20 d. 1, 2, Epithelium and loose connective tissue of conjunctiva ; 3, sclerotic ; 4 meridional, 5 radiating, and 6 circular fibres of ciliary muscle ; 7, ciliary process ; 8, ciliary part of retina ; 9, pigmentary layer on the posterior surface of the iris ; 10, the iris ; 11, the posterior elastic lamina ; 12, the cornea ; 13, conjunctiva ; 14, canal of Schlemm ; 15, in the anterior chamber points to junction of iris with sclerotic. (Stöhr.)

structure called the *tapetum*, while in carnivora and birds of prey it is brought about by reflection from cells which contain minute crystals and act like prisms.

The amount of light, moreover, which enters the eye is regulated by variation in the size of the pupil. There are contractile fibres radiating in the iris like the spokes of a wheel, and when these contract the pupil dilates. On the other hand, if too much light is entering the eye, a circular band of muscle fibre in the iris, near the margin of the pupil,

contracts, and the pupil is lessened in size. The iris is joined to the sclerotic by muscular as well as by connective tissue. The muscular 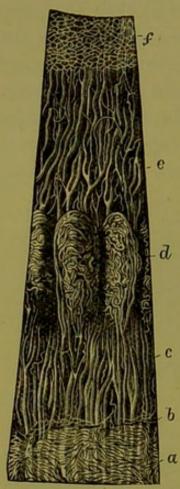fibres are disposed, partly so as to radiate from the junction of the cornea and sclerotic to that of the iris and choroid, and partly to form a ring round the outer border of the iris, as seen in Fig. 33. Together they form what is called the *ciliary muscle*, and this assists largely in accommodating the eye for the perception of objects at different distances. Just behind the ciliary muscle lies a curious modification of the choroid, consisting of a ring of tooth-like tufts of capillary blood-vessels, bound together by connective tissue, and pointing towards the pupil. These are the *ciliary processes*. The choroid and ciliary processes are lined internally by a thin transparent membrane, known as the *membrane of Bruch*.

FIG. 34.—Blood-vessels of the choroid and iris of the human eye seen from within. *a*, Capillary vessels of the choroid; *b*, serrated line of union of choroid with ciliary processes; *c*, veins of ciliary ring; *d*, capillaries of ciliary processes; *e*, radiating veins of ciliary part of iris; *f*, vessels of pupillary zone of iris. (Arnold.)

3. The innermost coat, the *retina*, is the terminal organ of vision, and is almost transparent, with a pinkish tinge, except at a point in the visual axis called the *yellow spot*, of which more anon. The retina contains the terminal branches of the optic nerve, which, piercing the sclerotic and choroid in the human eye at a point about $\frac{1}{10}$ of an inch nearer the nose than the antero-posterior axis of the eye, and forming an oval area known as the *optic pore*, spreads out in nerve fibres ramifying over all the

interior of the eye as far forward as the ciliary processes. These nerve fibres are the more transparent as they are simply axis cylinders, devoid in the retina of the white substance of Schwann. They are supported by connective tissue which is found in most parts of the retina as fibres passing radially, the *fibres of Müller*. The connective tissue also forms external and internal limiting membranes and a fine network through the substance of the retina, keeping the various elements in their proper places. Small blood-vessels are also found in the inner layers of the retina.
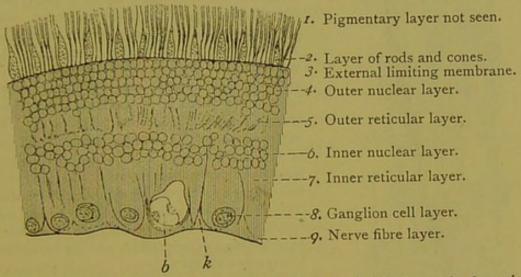

1. Pigmentary layer not seen.
2. Layer of rods and cones.
3. External limiting membrane.
4. Outer nuclear layer.
5. Outer reticular layer.
6. Inner nuclear layer.
7. Inner reticular layer.
8. Ganglion cell layer.
9. Nerve fibre layer.

FIG. 35.—Vertical section of human retina, × 240 d. *b*, Blood-vessel ; *k*, conical base of radiating sustentacular fibre of Müller. The base of several fibres uniting gives rise to the appearance of an internal limiting membrane. (Stöhr.)

After spreading over the *fundus* or concavity of the retina, the nerve fibrils turn outwards and become connected with a set of ganglionic cells (see Fig. 36), from which, again, fibres may be traced outwards for a certain distance. These fibres are believed to become connected with nuclei, which are found in two layers to the outside of the ganglionic cells, and from the outer layer of nuclei fibres pass to the true terminal sensory organ, the so-called *Jacob's membrane* or *layer of rods and cones*. This layer lies outside of and upon the external limiting membrane.

The rods and cones consist alike of an inner and an outer part.   In the cones, the inner part is thick and conical, and exhibits a longitudinal striation (Fig. 37); in the rods it is thinner: both are connected with nucleated fibres, internal to the outer limiting membrane.   The outer part of the rods
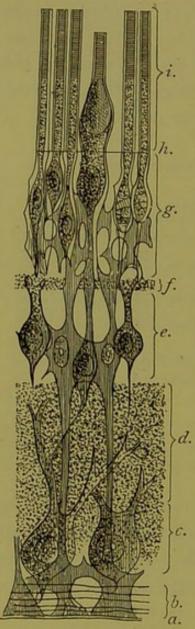
FIG. 36.—Diagram showing retinal elements. Two fibres of Müller with expanded bases at *a*, pass outwards as fine cylindrical processes, giving off slender lateral twigs (not shown in diagram) in the reticular layers *d* and *f*, and forming meshworks in the layers *e* and *g*. The spaces of the meshwork are occupied by nuclei. The fibres terminate in the external limiting membrane *h*.   Opposite *c* two ganglionic cells are seen, their inner processes continuous with optic nerve fibres in *b*, their outer processes breaking up into numerous twigs in *d*.   The nuclei of the layer *e* belong partly to the fibres of Müller, partly to cells which send many branching processes to the outer and inner reticular layers, and probably establish functional continuity between the ganglion cells and the rods and cones. The nuclei of *g* are surrounded by a thin layer of protoplasm, and are connected externally with the rods and cones by processes perforating the external limiting membrane, and internally by fine fibres known respectively as rod and cone fibres, with the network of the outer reticular layer.   The nuclei connected with the rods show one or two transverse dark bands.   The rods and cones of the layer *i* show the differentiation into an outer and inner limb. The outer limb of the cone is shorter than that of the rods.   (Zehender.)

is of a pink colour, and considerably longer than that of the cones, but both exhibit a transverse striation, and, under the influence of macerating reagents, tend to break up into highly refractile discs.   The rods are much more numerous than the cones, but the fore part of the retina has cones

only, while the part of the retina lining the iris has neither rods nor cones. On the other hand, in the yellow spot above mentioned we find cones but no rods. Here, too, we find the layer of ganglion cells at first thickened, but soon thinning, and there is formed in the centre of the yellow spot a short groove or depression, the *fovea centralis*, where the various layers of the retina above described disappear, and we find only a layer of cones with the fine terminations of the nerves. This spot is the seat of most distinct vision. Outside of, and in apposition with, Jacob's membrane lies a layer of hexagonal cells, containing, more especially on their inner side, a vast number of pigment granules of a brown colouring matter called *fuscin* or *melanin*. Under the action of light, the cells send processes carrying the pigment inwards between the outer segments of the rods and cones, and thus absorb the rays of light after they have passed through the retina. If the eye is kept in darkness for some time, these processes are withdrawn into the main bodies of the cells, and the layer of pigmented epithelium may then be easily detached from the adjoining layer of the retina (Fig. 39).
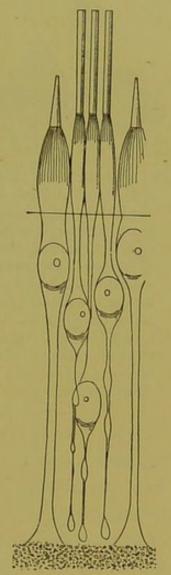
FIG. 37.— Diagram of rods and cones, showing faint longitudinal striation of inner limbs of rods and cones, and varicosities of the rod-fibres. (Max Schultze.)

Contents of the Eyeball.—Inside of, and closely adherent to, the retina we find a perfectly transparent, highly elastic bag called the *hyaloid membrane* (*hyalos*, glass), which might be compared to the membrane lining the shell of an egg. This bag is filled with a transparent

glassy-like jelly, like white of egg, called the *vitreous humour* (Fig. 30, p. 98), and composed of fluid, penetrated in all direc-
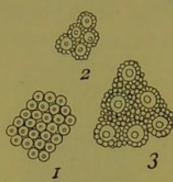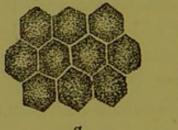

FIG. 38.—Rods and cones seen from without on removal of pigmentary layer. The larger circles represent the inner limb of the cones; the smaller central circles, the outer limb of the cones. In 2 and 3, the cones are surrounded by rods. 1, From the yellow spot; 2, from border of yellow spot; 3, from middle of retina.

tions by fine fibres and a few connective tissue cells. In front, the hyaloid membrane closely adheres to the circle of ciliary processes but not to the iris, and it splits into two layers or suspensory ligaments, which are attached to a capsule in which lies the *crystalline lens*. The suspensory ligament forms a ring called the *zonule of Zinn*, and bounded by the two layers and the lens is a triangular space containing fluid, and called the *canal of Petit*. The ligament, it may be noted, is much plicated by following the convolutions of the ciliary processes, and the posterior layer is perforated with numerous apertures (Fig. 30).

The *lens* is composed of fine flattened fibres hexagonal in cross section, and with serrated edges which fit exactly into one another, and are bound together by a kind of cement substance. The fibres run in an obliquely meridional direction (see Fig. 41, C), not forming complete semicircles from pole to pole, but fixed at their ends to a tri-radiate mass of cement substance, whose rays form angles of
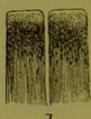

FIG. 39.—Hexagonal pigmented cells covering Jacob's membrane. *a*, Surface-view; *b*, cells seen from the side, sending fine processes between rods and cones. The lighter portion in the centre of the cells in *a*, indicates the non-pigmented nucleus. (Max Schultze.)

120° with one another, and, as they pass through the substance of the lens, are rotated like a wheel in motion

through an angle of 60°. The lens, like the capsule which holds it, is perfectly clear and transparent. Should it become ópaque, we have the disorder known as *cataract.* It has a biconvex form, its front surface being somewhat more flattened than that behind, but it is highly elastic, and the curves are constantly changing as the eye is accommodated for near and distant objects. The capsule surrounding the lens is very thin and elastic, and, by the tension of the anterior suspensory ligament, the surface of the lens is kept slightly flattened. In its earliest stages of development, the lens is formed by an invagination or growth inwards of a process of the deepest layer of the epidermis, which is cut off as a closed sac. The central cavity is obliterated by the elongation of the cells at the back of the sac, the cells in front remaining small and cubical, and forming the
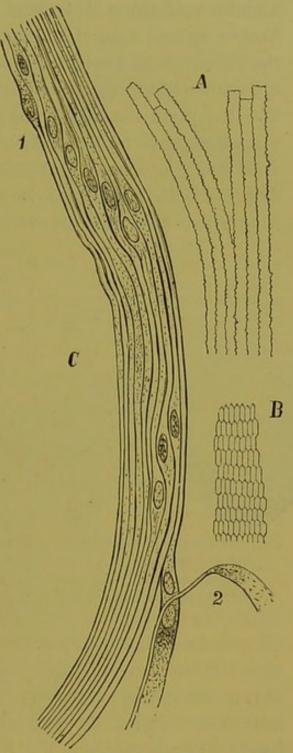
Fig. 40.—Lens fibres. A, From eye of ox showing serrated edges; B, cross section of lens fibres from human eye; C, fibres from the equatorial region of the human eye. The fibres are seen edgewise except in A and at C, 2. Near 1, nuclei of lens fibres. (Schwalbe, after Kölliker and Henle.)

anterior epithelium of the lens. The lens may be artificially broken up into a set of concentric layers (Fig. 42), in which the fibres run in a meridional direction, and the outer layers are softer and more gelatinous than those towards the centre. The lens from the eye of a lightly boiled fish affords convenient material for the study of the structure of the lens. It appears as an opaque white ball, but when the outer part is detached with a knife an inner translucent core is found, from which thin transparent sheets may be readily peeled
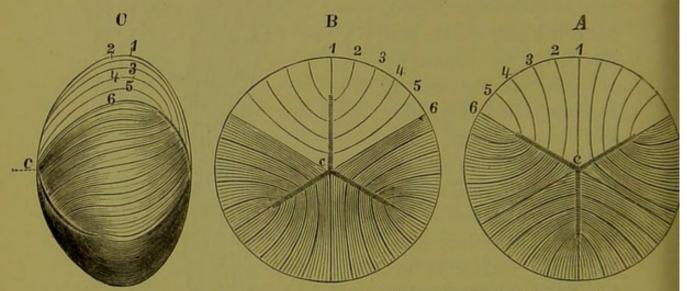

FIG. 41.—Diagram of arrangement of lens fibres. A Posterior, B anterior, and C lateral view. *c*, in each figure, indicates the centre of the tri-radiate cement substance. The numbers 1 to 6 indicate the same six lens fibres, the course they take being seen by comparison of the three figures. (Schwalbe.)

off and broken up into fibres. The iris, to have perfect mobility, hangs free, not only of the cornea in front, but also of the lens and its suspensory ligament behind, except in its central part round the pupil, where it rests lightly on the lens. The space behind the iris and in front of the lens and suspensory ligament is called the *posterior chamber*. This is filled with fluid, which is similar to, and in communication with, the aqueous humour in the anterior chamber. We thus see that the contents of the eyeball are all transparent, and light traversing the eye must pass first

through the conjunctiva and cornea in front, then through the aqueous humour, thereafter through the lens with its capsule, and finally through the vitreous humour and the hyaloid membrane.

The Optic Nerve. — The nerve fibres converge from all parts of the retina to the optic pore, and there passing through a membrane in which are many fine openings for their passage, the *lamina cribrosa*, they are grouped together into a bundle
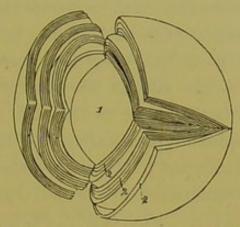
FIG. 42.—Laminated structure of the crystalline lens. The laminæ are split up after hardening in alcohol. 1, The denser central part; 2, 2, 2, concentric outer layers. (Arnold.)

forming the *optic nerve*. The optic nerve from each eye passes backwards, and entering the hollow of the cranium by a passage at the back of the orbit, joins with its fellow in a union called the *optic commissure*. At the commissure some of the fibres pass directly upwards into the brain, but in the human eye the most of the fibres from the inner or nasal half of each retina decussate, or in other words
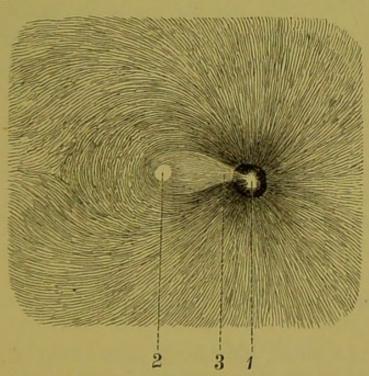
FIG. 43.—Course of nerve fibres in posterior part of retina. 1, Optic pore; 2, yellow spot (*macula lutea*); 3, fibres to yellow spot. (Schwalbe.)

cross over, and pass backwards to the half of the brain

opposite to the eye from which they have come, while fibres from the outer or temporal (next the temples) side of each retina pass back to the brain on the same side as the eye from which they have sprung. Hence it will be seen that almost all the fibres affected by rays of light which come from objects on the left side of the body (*a*, Fig. 44) will transmit impressions to the right side of the brain, while luminous impressions from the right side of the eyes will be transmitted to the left half of the brain. The bundles of nerve fibres continued behind the optic commissure are known as the *optic tracts*, and they pass to certain ganglia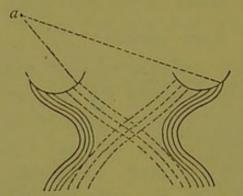 at the base of the brain, from which again fibres pass to the occipital or posterior part of the cerebral hemispheres, the stimulation of which gives rise to a sensation of light.

FIG. 44.—Diagrammatic representation of decussation of fibres of the optic nerves.

But the eye is in connection with other nerve fibres besides those of the optic nerve. We all know how sensitive the eye is to touch, and how acutely painful is any lesion of the eyeball. Impulses giving rise to tactile or painful sensations are sent to the brain through the medium of branches of a nerve known as the ophthalmic division of the fifth cranial, or great sensory, nerve of the head, from which there also pass to the iris several branches known as the long ciliary nerves, to whose function reference will shortly be made.

Again, the eye, as a whole, and certain parts within the eye, can be moved under the influence of muscular contraction, and to effect these movements we have the oculo-motor or third cranial nerve, and the fourth and sixth cranial nerves. The fibres of the third cranial which supply the

sphincter of the iris pass through a ganglion known as the *ciliary ganglion,* where they meet with fibres from the sympathetic system, and a branch from the ophthalmic nerve. From the ganglion a large number of twigs, the short ciliary nerves, pass to the back of the eyeball, where, having pierced the sclerotic coat, they run forward between the sclerotic and choroid coats to the ciliary muscle, the iris, and the cornea. Stimuli pass by the short ciliary nerves, as a result of which the pupil may vary in diameter, or the eye be accommodated for the perception of objects at varying distances.

Movements of the Pupil. — Various influences may cause change in the size of the pupil. The brighter the light entering the eye, the nearer the object we look at, or the more we converge the two eyes, the more the pupil contracts. In certain stages of poisoning by opium, tobacco, alcohol, chloroform, and physostigmin, in sleep, or in unconscious states as during an epileptic fit, the pupil may be contracted to a mere pin-hole aperture. Dilation of the pupil occurs when the light is dim, when the eye is looking at distant objects, when respiration is obstructed, or the body strongly stimulated ; under the effect of certain drugs, such as belladonna, or its active principle atropin, by Indian hemp or hyoscyamin ; in the later stages of poisoning by alcohol, chloroform, and other substances ; and under the influence of mental emotions, such as fear.

This change in size of the pupil is an involuntary movement, and goes on without consciousness upon our part, unless we are directly observing it in a mirror. It is of the nature of a reflex act. The usual exciting cause of the movement is a variation in the amount of light entering the eye, and a consequent variation of the amount of stimulus to the optic nerve. If the optic nerve is cut, or if the

centre to which it passes in the brain is destroyed, the pupil no longer contracts when light falls on the retina, although the oculo-motor or short ciliary nerves may still be directly stimulated by electricity or mechanical irritation, so as to cause contraction. Moreover, the third nerve contains at least two sets of fibres, stimulation of one of which causes contraction of the pupil, of the other, movements of accommodation, and, as might be expected, these fibres originate in different centres in the brain. These centres are situated close to each other in the basal ganglia, and on a lower level than the cortical centres involved in conscious vision.

The pupil is caused to dilate by stimulation of the sympathetic nerve which, coming from a ganglionic centre situated in the neck, and having entered the cranial cavity, becomes apposed to the ophthalmic nerve, and is given off to the eye from its nasal branch as the long ciliary nerves. There has been much discussion as to its mode of action, but apparently it supplies the dilating muscular fibres of the iris. The oculo-motor to the sphincter of the iris, and sympathetic to the dilating fibres of the iris, would thus seem to act as antagonists to each other. Moreover, they seem to keep up a constant balancing tonic action, because if one is injured the other immediately shows its power. For instance, if the sympathetic fibres be cut, the pupil will at once contract, and *vice versâ*. But this is merely a particular instance of the general law which regulates the condition of the muscles of the body, so long as their nerve supply is normal and in healthy action. Another point of interest in regard to the human eye is that a strong stimulus to one eye will cause contraction of both pupils. This is probably due to the incomplete decussation of the optic nerves, the fibres from one eye passing, as we have seen, to centres on both sides of the brain ; for in animals that

have a complete decussation, and want the power of binocular vision, this phenomenon is absent.

We should note in passing that the foregoing explanation of the mechanism of contraction and dilation of the pupil has been called in question by some physiologists. They deny that the so-called dilator of the iris consists of true - muscular tissue at all, and maintain that the sphincter action of contraction is the only really muscular act. Dilation is attributed to elastic recoil, the sphincter being held to be inhibited or thrown out of action by stimulation of the sympathetic. When the pupil contracts, the elastic radiating fibres are stretched ; when the muscle ceases to act, elasticity comes into play, and the pupil dilates. Recent observations seem to show that changes in the calibre of the blood-vessels of the iris, brought about by nervous action, are not the cause of variations in the diameter of the pupil. The iris of birds contains specially developed striated muscular fibres, and a more careful examination of such eyes may yet throw light upon this problem.

Drugs may act either directly upon the muscles of the iris, or indirectly through the nerve centres. Thus, even in an eye removed from the body, and cut off from all central control, atropin will cause dilation, physostigmin contraction of the pupil. The explanation of this is difficult, if we suppose that two antagonistic muscles are at work in the eye, for we would expect the poison to act on each alike, and that the pupil would remain unchanged in size. On the other hand, if there is only one muscle at work, we would say that atropin paralyses it, while physostigmin excites it to continuous and prolonged activity. The variation in size of the pupil from emotion, obstructed respiration, and the like, is, on the other hand, of a central kind—that is to say, in such conditions the activity of the central nervous system is augmented or diminished

I

with a corresponding effect upon the innervation of the eyes.

The observation has been made that the pupil of the eye of a cat isolated after death, and with even the posterior segment of the eye cut off, will slowly contract on continued exposure to light. This appears to indicate that the iris is susceptible to the action of light even without the presence of a nervous mechanism.

II.—PHYSIOLOGY OF VISION

The optic nerves are the nerves of vision. When stimulated or injured no pain is caused, but only a luminous sensation is aroused. Nor are the nerve fibres sensible to light, except in and through the retina. Light falling upon the exposed optic nerve will cause no sensation, but if the nerve be now affected by mechanical, electrical, or chemical means, a sensation of a flash of light is experienced. The sensation, however, is one of mere luminosity; it is not accompanied by the perception of any object. In order that an object may be perceived, an image of it must be formed on the retina, and hence we note the double function of the eye, the power of responding to light, due to the structure of the retina, and the power of perceiving objects due to the nature of the transparent media in front of the retina.

In many of the lower forms of animals we find nerves ending in coloured spots in the skin, and through these it may be the animal experiences a sensation of a special kind of light; but, in the absence of a lens or other refractive media, images cannot be formed on these spots, and such animals can have no visual perception of external objects. It will conduce, therefore, to a clear understanding of this·

matter, if we consider briefly the nature of the stimulus—light—and the laws of its transmission through various media, that is to say, the laws of dioptrics.

1.—LAWS OF DIOPTRICS

The Physical Nature of Light.—It was once held that a luminous body shoots out from itself minute particles, which, passing to the observer's eye, give rise upon impact to the sensation of light. This corpuscular theory has now been entirely disproved, and it is generally held by physicists that the undulatory theory, first enunciated by Thomas Young, affords a satisfactory explanation of all the phenomena of light. According to this view, light, objectively considered, is simply a mode of motion of a substance called the luminiferous ether which pervades, not only what is commonly regarded as space, but also all translucent substances. By the molecular movements of luminous bodies this ether is set vibrating in series of waves. The component particles of these waves may be conceived to move at right angles to the direction of the ray of light, just as waves rise and fall while spreading outwards when the surface of calm water has been agitated by a stone. Thus a cork floating on the water, traversed by a wave, oscillates up and down nearly at right angles to the direction of the wave. These wave-like movements of the ether impinging on the retina set up in it changes which result in the sensation of light, but the sensation in no way resembles its physical cause, although it varies with variation of the stimulus. The intensity of the sensation varies with the amplitude of the waves. Large waves give rise to a sensation of bright light, small waves to a sensation of dim light. Again, the sensation of colour depends upon the rapidity with which the waves follow one another. This rapidity,

though inconceivably great, may still be accurately determined. Ordinary sunlight, as Newton showed, is composed of a series of colours blended together, but yet separable one from another, because each colour is due to a series of waves differing in rate of succession from the others. Thus the waves of red light follow each other at the rate of about 435 millions of million times per second, while those of violet light succeed each other at about 764 millions of million times per second. Between these, we have an infinite number of series of waves, each giving rise to a special colour sensation, and so between the *red* and the *violet* of the spectrum we have a gradation of colour roughly described as *orange, green, blue,* and *indigo*, but each of these is itself made up of countless shades, which melt as gradually and imperceptibly into one another as the colours in a sunset sky. The eye is not sensitive to vibrations of the ether succeeding each other more slowly than those of red light, although it may be demonstrated that these exist and originate electrical and thermal phenomena; nor to those which come more quickly, although these have marked chemical activity, and give rise to fluorescence.

Reflection and Refraction.—Light waves are propagated through the ether at about 190,000 miles per second, but the rate varies according to the medium through which the light is passing. When the medium is homogeneous the ray passes in a straight line. When it meets a polished surface it is reflected; and the angle which the *reflected* ray makes with a perpendicular to the surface is equal to that which the ray meeting the surface, or, as it is called, the *incident* ray, makes with the same perpendicular. Further, the incident ray, the perpendicular, and the reflected ray will all be in the same plane. Few surfaces, however, are so highly polished as to conform entirely to the above laws. A certain part of the ray is usually

irregularly reflected or scattered, and it is owing to this fact that objects become visible, for it can be easily understood that if the rays were reflected entirely to the eye we would only be aware of the luminous body, and not of that which reflects the light.

When a ray of light passing through one transparent medium, such as air, meets another, such as water, perpendicularly, part of it is reflected upon itself, and part passes on in the same straight line through the water. If, on the other hand, the ray meets the surface of the water obliquely, the part which passes through the water continues in the same plane as before, but no longer passes in the same straight line. It is bent or *refracted* out of its course.

Some crystals have a power of *double* refraction—that is to say, the ray of light entering them is broken into two rays, each of which is deflected from the original course ; but as in explaining the phenomena of vision we do not have to deal with such substances, let it be understood

FIG. 45.—Diagram illustrating the law of the reflection of light from a plane surface. *i*O, Incident ray ; O*r*, reflected ray.

that what we have to say with regard to refraction refers merely to simple refraction or bending of the ray.

The *laws for single refraction* have been thus stated [1]—

1. Whatever the obliquity of the incident ray, the ratio which the sine of the incident angle bears to the sine of the angle of refraction is constant for the same two media but varies with different media.

2. The incident ray and the refracted ray are in the same plane, which is perpendicular to the surface separating the media.

This ratio of the sines of the incident and refractive angles is known as the *index of refraction* ; and if the ray

[1] Ganot's *Physics*, p. 466.

be supposed to pass from a vacuum through any transparent substance, this ratio is known as the *principal index of refraction* for that substance, and is commonly represented by the letter μ.

Knowing the index of refraction for any two media, we can calculate the direction which the ray of light will take as it passes through them.

Each singly refractive substance, then, has always the same bending power due to its special elasticity and consequent interference with the velocity of the ray of light. Water interferes more than air, glass than water; the diamond bends the ray of light more than any other known substance, or, in other words, is the most refractive substance known.

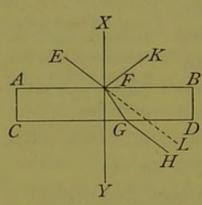*Effect of refraction on a ray passing through glass with parallel surfaces.*—Suppose the ray EF (Fig. 46) passing through air meets obliquely the upper surface AB of a plate of glass having parallel surfaces. Part of the light will be reflected in the direction FK, part will pass through the plate, but not in the original direction FL; it will be bent towards XY, the perpendicular to the surface, and will take the path FG. Meeting the surface CD, it now passes out into the air, where it immediately regains its former velocity, or in other words, is bent back again to its former direction, so that it now emerges as GH, not indeed in the same straight line as before, but in a parallel direction to its former course.

FIG. 46.—Diagram illustrating the refraction of a ray of light. For description, see text.

Effect of refraction when light passes from air through a prism.—When light falls obliquely on the sides of a prism it is doubly bent, as may be seen from the accompanying

figure. The ray GH (Fig. 47) meeting the surface AB at H, is bent towards DE in the direction HK, and emerging through the surface AC is bent away from EF in the direction KL, that is to say, it is bent away from its original course, and deflected towards the base of the prism.
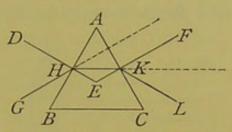

FIG. 47.—Diagram illustrating refractive power of a prism.

The amount of deflection depends upon the shape and material of the prism, and on the angle at which the ray of light impinges on its surface.

Action of Lenses.—A similar deflecting action is exercised by lenses, which may be looked upon as resembling two prisms in apposition by their bases or edges. Thus in Fig. 48, A and B represent pairs of prisms set respectively base to base, and edge to edge; C, D, and E are convex lenses, or, in other words, are thicker at their centre than at their circumference, and would exercise a deflecting power upon rays of light similar to that of A ; F, G, and H are concave
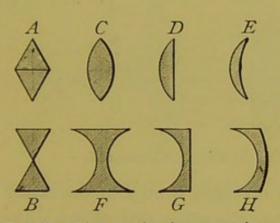

FIG. 48.—Diagram showing comparison of lenses to prisms set base to base or edge to edge. C, Biconvex; D, plano-convex ; E, concavo-convex ; F, biconcave; G, plano-concave; H, convexo-concave lens.

lenses, being thinner at their centres than their circumference, and would deflect rays of light in the same way as B. The biconvex lens is of most interest for our present purpose, for, like the transparent media of the eye, it has the property of condensing or focussing rays of light.

The common burning-glass or *biconvex lens* has, as a rule, spherical surfaces. If AB (Fig. 49) represent a biconvex lens, and the line CF its principal axis, *i.e.* the straight line

through the centre of curvature of its two surfaces, all rays parallel to CF meeting the surface ADB, will be brought to a focus at very nea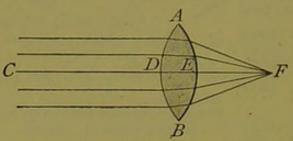rly the point F, which is called the *principal focus*; and, conversely, rays spreading from F will pass through the lens, and emerge in a parallel direction.

FIG. 49.—Diagram illustrating course taken by parallel rays of light refracted by biconvex lens.

If rays diverge from a point *f* (Fig. 50) in the axis of the lens *outside* of the principal focus, they will be brought to a focus at a point *f'* on the other side of the lens known as its *conjugate focus.*
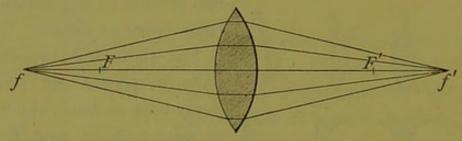

FIG. 50.—Diagram illustrating the law of conjugate foci.

If, as in Fig. 51, the rays diverged from *f* to the *inside* of F, they would still diverge on the other side of the lens ;

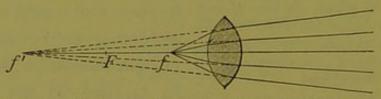FIG. 51.—Diagram illustrating position of virtual focus.

but now if produced backwards, would form a *virtual focus* at *f'*.

Formation of Images by Biconvex Lenses.—Any object at which we look may be regarded as made up of an aggregation of points, each of which sends a pencil of rays of light to the eye, and the main value of the lens for purposes of vision is its power of forming images of objects

by combining again the scattered rays. Thus all the rays from A falling on CD (Fig. 52) may be collected at the point A', all the rays from B at B', and rays from all intervening points of AB will meet at points along the line A'B', and thus an image of AB is formed, but *upside down* or *inverted*.

The *size* and *position* of the image depend on the position of the object with regard to the principal focus of the lens, and can be calculated by simple mathematical formulæ. In Fig. 52, for example, the rays from the point A of the object AB may be supposed to be brought to a focus by the lens CD at the point A'. Those from B
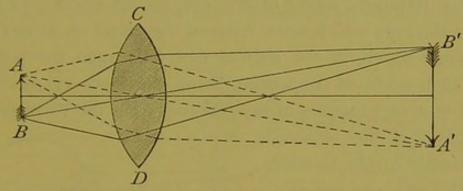

FIG. 52.—Formation of an image by a biconvex lens.

at B', and all intermediate points in AB, at corresponding points in A'B'.

We are now in a position to understand why a lens is required for vision. Were light simply to pass through the pupil and fall on the retina without refraction, from each point in the field of vision a cone or pencil of rays would pass to the retina and form a circle of light upon it, and these circles overlapping one another, as in Fig. 53, would simply give a sense of diffused light, and not the perception of each point separate one from another. But suppose the pupil were narrowed to the finest point, so that only one ray of light would pass in from each point of the object, as in

Fig. 54, the amount of light admitted would be so infinitesimally small as to be unable to affect the retina.
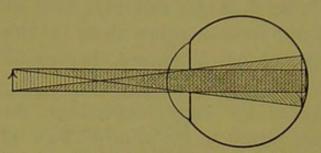

FIG. 53.—Diagram showing overlapping of rays in the absence of a lens.

In avoiding overlapping, the amount of light admitted has become infinitely little ; or, in other words, as the pupil diminished in size the object would appear dimmer and dimmer, until it ceased to be seen altogether, for the amount of the stimulus would be too small to excite the sensation of vision. But the refractive media of the eye *acting like a lens* condense the rays which have entered the pupil so as to form an image which, in the normal eye, falls upon the retina ; and each point of the image, being the focus or meeting-point of a vast number of rays coming from the corresponding point of the object, is sufficiently bright to stimulate the retina to action.

We may easily prove that such is the case. If an eye removed from its
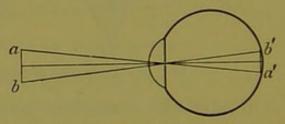
FIG. 54.—For explanation, see text.

socket be stripped posteriorly of the sclerotic coat, an inverted image of the field of view will be seen on the retina ; but if the lens or other part of the refractive media, be removed, the image will become blurred or disappear altogether.

There are, however, two defects in ordinary spherical lenses which, as they affect the eye, deserve our notice.

Spherical Aberration.—Any one who has attempted with a burning-glass to focus the rays of the sun upon a sheet of paper must have noticed that the circle of light, at first large and dim, gets smaller and brighter for a time

and then enlarges again, but the image of the sun thus formed is never reduced to a mathematical point. This is due to what is called the *spherical aberration of the lens*, and a glance at Fig. 55 will enable us to understand it. The ray of light CD, which passes through the centre of the lens AB, in Fig. 55, is not refracted at all, but passes on in a straight line. Rays near CD, such as E, E, are slightly bent and intersect CD at a considerable distance from the lens. Rays meeting the surface of the lens at points nearer its circumference than E, E, such as G, G, or K, K, are more refracted, and intersect CD at points nearer the lens. Thus, as we pass towards the circumference, the rays are more and more refracted, and do not
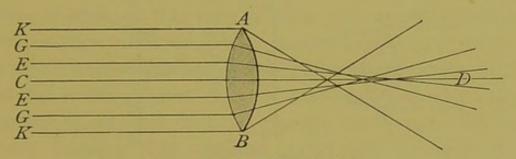
FIG. 55.—Spherical aberration.

meet all at one point. Accordingly, when we interpose a screen in the path of the rays, while a few may be accurately brought to a focus upon the screen, the great majority are either still converging or now diverging, and they form concentric rings of light which blend with one another, or diffusion circles, as they are sometimes called, and these blur the image formed by the accurately focussed rays.

By interposing a diaphragm, with a central aperture, the outer rays may be cut off and only those rays which pass near the centre will be brought to a focus, and thus the image will be made sharper. If the central part of the lens be more refrangible than the circumference, a similar

result will be obtained, for rays passing through the former will be more refracted, and thus be brought to a focus nearer those that have passed through the circumference. Such a provision as this exists in the human eye, the centre of the crystalline lens being more refrangible than the outer parts.

Chromatic Aberration.—The other defect in ordinary simple lenses is that when sunlight passes through them, owing to the different refrangibilities of the various coloured rays which go to make up white light, the sun's ray is broken up into its component parts, and some of these are bent more than others. This separation of the coloured rays is known as *dispersion*. The red rays being least
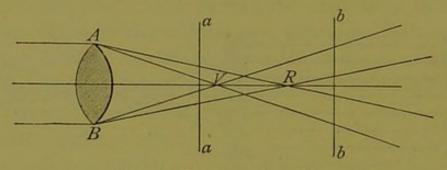
FIG. 56.—Chromatic aberration.

refrangible are less refracted than the orange, the orange than the yellow, and so on, the violet rays being most refracted of all. Thus, if rays pass through the lens AB (Fig. 56), we may suppose the red rays to intersect the main axis at R, the violet at V. If a screen be interposed in the position *aa*, there will be a coloured circular spectrum having the red to the outside and the violet to the inside ; but if the screen be placed at *bb*, the violet rays will now be outermost and the red rays to the inside. It was formerly supposed that the dispersive power of all bodies was alike, but it is now known that this is not so ; and by combining lenses of opposing action it has been found possible to do away, to a very great extent, with the disper-

sion of the light, although it is still refracted. Such a lens is usually composed of a concave flint-glass (A, Fig. 57), and a biconvex crown-glass lens (B, Fig. 57), and is said to be *achromatic*, or in other words, not colour-producing.

FIG. 57.—Achromatic lens. A, Plano-concave lens of flint-glass ; B, biconvex lens of crown-glass.

Optical Properties of a System of Lenses. —If the rays of light emanating from an object pass through a series of lenses, differing in shape and refractive power, but having their centres in one axis, the position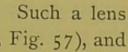 and size of the resulting image might be found by calculating and combining the effect of each lens in turn. This would, however, frequently lead to very elaborate calculations, and the researches of Gauss, Mœbius, Listing, and others have shown that for any system of centred spherical surfaces there exist six points known as *cardinal points*, through four of which pass planes perpendicular to the axis, and that if the position of these has been determined the direction of all rays of light through the system may be readily traced. The cardinal points are the *first and second focal*, *first and second principal*, and *first and second nodal* points, and the *planes* pass through the two first pairs.

1. The *first focal point* is so placed with regard to the system that all rays passing from it through the system, emerge in a direction parallel to the axis of the system, while all rays parallel to the axis before entering the system are, having passed through it, gathered at the *second principal focal point*. This also holds good for all points in the planes through the foci perpendicular to the axis.

2. The *first and second principal points* are so situated that in the planes passing through them perpendicular to the axis—the *principal planes*—there are correspondent

points on the same side of, and at the same distance from, the principal axis of the system, through which the refracted rays must pass. Thus each principal plane is the optical image of the other.

3. The *first and second nodal points* are such that all rays which before being refracted pass through one of them, seem after refraction to emerge from the other and in a direction parallel to what they had at first.

4. The *first principal focal length* is the distance between the first focal point and the first principal point.

5. The *second principal focal length* is the distance between the second focal point and the second principal point.

6. The *principal points* are at the same distance from
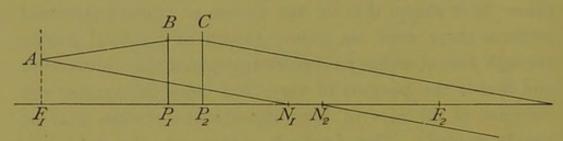
FIG. 58.—Diagram illustrating course of ray through a dioptric system.

each other as the nodal points, and the distance between the first focus and the first nodal point is equal to that between the second focus and the second principal point. Then the distance between the first principal and first nodal points equals the difference between the first and second principal focal lengths.

Given the cardinal points we may, then, trace the course of a ray through the system or calculate the position and size of the image of an object.

Suppose in Fig. 58 F_1F_2, P_1P_2, N_1N_2 represent respectively the first and second focal, principal, and nodal points. Any ray AB from the first focal plane incident upon the first principal plane passes parallel to the main axis to

C, and thence in a direction parallel to AN, the line joining A to the first nodal point.

To find the position of the image of any point A, we must trace the course of at least two rays from the point through the system till they meet. Thus, in Fig. 59, with the same
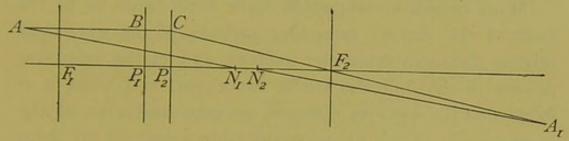

FIG. 59.—Image of a point.

letters as above, the ray AB *parallel* to the main axis passes through C, and thence through the second focus F_2, while from N_2 emerges a ray parallel to AN_1 which meets CF_2 produced, at A_1.

2.—THE DIOPTRIC SYSTEM OF THE EYE

It was stated (p. 109) that light, before falling on the retina, passes through a series of transparent refractive substances, viz. the cornea, aqueous humour, crystalline lens, and vitreous humour, and, with certain exceptions, which will be pointed out later, the eye may practically be considered as composed of a centred system, composed of a convex refractive surface, the cornea, and of a biconvex lens, the crystalline lens. The cornea in reality has a double surface, but the outer and inner surfaces are so nearly parallel that the two may be regarded as one; and although the lens differs much in the refrangibility of its different parts, its action as a whole may be taken as that of a homogeneous substance. The surface which exercises the greatest refractive influence is the anterior surface of the cornea, since the refractive powers of air and the

substance of the cornea differ in a marked degree. On the other hand, the aqueous humour approximates so nearly in refractive power to the substance of the cornea that the refraction in it may be neglected ; and, again, the refractive power of the vitreous is the same as that of the aqueous humour.

Many careful investigations have been made as to the form of the various refracting surfaces of the eye, their relative distances from one another, and of the refractive powers of the different media concerned, and while it is found that the eyes of different persons, and even of the same person, differ to a considerable extent in all these respects, yet certain measurements have been obtained which may be regarded as representing those of an *average normal eye*. These being known, we can determine the position of the cardinal points, and thus calculate the course of rays of light in the eye. The following figures represent the latest and most accurate determinations : [1]—

Index of refraction of the air . . . . . $n=1$.
Index of refraction of the aqueous humour and
    vitreous body . . . . $n'=1\cdot3365$.
Total index of refraction of the crystalline . . $n''=1\cdot4371$.
Radius of curvature of the cornea . . . $r=7\cdot829$mm.
Radius of the anterior surface of the crystalline lens $r'=10$mm.
Radius of the posterior surface of the crystalline lens $r''=6$mm.
Distance from the anterior surface of the cornea to
    the anterior surface of the crystalline . . . $=3\cdot6$mm.
Distance from the anterior surface of the cornea to
    the posterior surface of the crystalline . . $=7\cdot2$mm.
Hence, thickness of the crystalline . . . . $\epsilon=3\cdot6$mm.

From these data, the following results have been calculated :—

(A) Focal Points.

I. Surface of cornea.

First focal distance $f_0' = \dfrac{r}{n'-1} = \dfrac{7\cdot829}{1\cdot3365-1} = 23\cdot266$mm.

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[1] Landolt, *The Refraction and Accommodation of the Eye*, p. 79.

Second focal distance $f_0'' = \dfrac{n'r}{n'-1} = \dfrac{1 \cdot 3365 \times 7 \cdot 829}{1 \cdot 3365 - 1} = 31 \cdot 095\text{mm}.$

II. Anterior surface of crystalline.

First focal distance $f_1' = \dfrac{n'r'}{n''-n'} = \dfrac{1 \cdot 3365 \times 10}{1 \cdot 4371 - 1 \cdot 3365} = 132 \cdot 853\text{mm}.$

Second focal distance $f_1'' = \dfrac{n''r'}{n''-n'} = \dfrac{1 \cdot 4371 \times 10}{1 \cdot 4371 - 1 \cdot 3365} = 142 \cdot 853\text{mm}.$

III. Posterior surface of the crystalline.

First focal distance $f_2' = \dfrac{n''r''}{n'-n''} = \dfrac{1 \cdot 4371 \times 6}{1 \cdot 3365 - 1 \cdot 4371} = 85 \cdot 7117\text{mm}.$

Second focal distance $f_2'' = \dfrac{n'r''}{n'-n''} = \dfrac{1 \cdot 3365 \times 6}{1 \cdot 3365 - 1 \cdot 4371} = 79 \cdot 7113\text{mm}.$

(B) Principal Points.

I. The principal points of the cornea coincide with its summit.

II. The first and second principal points of the crystalline are at a distance of 2·12597mm. and 1·2756mm. respectively from the anterior and posterior surfaces of the lens.

(C) The Nodal Points of the crystalline coincide with its principal points.

Hence it is deduced that—

(1) The first principal focus of the eye is situated 13·7451mm. in front of the cornea. The remaining cardinal points of the eye are behind the cornea, and measuring from its anterior surfaces lie at the following distances.

(2) The second principal focus of the eye is situated 22·8237mm. behind the cornea. This distance, in other words, is the length in the normal eye between the cornea and the retina.

(3) The first principal point, 1·7532mm.
(4) The second principal point, 2·1101mm.
(5) The first nodal point, 6·9685mm.
(6) The second nodal point, 7·3254mm.

From Fig. 60 (p. 130) it will be seen that the principal points lie in the anterior chamber, the first nodal

K

point in the lens, the second nodal point slightly behind it, the first principal focus in front of the eye, and the second principal focus at the posterior surface of the retina. The diagram represents what has been called by Listing *the schematic eye*. By its aid we may easily trace the course of all rays of light entering the eye. The principal points and the nodal points are seen to be respectively very near each other, and if each pair be
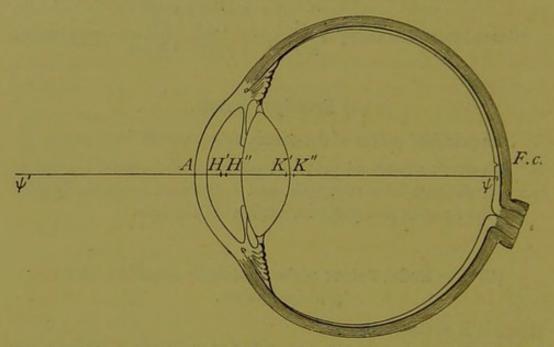

FIG. 60.—Schematic eye. A, Anterior surface of cornea ; ψ', ψ'', first and second principal focus ; H', H'', first and second principal points ; K', K'', first and second nodal points ; F.c., *fovea centralis* of yellow spot. (Landolt.)

regarded as combined into one point, we simplify the conception of the eye very much, reducing it to a system having a single spherical surface separating the air from the more refractive media of the eye behind. The principal point is then at the surface, and the nodal point at the centre of the sphere, the focal points being situated as before. Such a conception is known as the *reduced eye* of Listing.

3.—ANOMALIES IN THE EYE AS AN OPTICAL INSTRUMENT

While we may then form a conception of a mathematically correct eye, it must be borne in mind that all eyes present certain variations from the ideal form.

1. Thus the various refractive surfaces are not, as a rule, centred so that the optic axis or line joining their centres coincides with the line of vision, that is to say, with the line from the point viewed to the *fovea centralis* of the retina. The angle of the one axis to the other, where they meet at the nodal point, may be as great as 12°. This divergence of the optic from the visual axis is represented in Fig. 60, where it will be noted that the posterior end of the optic axis does not go to the *fovea centralis*.

2. Again, the centre around which the eye rotates is usually in the optic and not the visual axis, and, consequently, the line joining the point viewed with the centre of rotation of the eye, or, as it is called, the *line of regard*, does not usually coincide with the *line of vision*.

3. Further, we have seen (p. 124) that in ordinary lenses, white light is broken up into coloured rays which are not focussed at the same point, and we saw how we can correct this by combining lenses of different forms and dispersive powers. Similarly, in the eye, the rays of light are broken up into their constituent colours, but this is done only to a very slight extent, and does not interfere with ordinary vision. In fact, its existence can only be determined by careful experimentation. When we look at red letters on a violet ground, the eye is soon fatigued by the effort to focus both colours on the retina at once, and we experience an unpleasant jarring effect; or in looking at a violet flame which gives forth red and blue rays, we

may either see a red flame with a blue halo, or a blue flame with a red halo, according as the eye is accommodated for red or blue. This may be called the defect of *chromatic aberration.*

4. The blurring of the image caused by *spherical aberration* (p. 122) is almost entirely corrected in the eye by the varying refractive power of the media, especially of the
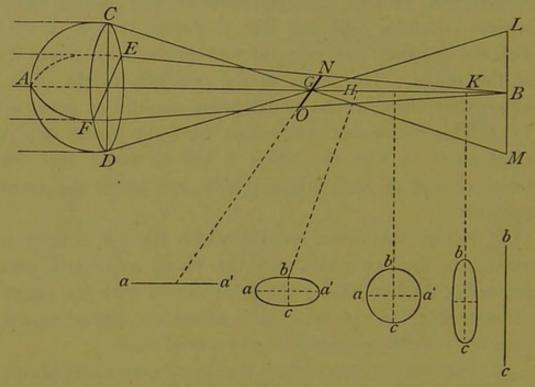

FIG. 61.—Astigmatism. The lens ACDEF has greater refractive power in the plane ACD than in the plane AEF ; rays in the vertical plane ACD will be brought to a focus at the point G, while those in the horizontal plane AEF are still converging to meet at the point B. If a screen be held at the point G, a horizontal line of light *aa'* will be seen ; if at the point B, a perpendicular line *bc* ; and if at intermediate points, ellipses of varying shapes as above.

lens, by the influence of the iris in cutting off the outer rays, and by the shape of the refracting surfaces, which are not spherical, but of forms known as ellipsoids of revolution, that is to say, surfaces formed by the rotation of an ellipse upon one of its axes.

5. *Astigmatism.* — But these surfaces, while better adapted for vision than spherical surfaces, are themselves

usually somewhat irregular in this respect, that their curvatures vary in different planes. In the vertical meridian the curve is in most eyes more convex than that in the horizontal ; and, as a result, rays in a vertical plane are brought to a focus nearer than those passing through the horizontal. Thus all rays diverging *from a point* cannot be exactly recombined to a point after passing through the eye, and a line is seen either in a horizontal or vertical direction according to the position of the retina, or there is a diffusion ellipse for intermediate positions. Hence the name *astigmatism* given by Whewell, from *a*, without, and *stigma*, a point. That most eyes are more or less astigmatic is shown by the fact that to almost every man the fixed stars seem to twinkle or send out scintillations radiating from a centre. Were our eyes perfect, the stars would appear as luminous points, not "star-shaped." Similarly, in looking at the bars of a window, the astigmatic eye cannot see both vertical and horizontal bars at the
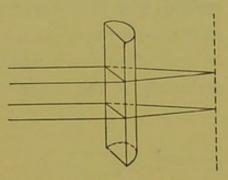

Fig. 62.—Cylindrical lens to correct astigmatism in the eye. Rays in two horizontal planes are brought to a focus, but do not approximate in a vertical direction.

same time with the same distinctness, one or other must be blurred by diffusion circles. Astigmatism may be *regular*, as above described, or *irregular*, the latter more especially being due to irregularities of the lens, while the former arises most commonly from the shape of the cornea. The effect is so slight in most eyes as to go unobserved, but it may be so great as to require the use of a lens consisting of the longitudinal segment of a cylinder, in which the convexity is greater in one plane than in another to compensate for the deficient convexity of curvature in one meridian as compared with the other (Fig. 62).

4.—ADJUSTMENT OF THE EYE FOR DIFFERENT DISTANCES

When parallel rays, such as come, for example, from a
star, fall upon the *normal eye* in a state of rest they are brought
to a focus on the retina.   If, however, the rays emanate from
a point within a distance of about 65 metres (71 yards), they
are sensibly divergent, and can only be brought to a focus
upon the retina by an effort, and the nearer the object viewed
is to the eye the greater must be the effort, until at last the
eye becomes unable to gather the rays to a point at the
retina, and the object is no longer distinctly seen.   If,
shutting one eye, we hold up a pencil in line with an object
at some distance it will be found that both cannot be seen
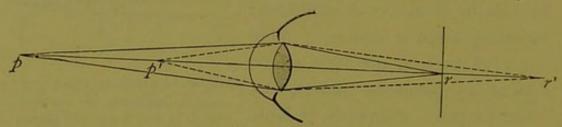distinctly at the same time.   If we see the distant object

FIG. 63.—For description, see text.

distinctly the outline of the pencil is blurred, and *vice versâ*.
The eye has the power of adjusting itself so that all rays
from beyond a certain near point may be focussed on the
retina.   Thus if the rays from a point *p* (Fig. 63) are re-
fracted so to meet at *r* the retina, *p* will be seen distinctly, but
if the point *p* be now moved to the point *p'*, unless the eye
be adjusted for the change, the rays from *p'* will be focussed
behind the retina, and the point *p* would be seen indis-
tinctly.   Now, there are two ways in which this adjustment
might be effected.   The length of the eye might be varied
to meet the varying distance of the focal point, just as a
photographer moves the sensitive plate of his camera back-
wards or forwards to bring it into focus.   But, as a matter

of fact, another process takes place in the eye. The retina is not moved backwards or forwards, but the refractive power of the crystalline lens is changed by an alteration of its thickness. The more curved the surfaces of a lens are, the greater is its refractive power. Now, when we look at distant objects, and no effort at accommodation is required, the anterior surface of the lens is kept flattened by the pressure of its capsule and by the elastic pull upon it of the anterior suspensory ligament—an elastic pull which involves no muscular strain, and consequently no fatigue. But when we wish to look at a near object, the ciliary muscle (see p. 101) contracting pulls forward the suspensory ligament
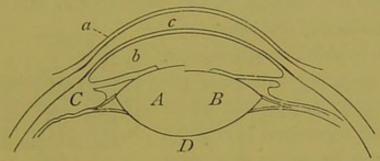
FIG. 64.—Mechanism of accommodation. A, The lens during accommodation with its anterior surface advanced ; B, the lens at rest ; C, position of the ciliary muscle ; D, the vitreous humour ; *a*, the anterior elastic lamina of cornea ; *c*, corneal substance proper ; *b*, posterior elastic lamina.

and diminishes its circle of attachment, its tension is lessened, the pull on the capsule of the lens diminishes, and the lens, by its own elasticity, assumes a more spherical shape, its anterior surface moving forward, and its power of converging rays being increased. The nearer the object the greater the effort required, and when long sustained the greater is the fatigue experienced. As a rule, however, we are unconscious of the effort, although, as will be seen, the feeling gives us valuable aid in judgment as to the distances of objects. The accompanying diagram (Fig. 64) represents the change, the right side B showing the condition of rest, the left A the state when the eye is adjusted for near

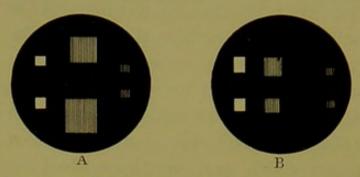sight.   The change in the curvature of the anterior surface of the lens may be demonstrated as follows : Let the observer in a dark room, looking at the side of the eye to be examined, note the reflections of a candle flame held to the other side, and in front of the eye observed.   Two bright points can be readily seen—one the reflection of the flame from the surface of the cornea, and one from the

FIG. 65.—Reflected images in the eye. A, for distant ; B, for near vision.

anterior surface of the lens—and, with care, a third, much fainter, from the posterior surface of the lens.   When the person whose eye is being examined is directed to look as at an object at a great distance, the three points of light will have the position shown in A (Fig. 65); and now on adjusting the eye so as to see an object close at hand the middle point of light moves forward, nearer to the corneal reflection, and becomes smaller as in B.   This is due to the bulging forward of the lens, and the consequent reflection of the light from a surface nearer the cornea, and more curved than before.   The experiment can be readily performed in daylight by means of the phakoscope invented by von Helmholtz, which
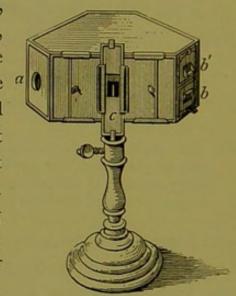

FIG. 66.—Phakoscope.   The observer looking through the aperture *a* sees images of the slits *bb'* reflected from the observed eye situated at the distant side of the phakoscope, and accommodated first for distance, and second for near vision, the regard in the latter case being fixed on the needle-point in the window *c*.

consists of a darkened box applied to the eye, with aper-
tures at convenient positions for the light, for the eyes of
the experimenter and of the person observed, and with an
opening through which the eye to be observed may look.
Careful measurements of the sizes of the reflected images
have shown that the image on the anterior surface of the
lens becomes smaller when we look at a near object, another
proof that the lens becomes more convex anteriorly. There
is also a slight increase in the posterior convexity of the lens.

The Near Point of Vision.—The range of accommoda-
tion is limited. It begins for objects at about 65 metres
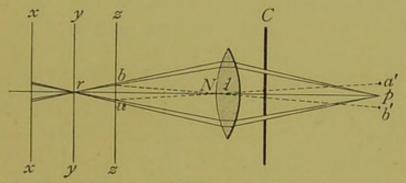(71 yards) from the eye, and for normal eyes reaches to

FIG. 67.—Scheiner's experiment. For description, see text.

within 20 centimetres (8 inches). The position of the near
point of any eye may be readily determined by the classical
experiment of Scheiner. It is performed as follows : In a
thick card make two small holes with a needle at a distance
not greater than the diameter of the pupil, and holding the
paper closely to the eye look at the needle through the
holes. If the needle be held 4 or 5 inches from the eye
two points will be seen, but as the needle is gradually
moved farther away the two points will be seen to coalesce
into one point, and they do so at the near point of vision,
namely, 8 inches from the eye.

The meaning of this will be understood from the diagram
in Fig. 67. If the needle is at the nearest point at which

the rays coming from it to all parts of the pupil can be collected to one point on the retina, the cones of rays passing through the apertures will be collected at *r*, and we see the needle single, but on bringing the needle nearer to the eye we are unable to adjust the eye for the divergent rays, and it is as if the retina were situated at *zz*, and two points *a* and *b* will be seen ; but as these are due to circles of diffusion and not to rays brought to a point, the image on the retina is blurred, and not so bright as before, owing to the lessened quantity of light admitted by the single hole. As the image is projected outward through the nodal point N, the image of *b* will be seen in the line *bb'*, and that of *a* in the line *aa'*, in other words, the real point seems to be split into two, one on each side of the true position.

The distances given above for the far and near points are those for a normal eye at rest, in which the optic axis is of such a length that parallel rays are brought to a focus on the yellow spot (Fig. 68, 1). Such an eye is called *emmetropic*, or an eye in measure. But many eyes are not so adapted ; they have the retina either before or behind the focal point, and are then said to be *ametropic*, or not in measure.   The axis may be too long, and parallel rays are focussed before they reach the retina (Fig. 68, 4), as in the short-sighted, *myopic*, or *hypometropic* eye ; or the axis may be too short, as in the long-sighted or *hypermetropic* eye, and the rays are brought to a focus behind the retina (Fig. 68, 3).   A short-sighted person, who desires to see distant objects, wears spectacles with concave lenses to make the parallel rays diverge, so that on passing through the eye they will be brought to a focus farther back than usual, and so upon the retina ; while in viewing near objects, as in reading, the book is held nearer the eyes to give greater divergence to the rays.   The long-sighted person, on the other hand,

wears convex lenses, so that the rays may be brought more quickly to a focus, and in reading he holds the book at
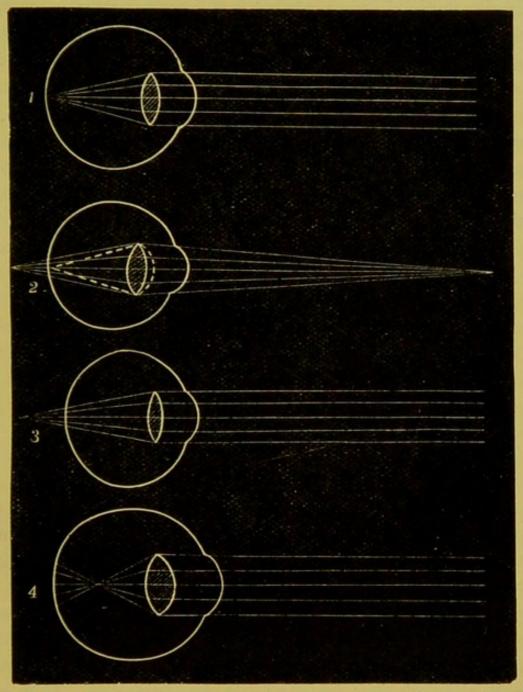

FIG. 68.—1, Emmetropic eye; 2, normal eye accommodated for near vision by increased curvature of the anterior surface of the lens; 3, hypermetropic eye; 4, myopic eye.

arm's length for a similar reason. Further, an eye of normal length may gradually lose its power of adjustment for near objects, a condition common in old age, and we have

what is known as the *presbyopic* eye. In the eye of an old person the parts are deficient in elasticity, and the fibres of the ciliary muscle are probably less powerful than in early life. The anterior surface of the lens cannot therefore become sufficiently convex for objects viewed a little beyond the near point of distinct vision. In other words, the near point in a presbyopic eye is farther back than normal, and hence, in reading, the head is thrown back and the newspaper held as far away as possible. In this case, too, convex lenses are used to compensate for the lost power of adjustment for near objects.

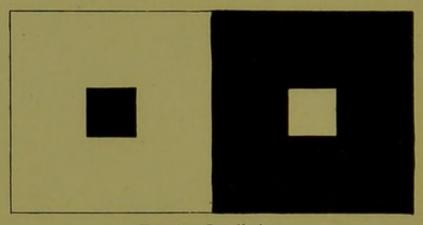**Irradiation.**—A minor result of defective power of

FIG. 69.—Irradiation.

accommodation is to be found in the phenomenon known as irradiation. When we look at a bright object on a dark ground it seems larger than when a dark object of similar size is seen on a light ground. People dressed in white look larger than when in black. Note also the two small squares in Fig. 69. The white seems larger than the black, although they are of exactly the same size. This is probably due in part to the formation of circles of diffusion, the more powerful stimulus of the rays from the white surface annulling the less intense rays from the dark border. An interesting example of this is the effect produced on the eye by the glowing filament of the electric lamp. The

filament may form a loop, but this is not seen when the full light of the lamp meets the eye. We see only a brilliant light. But if we cut off some of the rays by the intervention of a plate of smoked glass, or by winking the eyes rapidly, the filament is distinctly seen, although apparently broader than it really is on account of the intensity of its luminosity.

Entoptic Phenomena.—In describing the effects of refraction on the rays passing through the eye, we have hitherto spoken as if the transmitting media were perfectly transparent in all parts. It has now to be observed that in almost every eye there are small opaque bodies which intercept the light as it enters, and throw shadows on the retina. These shadows projected outwards give the impression of rounded or filamentous bodies floating in space. They may be well observed by looking with half-shut eyes at a white cloud, when they will be seen floating away and eluding our efforts to keep them at rest. They have been called on this account *muscæ volitantes*, and their fleeting character is due to the fact that they are not as a rule directly in the line of distinct vision, and in our attempt to gain a direct view of them we move the eye and with it the substance which gives rise to the appearances. The opaque particles may be either in front of the retina or in the retina itself, and one of the latter phenomena, namely, the shadows of the retinal vessels, is of especial interest, not only from its peculiar appearance, but also from the proof which it affords that the layer of rods and cones is the part of the retina sensitive to light. It may be studied as follows. In a dark room cast a bright ray of light sideways upon the cornea. This penetrating to the retina forms there a luminous image which itself is reflected to other parts of the interior of the retina. One of these reflected rays may in its course impinge upon

a retinal vessel which casts its shadow on the outer corre-
sponding part of the retina. The part of the retina upon
which the shadow falls, refers this outwards through the
nodal point of the eye. The path described is traced in
Fig. 70, A. The ray *b* passing to *c'* and reflected thence,
falls on a vessel *x* in the retina, and a shadow is cast at *d*
which is referred outwards in the direction *da'*. If now
the source of light be moved to *b'* the ray will pass to *c*,
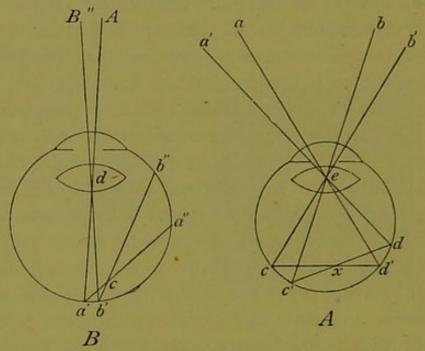be reflected in the direction *cd'*, and intercepted at *x*,

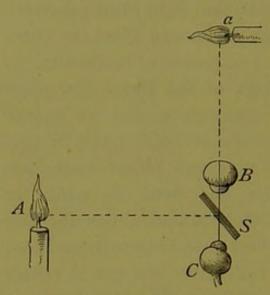FIG. 70.—Diagram to illustrate the formation of Purkinje's figures.

with consequently a shadow on *d'* which is referred out-
wards in the direction *d'a*. If the ray of light cannot enter
the eye by the pupil, but merely passes through the sclerotic,
we will have the result depicted in Fig. 70, B. A ray of light
entering at *a''* is intercepted by a vessel *c*, and the shadow
at *a'* is projected outwards to A. If we now move the source
of light so that the ray enters at *b''*, the shadow of *c* will
be formed at *b'* and projected outwards to B'', or, in other
words, we will see a dark line apparently moving from A
to B''.

As a result, then, of this play of light and shadow, there is seen dimly outlined on a darkly luminous ground, and moving as the light moves, an arborescent figure, the shadow of the arteries and veins of the retina. We do not see this under ordinary circumstances, because light enters the pupil from all parts of the field of vision, and no distinct shadows are cast upon the retina. H. Müller has proved, by a study of the mathematical conditions of this phenomenon, that the shadows of the vessels must fall upon the layer of rods and cones in order to give the result obtained, or, in other words, that light must penetrate the various internal layers of the retina and affect the outer layer before it can give rise to a sensation of luminosity.

Examination of the Interior of the Eye.—The pupil of a normal eye is black in appearance, and we cannot study by unaided vision the interior of another eye *in situ.* Does the eye merely absorb rays and reflect none outwards? Von Helmholtz, who has done so much in advancing the science of physiological optics, was the first to show that the eye does reflect rays outwards, and that with proper arrangements we may cause the eye to reflect so much light that its interior can be easily examined.

When walking in the street we can scarcely see into the interior of houses through the windows, because the amount of light emerging from within is so much less than the diffused light outside, and the difficulty is increased by the reflection of light from the glass. But we can see into the room better if the window is open, or if the room is lit up within. Similarly with the eye, the light entering is partially reflected outwards by the retina, but most of it is absorbed; and, further, the part reflected emerges in the same path as it entered, and by the refracting action of the eye is brought to a focus at the original luminous point. If, then, we place a light between our eye and that

of the person observed we cannot see into the other's eye, because the emergent rays are focussed at the flame and do not form an image in our eyes. If we bring our eye near to the observed eye, our own head intercepts the rays from without, and we cannot see the interior. But if a light (in Fig. 71) be placed to one side of the observed eye C, and its rays reflected into the eye by a piece of transparent glass, or better still, by a small concave mirror with a central aperture, these rays will illuminate the eye. Then part of the rays again reflected outwards will pass through the glass to meet and form an image at *a*, but being intercepted by the observer's eye B, the image is formed on his retina, and thus the interior of the eye C may be examined. It will be seen that this only holds good if both eyes are emmetropic. If one eye be myopic, the other must be hypermetropic to a corresponding degree, and in the ophthalmoscope—the instrument invented by von Helmholtz for the examination

FIG. 71.—Principle of the ophthalmoscope. (Fick.)

of the interior of the eye—there are usually convex and concave lenses by which the observer is able to counteract the effect of any degree of ametropia in the observed eye. In other words, if the observer's eye be emmetropic, the nature and curvature of the lens which must be interposed give an indication of the nature and amount of the ametropia of the observed eye. Thus, by the ophthalmoscope, we can see the interior of the eye, examine all its parts, and judge if it be healthy, while at the same time we determine any short or long-sightedness present.

The retina presents to the observer's eye the appearance of a red-coloured concave disk, with a whitish oval spot to its inner side where the optic nerve enters, from which are seen branching the retinal vessels, the veins being darker in colour than the arteries, and in the visual axis lies the yellow spot already described. The vessels of the *fovea centralis* are so fine as to be invisible to the naked eye, but they form a very close and fine network at this part of the eye. The retina being concave, all images formed on it larger than points must share in its concavity. This, however, is an advantage, for if the retina were flat, all the outer parts of any image formed upon it, not being exactly focussed, would be distorted, as on the plate of a camera, but on account of the retina's concavity each part of the image is focussed in its proper position, and distortion and blurring thus largely avoided.

While this is so, it is always to be borne in mind that although the whole posterior part of the retina may have formed upon it a fairly clear and distinct image of all the parts of the visual field, and although by an act of will we may without moving our eyes pay attention to the outlying parts, still the only part of the retinal image which gives rise to *distinct* vision is that formed upon the nerve terminations in the central depression in the yellow spot. In other words, if the rays of light from an object at which we are looking converge towards the optic centre, so as to form an open angle, and then diverging, are brought to a focus on the retina, to form a large image, we will not be able to see the whole object distinctly without moving the eye, so that a series of images of different parts of the object is formed consecutively upon the area of acute vision.

The Visual Angle. — The angle formed by the rays from the extreme limits of the object of vision at their point of convergence (the nodal point) in the eye is

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known as the *visual angle,* and the visual angle which any object subtends depends upon the size and the distance of the object from the eye.   A small visual angle is therefore a condition of distinct vision.   But there is a limit to this, for with most people, if the visual angle subtended by the object be less than 60″, the area of the retina stimulated will be so small that all separate points in the object seem to be fused into one in the mental picture obtained by the retinal stimulation.   Some carefully-trained observers with acute eyes may possibly distinguish from one another as separate points the en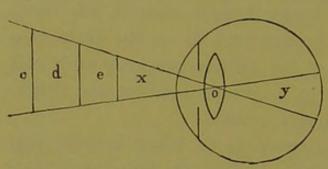ds of a line which subtends an angle of only 50″, the image of which in the average normal eye would have a length of ·00365 mm. or 3·65 μ.[1] The diameter of a retinal cone is 3·2 μ, but as the cones do not press against one another each cone corresponds

FIG. 72.—Visual angles. The objects *c, d, e,* though of different sizes, subtend the same visual angle, being at different distances from the eye.

to an area having a diameter of 4 μ.   If the image is so small as to fall entirely upon one cone all points in it will be fused together, but it is conceivable that an image not more than 1 μ in length might stimulate adjacent sides of two cones. In such a case, however, there must be a *mental* fusion of the effect, for images of less diameter than 3·65 μ are always seen as one, and not more than one, point, at least so far as observations have yet been made.   It matters not how large the object may be, if it is only far enough away to

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[1] The Greek letter μ is used to denote the thousandth of a mm., and is the unit of measurement for objects of microscopical size.   A mm. $= \frac{1}{25}$ of an inch : hence a *micromillimetre*, 1 $\mu = \frac{1}{25000}$ of an inch, and 3.65 $\mu = \frac{1}{6850}$ of an inch.

subtend the angle of 50″ it must appear as a point. The fixed stars we know to be vast suns, but they appear to us as mere points of light because their distance is so great that they subtend a very small visual angle. Nay more, many stars long supposed to be single have, by the aid of powerful telescopes, been shown to be double, triple, quadruple, or even multiple stars, at vast distances from one another, and yet appearing as one to the naked eye.
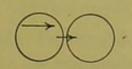

FIG. 73.—Diagram showing how an image smaller than the diameter of a cone may affect one, or more than one, cone at the same time. The image affecting two cones is actually smaller than that affecting one only.

For distinctness of vision the eye must have what we may call *resolving* power, the power of keeping each point of the image clear and distinct from its neighbour, and this power we have said is greatest in the yellow spot. For example, the two dots below are easily recognised as two, if

• •

we look directly at them ; but if we look a little to one side, the two will apparently fuse into one whenever their images are displaced from the yellow spot and fall upon an adjoining part of the retina. By means of a pencil we can map out on the page an area of irregularly oval shape corresponding to the oval shape of the yellow spot, an area in which the two dots are seen as double and not fused. The greater the distance between the dots, the further, *cæteris paribus*, from the yellow spot of the retina may they be distinguished as such, or in other words, the further we pass on the retina from the yellow spot the less resolving power does the retina possess.

We have indicated above the shortest distance between two points which will allow of their being seen as two. A much smaller area of stimulation of the retina is sufficient

to give rise to distinct vision. A luminous point or line may be seen as such which gives rise to an image that occupies only a very small part of a cone or row of cones. An object ·04 mm. ($\frac{1}{625}$ of an inch) in breadth at a distance of 25 mm. (1 inch) from the eye gives a retinal image of about ·002 mm. ($\frac{1}{12500}$ of an inch) in breadth, and yet it is distinctly visible. This is, however, by no means the *minimum visibile.* Objects as small as the $\frac{1}{400000}$ of an inch in diameter (about one-tenth of the length of a wave of light) may be seen with the highest powers of the modern microscope. It is hardly necessary to state that even these minute objects are many thousands of times larger than the molecules or atoms of matter dealt with by the physicist.

The Size of the Retinal Image.—The size of the image of an object upon the retina may be calculated by a simple formula if we know the size of the object, its distance from the nodal point, and that of the nodal point from the retina. In the average normal human eye the distance of the nodal point from the retina is approximately 16 mm., and from the nodal point to the anterior surface of the cornea 7 mm. Let the size of the object be represented by X, its distance in mm. from the anterior surface of the cornea by p, and therefore from the nodal point by $p + 7$. Then

$p + 7 : 16 : : X : x$, the size of the image; or $x = \dfrac{X \times 16}{p + 7}$.

Suppose, for example, the object looked at be the page of this book, which is nearly 182 mm. long, and that the book is held half a metre (500 mm.) from the eye. Then the length of the retinal image of the page will be

$x = \dfrac{182 \times 16}{500 + 7} = 5\cdot7$ mm., or a little less than one quarter

of an inch. Again the length of any small letter on the page is approximately 1 mm., hence the height of its

retinal image, the book being held as before, will be

$$\frac{1 \times 16}{500 + 7} = \frac{16}{507} = \cdot 03 \text{ mm., or about } \frac{1}{800} \text{ of an inch.}$$ The above-mentioned formula, however, gives only the length of any *diameter* of the object in a plane perpendicular to the line of vision. To calculate the *area* of the image on the retina we have only to remember that the area of the image is to the area of the visual field occupied by the object as the square of the distance of the image from the nodal point is to the square of the distance from the nodal point to the object. The flat retinal image cannot, of course, correspond in area to the superficial area of a solid body, but only to a part of the field of vision cut off by a plane projection of the object upon it. It is as if the visual field were a canvas, every point of which is filled by the representation of some external object, and the retinal image is an exact copy, but reduced in size, of nature's picture. The full moon and a ball held in the hand give alike a flat circular retinal image, but in the "mind's eye" each may be seen as a sphere, although the play of light and shade on the nearer object renders the effort of imagination easier with it than in the case of the more remote.

The Blind Spot.—It is interesting to note that near the area of greatest sensitivity to light we have a spot in the retina which is devoid of rods and cones, and hence is quite unaffected by images formed upon it. This is the *optic papilla*, or place of entrance of the optic nerve, and its diameter being about 1·8 mm., it subtends a visual angle of about 6 degrees. Lines drawn from the border of the optic pore to the nodal point and produced outwards will enclose a flattened cone whose base is contained within the visual field, and within which all objects will be invisible to the unmoving eye. Suppose, for example, the left eye being shut, the right eye be fixed upon the cross in Fig. 74.

When the book is held at arm's length, both cross and round spot will be visible ; but if the book be approximated to about 8 inches from the eye, the regard being kept steadily upon the cross, the round spot will at first disappear, but as the book is brought still nearer both cross and spot will again be seen. It may also be noted in this experiment, that there is no consciousness of a break of continuity in the visual field, no sensation as we might imagine there would be of darkness ; to put it generally, there being no stimulation, there is not consciousness of a lack, but a lack of consciousness.

An attempt has been made to determine the rate of decrease of acuteness of vision as we pass outwards from the yellow spot, and Volkmann holds that it diminishes proportionally to the square of the distance from the yellow

<p style="text-align:center">+   •</p>

<p style="text-align:center">FIG. 74.</p>

spot, but the determination is, in its nature, very hard to make, and much depends on individual peculiarities.

Action of Light on Retina.—This will be the more readily understood if we consider for a moment the intimate nature of the action of light on the retina. It has been experimentally observed that if the eye be kept in the dark for a time, and if light then be allowed to fall full on the retina, there is a change in its electrical condition. This phenomenon is evidence of change in the condition of the molecules of the sensitive parts of the retina, which might be merely a change of rate of molecular motion such as results from a variation of temperature of a body, or it might be due to a chemical transformation or rearrangement of the molecules so as to form new chemical substances.

That the latter is more probably the case may be held upon various grounds. If heat rays be substituted for light in the foregoing experiment the electrical change will not occur. Further, it has been observed in the frog's eye (the retina of which contains only rods, and which is also well adapted for the observation of the electrical change produced by light) that in the outer part of the rods of quiescent eyes there is a pigment of a purple colour derived from the pigmented layer outside of Jacob's membrane, and on exposure of the eye to ordinary light this purple changes to yellow and then to white. On removal of the light the pigment slowly reappears in the rods. This pigment is not found in the cones of the retina of other animals, and hence is absent in the yellow spot. As the yellow spot is the seat of acute vision in daylight we must infer that the purple pigment is not essential to vision, but we must not conclude from this that it has no visual function. For if we pass from darkness to bright light, the eye at first is dazzled until possibly the visual purple is bleached, or in other words, until the eye's sensibility to light is diminished ; and, on the other hand, if the eye has been exhausted by bright light we do not see objects well in a dim light until the visual purple is restored. In a dim light, the pupil of the eye is dilated, and rays affect the retina round the yellow spot. It would thus appear that visual purple assists vision in dim light while it is not necessary in bright light ; but as we have a chemical change in the purple pigment, so we may have in the yellow spot substances which undergo chemical change, although this be not manifest to the observer. The yellow spot is thus better adapted for acuteness of vision, for concentration of the attention upon minute detail, while the surrounding parts of the retina are more sensitive to the action of light and more fitted for observ-

ing bodies emitting or reflecting but a small quantity of light.

Amount of Light required to excite the Retina.—The smallest amount of light that will excite the retina cannot be stated, as so much depends upon the part of the eye affected, its state of vigour or exhaustion, its previous education, and the like. Thus the sailor will see land in the distance which is imperceptible to the landsman; the Oriental will distinguish shades of colour more accurately than the European; and the artist will differentiate where the untrained eye sees but one tint. Again, the exhausted eye will fail to see what is readily perceptible to the fresh eye of one newly wakened from sleep; and the star, whose faint light is unseen by direct vision, may be seen when its ray meets the retina a little to the outside of the yellow spot. Nay more, even when we are enveloped by the deepest darkness, and when the eyes are shut, the ordinary field of vision seems still irradiated by a faint pervading glow, known as the *specific light of the retina*, which upon slight pressure by the hands may be broken up into a mosaic of fleeting patterns. The sensations thus excited by pressure are called *phosgenes*. The retinal light is caused by changes in the retina due to variations in the blood supply.

Persistence of Retinal Impressions.—The substance of the retina is more or less affected according to the brilliancy of the light and the length of time during which it acts upon the eye. A feeble light acting for a short time will leave but a transient effect, while a strong light, such as that of the sun or of the electric spark acting for an instant only, may give rise to impressions lasting many minutes, or, if the exposure be prolonged, even to permanent damage to the eyesight. If we look directly at the sun and then turn our eyes to the ground, or towards a darkened cloud,

the image of the sun formed upon the retina has been as it were so deeply graven, the retinal structure has been so changed, that for several moments we fail to see the object towards which the eyes are turned, and we see a round red spot, or several red spots, if the eyes were not steady when the sun was in view. This spot is a spectrum or *after-image* of the sun projected outwards upon the visual field, moving with every movement of the eye, and seen even when the eyes are closed. If a piece of burning wood be shaken rapidly to and fro, we see a line of light, because adjacent points on the retina are consecutively stimulated, and the fusion of the after-images gives the sensation of continuity. A disk with alternate lines or sectors of black and white radiating from the centre will, when rotated rapidly, seem to have a uniform gray colour due to the fusion of the black and white spectra; but if seen by the light of the instantaneous
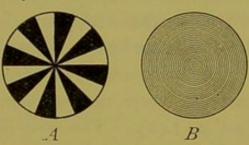

FIG. 75.—The disk A having black and white sectors, when rotated rapidly gives an even gray tint as in B.

electric spark, each black and white line or sector will be visible because the time of illumination and consequent stimulation of the retina is so short that there is no time for the superposition of the images one upon the other. Similarly, if various simple colours be painted on the disk, their spectra will, on rotation of the disk, be fused together, giving rise to a sensation of the colour due to their combination. If a series of twenty or thirty instantaneous photographs be taken at short but equal intervals of time of an animal performing some movement, as, for example, a horse leaping over a gate, the pictures fixed to a disk will, when rotating quickly, seem to coalesce each with its predecessor so as to give the impression of the

horse in actual movement.   This is the principle of the
toy known as the *Thaumatrope* or Wheel of Life.   Since
the after-image in the instances above mentioned has an
appearance similar to that of the object viewed, it is called
a *positive after-image*.   But there is another kind of after-
image, the *negative*, which is due to a slightly different
cause.   Suppose we look fixedly at an object for thirty or
forty seconds, so that the eye becomes fatigued, and then
turn our eyes to a surface of uniform tint, we will see an
image floating on the wall in which the lights will be
reversed—what was dark will be light, what was bright will
be dim.   In this case the rays of light reflected from the
wall have most effect upon those parts of the retina which
are least exhausted, while those parts formerly much stimu-
lated will now look dark, not being so easily excited to action.

The persistence of retinal impressions is probably in
part the cause of the phenomenon known as *irradiation*
(see p. 140).   The eye moving rapidly over the white
surface, and being more affected by its light, the dark
area seems the smaller.   It may also be that there is a
slight dispersion of light from the retinal elements directly
affected to those immediately adjoining, which makes the
image larger, and so leads to an erroneous judgment as to
the size of the white object.

A further and most interesting illustration of the per-
sistence of the retinal state may be studied as follows : Look
steadily for about half a minute at a disk with alternate
black and white sectors which is being slowly rotated.
Then turn the eyes to a sheet of paper upon which a
number of dark spots may be seen.   These will seem to
rotate in a direction contrary to that in which the disk was
turning.   The effect here is of the same nature as the
phenomenon often seen on the deck of a steamer.   If we
lean over the side of the vessel, and watch the water as

the vessel glides along, it soon seems as if the ship were stationary and the water near us in rapid motion in the direction opposite to that in which we are moving—the apparent rapidity gradually diminishing as we look at more remote parts of the water. If we now gaze at the deck, the part near us will seem to move towards the bow of the ship, the rest of the deck remaining fixed. Different parts of the retina have been stimulated by rays from different parts of the surface of the water apparently moving at different rates. But when the whole visual field is occupied by the deck, the various parts of which are fixed relatively to each other, the persistence of the retinal impression of greater movement in one part of the visual field than in the rest of it causes us to imagine that parts of the deck, which relatively to the rest of the deck are stationary, are actually in motion.

5.—SENSATION OF COLOUR

In considering the physical nature of light (p. 115), we saw that the shade of colour, according to the most likely hypothesis, depends on the rate of vibration of the luminiferous ether, and that solar or white light is a compound of all the colours in definite proportion. A body which reflects solar light to the eye without changing this proportion appears to be white ; if it absorbs all the light so as to reflect no light to the eye, it appears to be black. If a body held between the eye and the sun transmits light unchanged and is transparent, it is colourless ; but if translucent, it is white. If it transmits or reflects some rays and absorbs others, it is coloured. If, for example, it absorbs all the rays of the solar spectrum but those which give rise to the sensation of greenness, we say that the body is green in colour. But this greenness can only be perceived if the rays of light falling on the body contain rays having the special

vibratory rate that is required for this special colour.   For, if we use as our light any other pure coloured ray of the spectrum, say the red, its rays being absorbed the body appears to us to be black.   A white surface seen in a red light seems to be red, in a green light, green, as it reflects all colours alike, absorbing none. To the normal eye the *colour* depends, then, on the nature of the body and of the light falling upon it, and the *sensation of colour* only arises when the body reflects or transmits the special rays to the eye.   If two rays of
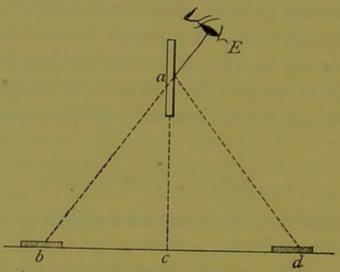
FIG. 76.—Lambert's method for studying combinations of colour.   The rays, *e.g.*, from the red wafer *d* reflected by the glass plate *a* to the eye E are pro- jected outwards and superposed on the blue wafer *b*, which appears of a rose colour.

different colour affect one part of the retina at the same time, they are fused together, and we have the sensation of a third colour different from its cause.   Thus, if red be removed from the solar spectrum, all the others com- bined will give a sensation of a greenish yellow, although we cannot, with the unaided eye, analyse this into its com- ponents.

Fig. 76 shows a method by which different-coloured rays may be made to converge from two bodies on the same part of the retina.   Von Helmholtz gives the follow-

ing table as the result of mixing the pure colours of the spectrum :—

	V.	B.	G.	Y.	R.
R.	Purple.	Rose.	Dull Yellow.	Orange.	Red.
Y.	Rose.	White.	Yellow Green.	Yellow.	
G.	Pale Blue.	Blue Green.	Green.		
Bl.	Indigo.	Blue.			
V.	V.				

Thus a mixture of red and violet gives purple, of yellow and blue, white. Here we must guard against a possible error. The effect of say yellow and blue light acting at once on the eye is to cause a sensation of white light ; but if we mix blue and yellow *pigments* the mixture looks green, because the one pigment cuts off the rays at the red end, the other those at the violet end of the spectrum, and the only rays reflected are those of the green or middle part of the spectrum. In the one case we have a combination of colours, in the other each absorbs a part of the spectrum previously seen when the pigments were unmixed.

Similarly, if the colours of the spectrum be painted upon

a disk, in due proportion and in proper series, the disk will, when quickly rotated, look white. This is due to a fusion of colour effects, not to a mixture of the pigments.

Complementary Colours. — When one colour is separated from the spectral series, the rest, as we have said, may be combined in the retina to give a sensation of one colour, and this colour will, if recombined with the one originally separated, give the sensation of white light. These two colours, then, are said to be complementary to each other, and every colour in the spectrum may thus be said to be the complement of all the others. By combining colours at opposite ends of the spectrum, the effect of the intermediate colours may be produced ; but the lowest and highest of the series, the red and the violet, cannot be thus formed. They may be regarded, therefore, as primary colours — colours which cannot be produced by the fusion of others.

If to *red* and *violet* we add the colour whose vibratory rate is about midway intermediate, viz. *green*, we may, by their combination, give rise to a sensation approaching that of *white* light. Consequently these three colours have been designated the *fundamental* colours.

Colour as dependent on the Retina. — Our perception of colour depends, however, not only on the physical stimulus of light, but also on the part of the retina affected. In and around the yellow spot where the cones are most numerous, the power of distinguishing shades of colour is greatest. Instead of seven colours in the spectrum more than two hundred different tints may be distinguished. Outside of this central area lies a middle zone in which much fewer tints are seen, these being confined, indeed, to shades of blue and yellow ; while in the front part of the retina all colour tints are lost, and objects give rise simply to the sensation of dark shadowy

bodies without colour. Moreover, the range of spectral colours varies with the individual.

Colour Blindness.—Every colour has three qualities : (1) *hue*, or tint, as when we speak of red, green, or violet ; (2) *purity*, or degree of saturation (due to a greater or less admixture with white), as when we designate a red or green as deep or pale ; and (3) *brightness*, or intensity, or luminosity, as when we describe the tint of a red rose as dark or bright. On comparing two colours we say they are identical when they agree as to these three qualities. Observation has shown that in thus assorting colours, about ninety-six out of every hundred men will agree as to identity or difference of colour, and may be said to have *normal colour vision*, while the remaining four men will show a defective perception of colour, and are called *colour blind*. It is curious that colour blindness is about ten times less frequent in the female sex. This condition is congenital and incurable. It is due to some unknown peculiarity of the retina, or nerve centres, or both, and it is to be distinguished from transient colour blindness, sometimes caused by the excessive use of tobacco and by disease. There is probably no such condition as absolute colour blindness, in the sense of total insensibility to colour ; a few rare cases have been noticed in which there was apparently only one colour sensation ; a few cases occur of failure to distinguish blue from green, and insensibility to violet is rare. The common form of defective colour vision is *Daltonism* or *red-green blindness*, of which there are two varieties—the *red-blind* and the *green-blind*. In each variety there are many gradations of sensibility. To the red-blind red appears as a dark green or greenish yellow, yellow and orange appear as dirty green, while green is green and brighter than the green of the yellow and orange. A green-blind person, on the other hand, would call red

dark yellow, yellow would be yellow except a little lighter than the red he calls dark yellow, and green would be described as pale yellow. When asked to look through a spectroscope at the spectrum, the extreme or low red is absent to the red blind, and the brightest part of the spectrum appears to him to be the green, while to the normal eye and to the green-blind eye the spectrum is most luminous in the yellow.

Seeing that green lights imply safety, and red lights danger, on our railways, and that in navigation a green or red light on the port or starboard side shows the course a vessel is taking, it is evident that no one who is red- or green-blind should be employed in the services, and accordingly various tests are now in use for the detection of such defects. The most efficient is the wool-test of Holmgren, which consists of three skeins of wool dyed with *standard test colours*, namely, a light green, a pale purple or pink, and a bright red. Other skeins of reds, oranges, yellows, yellowish greens, pure greens, blue greens, violets, purples, pinks, browns, and grays, all called *confusion colours*, are provided, and the examinee is requested to select one and match it with one of the test colours. Suppose the light green skein is shown first. If the examinee matches grays, brownish grays, yellows, orange, or faint pink with this, he is colour blind. Then he is shown the purple skein. If he matches with this blue or violet he is red-blind, but if he selects only gray or green he is green-blind. Finally, he may be shown the red skein, having a bright red colour, like the red flag used on railways. A red-blind person will then match with this green or shades of brown, which to a normal eye seem darker than red ; while if he be green-blind he will select shades of these colours which look lighter than red. Violet blindness is recognised by the examinee confusing red and orange with purple.

Coloured after-images.—The power of the retina in distinguishing colours depends also upon its freedom from fatigue. As there may be after-images of form, so there may be after-images of colour, and these after-images may be negative or positive. If *positive*, we see with the eyes shut the same colour as we have just been looking at ; if *negative*, we see the complementary colour, and as we continue examining it we find the colour changing and fading away, the lighter tints merging into the darker. The eye fatigued by gazing at a red square, will, when turned to a white surface, seem to see a bluish-green square on the white ground, for the fatigued eye responds more readily to the stimulus of the other colours of the spectrum ; and these give, when fused, the complementary colour (p. 158). Similarly, a white square seen against a bluish-green background will have a reddish tint, probably because the eye moving quickly over the coloured field, and becoming thereby fatigued, responds more readily to the red rays in the white light than to its other component parts. This is known as the phenomenon of *contrast*.

Theories of Colour Vision.—How comes it that we can perceive differences in colour? This question has never been satisfactorily answered, because the changes caused in the retina by the action of light are too minute to allow of direct observation. Many hypotheses have been framed, but none of them meets all the requirements of the case. We may look for the cause in various directions. We might suppose a molecular vibration to be set up in the nerve-endings synchronous with the undulations of the luminiferous ether, without any change in the chemical constitution of the sensory surface ; and we might suppose that where various series of waves corresponding to different colours act together, these are fused together, or interfere with each other in such a way as to give a

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vibration of modified form or rate corresponding somehow to the sensation arising in consciousness. Or again, we might suppose that the effect of different - coloured rays is to promote or retard chemical changes in the sensory surface, which again so affect the sensory nerves as to give rise to differing states in the nerves and nerve centres with differing concomitant sensations. The former of these lines of thought guided Thomas Young, the great expounder of the
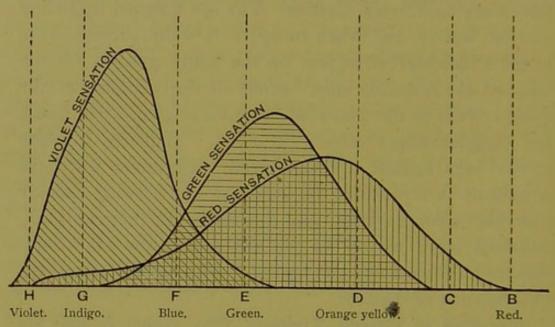

Fig. 77.—Diagram to illustrate the Young-Helmholtz theory of colour vision. The lines with the letters B, C, D, etc., below the curves indicate certain fixed lines in the solar spectrum, whose wave-length has been determined. Take D, the height of the two curves above it indicates the degrees of stimulation of the two sensations red and green that produce orange-yellow. Again, at E we see a mixture of the *three* sensations that produce spectral green. (Report of the Committee of the Royal Society on Colour Vision.)

undulatory theory of light, in his attempt at explaining colour perception ; and his theory adopted and worked out by von Helmholtz has been received with much favour. He supposed that there are three fundamental colour sensations—red, green, and violet—by the combination of which all other colours may be formed, and that there are in the retina three kinds of nerve elements, each of which is specially responsive to the stimulus of one colour, and much

less so to the others. If a pure red colour alone act on the retina, only the corresponding nerve element for red sensation would be excited, and so with green and violet. But suppose the colour be mixed, then the nerve elements will be set in action in proportion to the amount of constituent excitant rays in the colour. Thus, if all the nerve elements be set in action, we shall have white light; if that corresponding to the red and green, the resultant sensation will be orange or yellow; if mainly the green and violet, the sensation will be blue or indigo, and the like. Von Helmholtz succinctly puts it as follows :—

(1) Red excites strongly the fibres sensitive to red, and feebly the other two—sensation, *red*.
(2) Yellow excites moderately the fibres sensitive to red and green, feebly the violet—sensation, *yellow*.
(3) Green excites strongly the green, feebly the other two—sensation, *green*.
(4) Blue excites moderately the fibres sensitive to green and violet, and feebly the red—sensation, *blue*.
(5) Violet excites strongly the fibres sensitive to violet, and feebly the other two—sensation, *violet*.
(6) When the excitation is nearly equal for the three kinds of fibres, then the sensation is *white*.

Another mode of expressing the theory is to say that each primary sensation of red, green, and violet is excited in some degree by almost every ray of the spectrum, but the maxima of excitation occur at different places, while the strength of stimulation in each case diminishes in both directions from the maximum point. Thus, when the three sensations are equally excited, white light is the result; green is caused by a very weak violet sensation, a stronger red, and a still stronger green sensation. At each end of the spectrum we have only the simple sensations of red and violet, and all the intermediate colour sensations are compounds of varying proportions of the three primaries.

According to this theory, red blindness is attributable to the absence of the red sensation, and green blindness to the absence of the green sensation. When the green and violet sensations are equal in amount, a red-blind person sees what is to him white, and when the red and violet are equal a green-blind person will have a sensation of what in turn is to him white, although to the normal eye these parts are bluish green in the one case and green in the other, as the green sensation is in each added to the sensations of red and blue.

But while this theory explains certain phenomena of colour blindness, of after-images, and of colour contrast, it is yet open to serious objections. There is no proof, one way or other, of the existence of three kinds of nerve elements corresponding to the three fundamental colour sensations. Again, it does not explain how red should have to the colour-blind person a similar appearance to green, or how it should give rise to a sensation of colour at all, any more than heat rays which are invisible. Further, if red rays are a necessary constituent of white light, the colour blind should not be able to see white as we do, nor to distinguish white from bluish green—the complementary colour of red. And yet such distinctions can be made, although it may be argued that a colour-blind person does not see white in the same sense as white is white to a person having normal colour vision. A strong objection to the Young-Helmholtz theory is that in cases of colour blindness following injury to the eye, only the blue of the spectrum is seen, all the rest appearing as white. Here it is impossible to understand how a sensation of *white* can be experienced if the sensations of red and green are lost, for the theory is that white can only be experienced when the sensations of red, green, and violet are all three present.

Stanley Hall likewise adopts an anatomical basis for his

theory of colour perception. He holds that only the cones are sensitive to colours, and that these may be regarded as built up of a series of disks like a pile of coins, the lowest of which is the largest. Different disks respond to different colour tones, and give rise to different excitations of the nerve centres. While the disk formation of the cones is undoubted, this theory is open to the same objections, on subjective grounds, as that of Young and von Helmholtz.

Other theories of colour perception proceed upon the assumption of chemical changes in the retina under the influence of light. That light does play an important part in physiological action is a well-known fact. Green plants, for instance, can only grow healthily when exposed to the light ; if kept in a dark chamber they quickly blanch, and use up only the reserve material stored up in themselves, because they have no longer the power of obtaining carbon from the carbonic acid of the air. And yet, though this is so, it is also known that direct rays of light have a retarding influence on the growth of certain parts of plants. If a plant is placed in a window, it bends outwards towards the light, because the side of the stem away from the light grows the faster ; similarly leaves of plants grown in the dark, like rhubarb, have long thin stalks which have derived their nourishment from the root, and have not been affected by light. So Hering holds with regard to the retina.

According to Hering's theory certain fundamental sensations are excited by light or by the absence of light. These are white, black, red, yellow, green, and blue, and they may be arranged in three pairs, the one colour in each pair being complementary to the other, thus—white to black, red to green, and yellow to blue. Hering further supposes that when rays of a certain wave-length fall on visual substances existing in the retina destructive changes occur, while rays having other wave-lengths cause constructive changes.

Thus, suppose a red-green visual substance exists of such a nature that when destructive and constructive changes occur no sensation is experienced, then when destructive changes are in excess by the action of light of a certain wave-length there is a sensation of red, and when constructive changes occur by the action of shorter waves the sensation is green. In like manner a yellow-blue visual substance by destructive changes gives a sensation of yellow, and by construc-
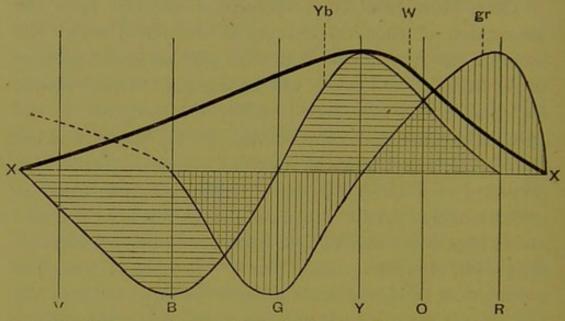
FIG. 78.—Diagram to illustrate Hering's theory of colour vision. The vertical shading represents the red and green, and the horizontal shading the yellow and blue, antagonistic pairs of sensations. The thick line indicates the curve of the white sensation. All above the line X X indicates destructive changes in the retinal substances, and all below constructive changes. See text. (Report of the Committee of the Royal Society on Colour Vision.)

tive changes a sensation of blue; and a white-black visual substance by destructive changes gives white, and by constructive changes black. The member of each pair is thus antagonistic as well as complementary. The red-green and yellow-blue substances are tuned, as it were, to rays of different wave-length. Thus, in the red end of the spectrum, the rays cause great destruction of the red-green substance, while they have no effect on the yellow-blue substance. Hence the sensation is red. Again, the shorter waves

which correspond to the yellow of the spectrum cause great destruction of the yellow-blue substance, while their destructive and constructive effects on the red-green substance neutralise each other. Hence the sensation is yellow. Still shorter waves, corresponding to green, cause construction of the red-green substance, while their influence on the yellow-blue substance is neutral, and hence the sensation is green. Again, the shorter blue waves cause construction of the yellow-blue substance, while their action on the red-green substance is neutral, and hence the sensation is blue. At the blue end the short waves are supposed to cause destruction of the red-green substance, and thus give violet by adding red to blue. Orange is caused by excess of destructive changes, and greenish-blue by excess of constructive changes in both substances. Finally, when all the rays of the spectrum fall on the retina, the constructive and destructive changes in the red-green and yellow-blue substances neutralise each other, but the destructive changes are great in the white-black substance, and we call the effect white. Colour blindness, in the form of red-green blindness, is, according to this theory, due to the absence of the red-green substance, the other two substances remaining. The phenomena of coloured after-images are thus accounted for :—

Suppose the retina to be acted on by red light, destruction of material takes place—the effect continuing, it may be for a time, after withdrawal of the red light—giving the positive after-image. Then comes the upbuilding of the material under the influence of nutrition, assisted by the action of light of shorter wave-lengths, and the negative after-image—green—is perceived. So with yellow and blue, and white and black. That such differences of chemical action are possible, or probable, we may well believe from a consideration of the variation in the actinic effect of different

rays of the spectrum, and from the action of light upon the pigments of the retina. This theory is also in harmony with what has been observed in connection with many other processes in the body, such as secretion, innervation, and the like, in which tissues, having reached their highest point of vitality through nutrition, disintegrate during functional activity. Serious objections to the theory have, however, been raised. One is thus stated by Ladd[1]:—"A light composed of red and green may be made to seem to the eye the same as a light composed of yellow and blue. If, then, the eye is fatigued to red, instead of the red-green mixture appearing greenish, and so distinguishable from the yellow-blue mixture, they both appear the same to the fatigued eye." It has also been pointed out that the two sensations of each pair do not always coexist. One may be present and the other absent. Thus, when the intensity of the light of the spectrum has been much reduced, the green persists long after the red has disappeared ; and after the excessive use of tobacco, yellow may disappear, and blue is the only sensation left. One is also at a loss to understand how colour sensations, so different from one another as red and yellow, can be alike due to destructive changes of retinal substances, or how yellow and green, whose periods of vibration are so nearly alike, can give such antagonistic physiological effects. Such considerations demand the existence not of one but of three visual substances. On the whole, however, speculative as it is, Hering's theory accounts for a larger number of the phenomena of colour vision than that of Young and von Helmholtz.

In a new edition of his great work, *Handbuch der Physiologischen Optik*, now appearing in parts, von Helmholtz reviews the subject of colour vision, and materially modifies the theory as first announced by him about 1856, and since

[1] Ladd, *Outlines of Physiological Psychology*, p. 268.

then termed the Young-Helmholtz theory. He now states that luminosity or brightness plays a more important part in our perceptions of colour than has been supposed. He also, by analysing the colours of the spectrum with great care, has been able, from these data, to determine three fundamental colour sensations, the first *red* (*a*), which is a highly saturated carmine-red, the second *green* (*b*) like the green of vegetation, and the third *blue* (*c*) like ultramarine. Each spectral colour is made up of certain proportions of these fundamental colours, or a combination of two of them added to a certain amount of white. Thus 100 parts of green are composed of 15 of *a*, 51 of *b*, and 34 of *c*; or, to take other examples, spectral red will contain, per cent., 42 of *a*, 1 of *b*, and 57 of white; yellow, 11 of *a*, 14 of *b*, and 75 of white; and blue, 2 of *a*, 11 of *c*, and 87 of white. The white gives the element of brightness. According to this view, it is not necessary to suppose that in the red-blind the red-perceiving elements are awanting, or that in the green-blind the green-perceiving elements are absent, but that these elements may be stimulated with intensities different from those affecting the normal eye. Suppose that in the eye of a colour-blind person the curves of intensity representing the red and green coincided, or, in other words, that the elements responsive to red and green in the abnormal eye were stimulated with intensities equal to that of red in a normal eye, the sensation would be yellow, as we find to be the case in so-called green blindness. Again, if in a similar way the red curve coincided as regards intensity with the green, the general effect would be that of a red-blind person, the red end of the spectrum would appear to be green, and no red would be visible. This theory does not profess to state what may occur in the retina in the way of chemical change, as is attempted in the theory of Hering.

Captain Abney and Major-General Festing have also investigated the question of colour sensation by photo-metrical methods, and have been able to mark out the curves of luminosity both of normal and of colour-blind eyes. Their observations support the Young-Helmholtz theory, and indicate clearly that the peculiar sensations of colour experienced by colour-blind people are due either to the different intensities of the three primary colour sensa-tions, or to the absence of one or more of those sensa-tions.[1]

6.—Binocular Vision

Having considered the eye as an optical instrument, we have next to inquire how the two eyes act together, and what are the advantages of binocular over monocular vision.

Movements of the Eye.—When we wish to change our field of view, we may do so either by moving the head as a whole, or the eyes alone. The eyes move very freely in their sockets, but, as we shall see, their movements have certain limitations. The orbits—the cavities of the skull in which the eyes are set—contain the muscles by which the eyes are moved, nerves, vessels, glands, connective tissue, and, lastly, a considerable quantity of fat, which forms an elastic cushion on which the eyeballs rest. The depth of setting of the eyes in the orbits varies in different people, and in the same person from time to time ; but, as a general rule, the eyes are so situated that one may, without moving the head, look outwards and slightly backwards to either side. We may readily prove this by standing erect with the back of the head against a wall. If some bright object on a level with the eyes, and touching the wall, be moved gradually outwards from the head, it will, at a certain point

[1] *Philosophical Transactions*, 1886, 1888, 1892.

(about 8 inches to 1 foot), become visible. The head being kept fixed, a similar point may be determined for the other side of the head ; and a straight line drawn from these points through the outer angles of the orbits will be found to meet at an angle of about 90° ; or, in other words, if the head be considered as placed within a circle, only one quadrant of the circle is shut off from the visual field, namely, that in which the head lies.

The movements of protrusion and retraction of the eye-balls are involuntary, and of little importance for vision, but rotatory movements of the eyeball require careful considera-tion. These take place round a centre of rotation which, according to Donders, lies 1·77 mm. behind the centre of the visual axis, or 16·05 mm. from the vertex of the cornea. We may conceive of three axes passing through this centre, an *antero-posterior*, a *transverse*, and a *vertical* axis, and each of these axes may be regarded as lying in
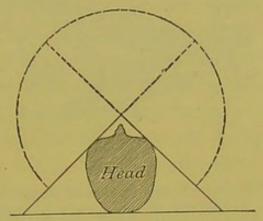
FIG. 79.—Diagram to illustrate the fact that we can see objects in a plane behind a transverse vertical plane through the two eyes.

planes which, passing through the coats of the eyeball, divide the ball into two nearly equal parts, an upper and lower, an outer and inner, and an anterior and posterior. These axes and planes have a certain fixed position, the *primary position*, with reference to the orbit when the eye is at rest. If the eyeballs rotate on the antero-posterior or visual axes from the primary position, either vertically or horizontally, the eyes are said to have assumed a *secondary position*, and a *tertiary position* if they move in an oblique plane, so as to look inwards, and at the same time upwards or downwards. In the secondary position, there can

be no rotation of the eye around the antero-posterior axis, but in the tertiary position there is always more or less rotation upon all three fundamental axes—on the antero-posterior, for example, it may be even more than 10°. Such *circular rotation*, or rolling of the eyes, takes place when the head leans towards either shoulder. In this case the direction of rolling is such as tends to counteract the deviation of the head.

The Ocular Muscles,—The movements of the eye are caused by the action of six muscles. Four of these, the direct muscles or *recti* (Fig. 80), pass forwards from the back part of the orbit to be inserted severally on the upper, lower, inner, and outer sides of the eyeball, and their action is easily understood. When the *inner* muscle contracts, the eye rotates on its vertical axis and looks inwards, and when the *outer* acts, outwards. When the *upper* contracts, the eyeball rotates upon its transverse or horizontal axis and the eye looks upwards; when the *lower* contracts, the eye looks down.

FIG. 80.—Diagram of muscles of right eye. 1, Elevator of the eyelid; 2, superior oblique muscle; 3, superior direct muscle; 4, 4′, external direct muscle cut in order to show part of the optic nerve, and 7, the internal direct muscle; 5, inferior oblique muscle; 6, inferior direct muscle. (Schwalbe.)

It must be borne in mind, however, that as the upper and lower *recti* pass somewhat obliquely outwards to their places of insertion in the eyeball, there is a slight inward direction given by them to the line of vision in addition to the deviation up or down. To correct the inward deviation, and, in general, to give circular rotation to the eye, two oblique muscles exist. The *upper* (superior oblique),

passing forwards along the inner wall of the orbit, passes through a small fibrous ring attached to the bone, and turns like a rope on a pulley backwards and outwards to be inserted into the upper surface of the eyeball. The other (inferior oblique), arising from the front part of the inner wall of the orbit, passes backwards and outwards under the eyeball, and is inserted into its outer part. The upper oblique muscle rotates the eye downwards and outwards, the lower upwards and outwards. The outer or inner direct muscle (external or internal rectus) alone suffices to rotate the eyes outwards or inwards in a horizontal plane. To cause upward or downward rotation vertically, the upper rectus and the lower oblique, or the lower rectus and upper oblique, come into play. For oblique movements, the two recti adjoining the quadrant, into which the fore part of the visual axis moves, together with one of the oblique muscles, act simultaneously. Further, since we habitually use both eyes in looking at an object, it will be readily understood how delicate and accurate the co-ordination of the muscular action must be. In looking upwards or downwards similar sets of muscles will of course come into play ; but in looking sideways the outer set of one orbit acts at the same time as the inner of the other, and, in converging the eyes upon a near object, the two inner sets will co-operate. The ocular muscles in all voluntary movements tend to render the view of the object we wish to look at distinct, by the formation of its image on the yellow spot, and they cannot act so as to lead to the formation of images on non-corresponding points of the retina (see p. 177). We cannot look upwards with one eye while the other eye is turned downwards, nor can we look with the right eye to the right and the left eye to the left at the same moment. It has been pointed out by Le Conte that in drowsiness, intoxication, and death, when the eyes are in a purely passive state, the

visual axes diverge slightly, and for this reason the intoxi-
cated man sees double. Le Conte attributes this to the
divergence of the axes of the orbits of the human skull, and
holds it probable that "in a state of perfect relaxation or
paralysis of the ocular muscles the optic axes coincide with
the axes of the conical eye-sockets, and that it requires
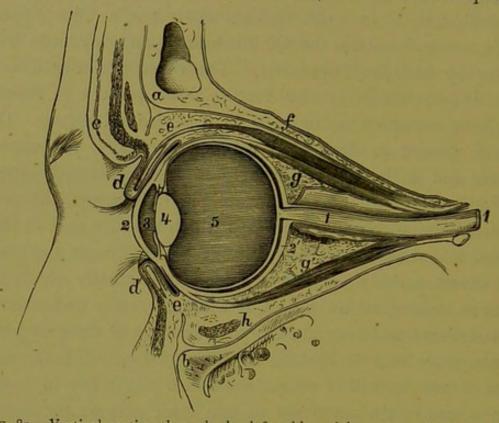
FIG. 81.—Vertical section through the left orbit and its contents in the orbital
axis and with eyelids open. *a*, Frontal bone above orbit; *b*, upper jaw-bone
below orbit; *c*, thickened bone for eyebrow; *d* upper, *d'* under eyelid with
eyelashes; *e, e*, meeting of conjunctivæ of eyelid and eyeball; *f*, muscle that
elevates upper eyelid; *g*, superior direct muscle; *g'*, inferior direct muscle;
h, cross section through inferior oblique muscle; 1, optic nerve; 2, cornea;
3, anterior chamber; 4, lens; 5, vitreous humour. (Schwalbe.)

some degree of muscular contraction to bring the optic
axes to a state of parallelism, and still more to one of con-
vergence, as in every voluntary act of sight."[1]   The
doubling of the image caused by external deviation of the
fore part of the visual axes may be studied if we press upon
the outer border of each eyeball with the fingers.   All

[1] Le Conte, *Sight*, p. 255.

objects in view are now seen double, and if the right eye be shut the left image disappears, and *vice versâ*.

How an Object is seen as One with Two Eyes.— When we look at an object in the far distance the antero-posterior axes of the eyes are parallel, and an image of the object will be formed upon the spot of distinct vision in each eye. Again, when the object viewed is near at hand, the visual axes converge, so that the image is still formed upon the yellow spot of both eyes, and the object is seen as single. This sensation of oneness arises from the habitual use of these areas of the retinæ for the observation of one and the same point, and from the attention given to that point alone as distinguished from all others in the visual field. But if we displace one of the visual axes by pressing with the finger upon the corresponding eye we will seem to see all objects doubled, one image being stationary, the other moving as we vary the pressure. The reason for this is as follows : under ordinary circumstances the mind projects the image formed in the eye outwards in the direction of the visual axis, and this being now mechanically displaced the object seems to be in motion.

But, further, since the whole field of normal vision seems single when seen with both eyes, it follows that the retinæ, as a whole, act in combination, and give a single image of that which is focussed upon them. Now, suppose we hold two pencils upright in the middle plane of the body, but at different distances, we can voluntarily fix our attention upon one or other, and the one upon which we concentrate our regard will appear single, while the other will be indistinctly seen and will seem double. The image of that one to which we specially attend is single because the visual axes converge upon it, but the other is indistinct and double because its images on the two retinæ are not in the line of regard, and not upon points which habitually act

together. For each person there is always a certain *visual field*, determined in shape by the outlines of the eyebrows, nose, and cheeks, and by the position of the eyes in regard to them, a field from each point of which rays entering the eyes always fall upon corresponding points in the two eyes.
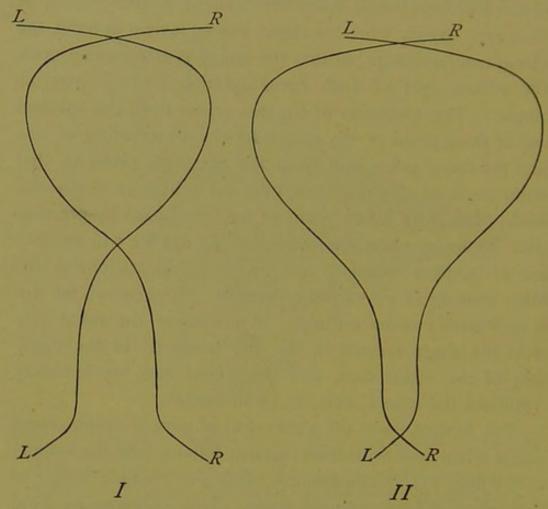
Fig. 82.—Binocular visual field. If a sheet of paper be held so as to touch the brow and prominence of the nose, the binocular visual field will be seen as in the space in I, bounded by the lines L and R. If the paper be held a few inches from the face the area visible to both eyes will have the shape seen in II.

If, the head being fixed and both eyes open, the extent of the whole visual field be noted, and if the right and left eyes be alternately closed and opened, it will be found that the projection of the eyebrows and nose cuts off from each eye a certain part of the visual field which is visible to the

other eye, and that there is a central area common to both eyes, or a *binocular visual field*, shaped as in Fig. 82. This area bears a fixed form and magnitude, and from it alone can rays of light enter both eyes. From each point in this field the rays of light entering the eyes must, for a given state of accommodation, fall upon the same points of the retinæ. To each point, then, in the binocular visual field there is a corresponding point in each retina ; and, again, the right side of the right retina corresponds point for point with the right side of the left retina, and, similarly, the left side of the right retina corresponds with the left side of the left retina. Thus it follows that the upper halves correspond, and likewise the lower. The yellow spots form corresponding areas, and when the images of a small object formed. upon these, and projected outwards by the mind upon the visual field, coincide in position the object is seen single.

FIG. 83.—Diagram of one form of horopter. (Müller.)

If, for example, the eyes are so directed that the images upon them of the point A (Fig. 83) are projected outwards so that the lines of projection meet at A, we will see A as one point, and any other point in its near vicinity, such as B, will likewise be seen single, because its images are formed upon corresponding points of the retinæ. If we describe a circle whose circumference passes through the point of sight and the two optic centres, it may be mathematically shown that rays from all points of this circle fall upon corresponding points, and objects on it are seen

single.   Müller called this circle the *horopter*; and, for
different positions of the eyes, the horopter may assume
complicated forms, but in any horopter all points are seen
single.

We are now able to understand how a double image is
seen when objects not in the horopter are seen double.
Suppose in the case of looking at the pencils we represent
the nearer one by *p* (Fig. 84), the farther by *p′*.   Then,
when the eyes are converged on *p*, the images of *p′* are not
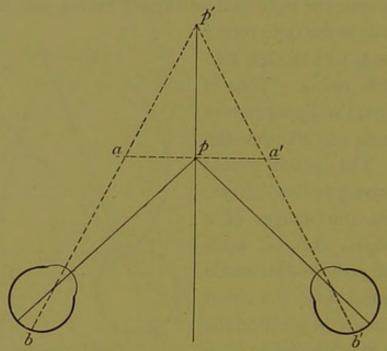
Fig. 84.—Diagram to illustrate formation of homonomous double images.

formed on corresponding points of the retinæ, but are each
to the *inner* side of the yellow spot at *bb′*, and two faint
images of *p′* are seen, one on each side of, and at the same
distance from, the eyes as *p*, viz. for the left eye at *a*, for the
right eye at *a′*.   On shutting one or other eye, the image
on the same side disappears, and it is said to be *homo-
nomous*.   But if the gaze be fixed upon *p′* (Fig. 85) a
double image of *p*, formed *external* to the yellow spot on
both eyes, is mentally projected outwards to the distance of
the plane *a′a* through *p*, and now on shutting one or other

eye the image on the opposite side disappears, and it is hence said to be *heteronomous*.

Now, as a rule, we are not conscious of the formation on the retina, nor does the mind project outwards this double image. It is only by special attention to the action of both eyes that we become conscious of it ; and, at a first attempt, it is sometimes difficult to convince a person that a double image is, as in the above experiment, visible. The reason of this is, that attention is paid to the object directly looked at and not to the fainter double images ; and also
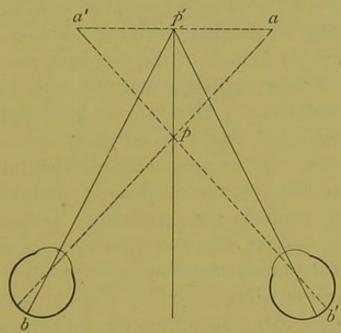
Fig. 85.—Diagram to illustrate formation of heteronomous double images.

because where we do try to see two objects at different distances at one and the same time, the minds of most people attend only to the image formed by the right eye and disregard that of the left. Thus, if you tell a person to point with the finger at a distant object, both eyes being open, and then ask him, while holding the hand steadily, to shut the right eye, he will seem to be pointing to the right of the object, and not directly at it ; but if he shuts his left eye he will seem to be pointing correctly. This applies more especially to right-handed persons, the reverse being

the case with those who are left-handed. By careful observation, we can note the two images of the finger pointing, and may bring the more distant object between the images, and then, whether the right or left eye be shut, the finger will not seem to be pointing directly at the distant point. Still another reason why we neglect double images is that these are often so large as to overlap one another, and so be practically indistinguishable; and the effect of the two combined in a psychical process by the mind is to lead to the perception of the third dimension in space, or in other words, the perception of *solidity*.

Perception of Solidity. — When we look at a solid body the images formed in the two eyes are not exactly the same, because the right and left eyes view it from different standpoints. This can be best appreciated by viewing some small object at no great distance from the eye, *e.g.* a book. If we alternately examine the book with the right and left eye, the other being meanwhile closed, and compare mentally the appearances presented to the two eyes, we observe that the right eye sees more of the right side of the book, the left more of the left. If we then note what area of background is hidden by the two images, we find that the part hidden from the right eye by the book is different from that for the left. Now, with both eyes open, let vision be accommodated for the background, but examine the effect produced by the interposition of the book. We are then conscious of a solid opaque body obscuring part of the background completely, while to either side of this is a spectral transparent image of the sides of the book through which the wall seems to be seen. On shutting the left eye the solid body seems to move to the left, rendering the left spectral part opaque, because the part of the wall formerly seen by the left eye is no longer visible, and similarly for the right. It will further

be noted, as we converge the eyes on the book, that the spectral parts disappear, and we see the one solid body only. Lastly, if we look at the book fixedly for some time, one eye being shut, and then if we look with both eyes, it is at once seen that the book stands out in much bolder relief, the various sides and borders taking their natural inclination in reference to space. A suitable object for the study of this phenomenon is a truncated pyramid upon which we look vertically downward. With both eyes open the appearance presented is that seen in B (Fig. 86). Keeping the head in the same position, but looking with the left eye
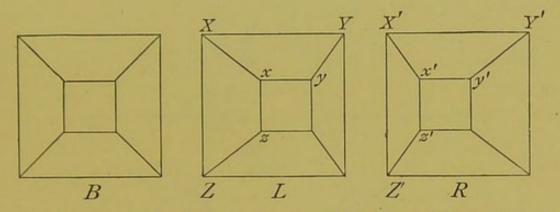
FIG. 86.—Appearance of a truncated cone seen from above with B, both eyes, L, left eye, or R, right eye.

only, we will see the cone as in L, or with the right eye only, as in R.

The Stereoscope.—The combination of L and R, so as to give the appearance of solidity to the eye, may be made by the *stereoscope*, an instrument invented by Wheatstone, who first noticed that the perception of solidity was due to the dissimilarity of the images presented to the retinæ. In its simplest form the reflecting stereoscope consists of two mirrors placed at right angles to each other, as in Fig. 87. The eyes, looking into these obliquely, see reflections of the dissimilar figures R and L representing the appearances as seen by each eye individually; and

the images, mentally projected backwards in the line of vision, are combined at the point of intersection of the optic axes, and we seem to see the single solid object as we would if we were looking at it with both eyes.

Brewster's refracting stereoscope is the one in common use.   In this instrument the optical effect is obtained by means of two lenses so arranged that rays of light passing from the stereoscopic pictures impinge on the retina, and are projected backwards so as to converge and meet at points
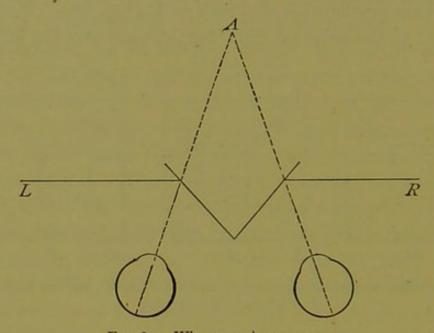
FIG. 87.—Wheatstone's stereoscope.

behind the plane of the pictures, as in Fig. 88.   Each eye thus sees its own picture, but corresponding points are brought to a focus, and in the union of all we have one picture in relief.

The *apparently differing distances* from the eye of different parts of the combined picture are due to the differing distances between corresponding points of the constituent pictures.   Those pairs of points which are nearest together stand out in highest relief, or in other words, require the greatest convergence of the optic axes, while those which are most distant from one another seem

most remote in the combined picture. In Fig. 86, p. 181, the points $\begin{smallmatrix} X, Y, Z \\ X', Y', Z' \end{smallmatrix}$ are respectively at equal distances from one another, and consequently seem to be in the same plane in B. Similarly $\begin{smallmatrix} x, y, z, \\ x', y', z', \end{smallmatrix}$ are at equal distances from one another, and seem to be all in one plane, but the dis-
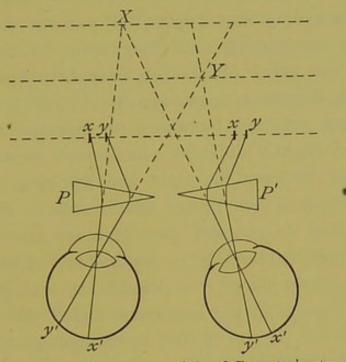
FIG. 88.—Diagram illustrating the principle of Brewster's stereoscope. The points *x*, *x* forming images *x'*, *x'* are projected outwards and coincide at X; the points *y*, *y*, being nearer to one another than *x*, *x*, appear to coincide at a point Y in a plane nearer to the eyes than X. (After Landois and Stirling.)

tance between any pair of these being less than the distance between any pair of the set $\begin{smallmatrix} X, Y, Z, \\ X', Y', Z', \end{smallmatrix}$ the plane *xyz* seems nearer than the plane XYZ. Hence the truncated apex of the pyramid seems nearer the eye than the base. But if we transpose R and L so that R is opposite the left eye and L opposite the right, then the points $\begin{smallmatrix} x, y, z \\ x', y', z' \end{smallmatrix}$ will respectively be farther from each other than $\begin{smallmatrix} X, Y, Z, \\ X', Y', Z', \end{smallmatrix}$ and we seem to be looking into a hollow pyramid,

whose apex is directed away from us. In Fig. 88 the points *x*, *x*, being farther apart than *y*, *y*, are combined at X in a plane behind that through Y, the point of combination of *y*, *y*.

It is indeed unnecessary to have a stereoscope to get the combined effect. If we merely fix the eyes upon the diagram, but accommodate the vision for distance, we will see the two diagrams apparently moving towards each other and overlapping until they seem to coincide, when suddenly the effect of a solid body between two faintly visible flat diagrams is perceived. Ordinary stereoscopic pictures are obtained by taking photographs of the same scene from slightly different standpoints, corresponding to the distance between the right and left eyes. These are fixed to a card in their proper relationship to the right and left eye ; and if reversed, they give an inverted picture, all solid bodies seeming to be hollow. Even with the pictures properly placed it is possible, by a simple arrangement of lenses, as in the instrument called the *pseudoscope*, to displace the picture so that our judgment of the size of objects is disturbed by the apparent alteration in their distance from us.

The Telestereoscope.—The stereoscopic effect depending upon the distance between the eyes, it will naturally be greater, the greater the distance. We cannot, indeed, increase the distance between the eyes, although a small solid body stands out in higher relief when near the eyes than when far away, because the visual axes are more convergent. But von Helmholtz has invented an ingenious instrument by which the eyes are virtually separate and a more powerful stereoscopic effect obtained. It is known as the *pseudoscope* or *telestereoscope*, and the principle of its construction is as follows. Two mirrors are placed parallel and a little to the side of the mirrors used in Wheatstone's

stereoscope (Fig. 89). The rays from the object to the outer mirrors are reflected to the inner mirrors, and thence to the eyes. It thus happens that rays falling on mirrors much more distant from each other than the eyes, enter the eyes as if coming directly to them from the object. We are thus able to see, as it were, more of the sides of the body than we could under ordinary circumstances; distant objects seem to be brought nearer, judging by their greater relief, and all parts of the field likewise stand out in a more marked manner than usual.

In viewing the different parts of a solid body, or the apparently nearer and more remote parts of a stereoscopic picture, there is a constant movement of convergence or divergence of the eyes, and hence it was maintained that a prime factor in the percep- tion of solidity is the sense of muscular effort required in moving the eyes from point to point. This theory, how- ever, is negatived by the fact
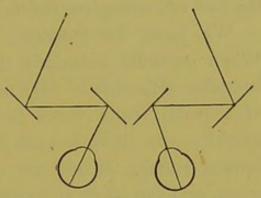
FIG. 89.—Telestereoscope. For explanation, see text.

that we have quite a correct perception of the spatial relations of objects when seen by the instantaneous flash of lightning, a flash which takes place so rapidly that there is no time for all the complicated processes involved in muscular action. Similarly, the stereoscopic effect is seen when the picture is seen by the light of the electric spark; that is to say, in a time not exceeding the $\frac{1}{24000}$ part of a second. But though the time of stimulation of the retina is momentary, there is an appreciable time lost in the physical change of the condition of the retina, in the passage of the nerve current, in the arousing of sensation and the fusion of the stimuli. Wheatstone held that,

in the fusion of two images not mathematically similar, the mind *superadds* the perception of solidity. If the points in the two pictures are so far apart that the converging apparatus is unable to bring them to a focus, we only see two flat pictures. If the two pictures are exactly similar, and their points may be exactly fused, the result is a flat picture. The mental fusion is the cause of the new sensation. The fusion in ordinary circumstances is to all intents and purposes complete. The external world presents itself to us with each object clearly single and defined. It is only when we pay close attention and carefully analyse our visual sensations that we can detect the fact of incomplete fusion.

We have, for example, the sensation of *luminosity*. When carefully examined this is found to be due to the irregular reflection of rays of light from the uneven surface of a body; calm water is non-luminous, rippling water sparkles with light, but the amount of light going from the broken surface to one eye differs from that going to the other, and the effort at fusion of the darker and the lighter gives rise to the sensation of luminosity. The combined stereoscopic picture is luminous from the superposition of darker and lighter spots in the one picture, or the reverse in the other. And yet the fusion is incomplete when we look into the matter closely. By an effort of will we can allow the dark or the light to preponderate. Suppose we have two stereoscopic pictures, as in Fig. 90, one of which is light on a dark ground, the other dark on a light ground, we can, by a voluntary effort, superpose the one over the other and give rise to the impression of a luminous solid body; but we can also easily alter the depth of the grayish luminosity by paying attention to the dark or the light picture at will.

We have here, indeed, an analogy to the detection

by the ear of the elements of a compound tone. The practised ear is able to separate and attend to any one elementary tone, or, on a larger scale, to any individual instrument in an orchestra ; and the mind may dwell only on the harmonious fusion, experiencing a pleasure from the combination, or it may give itself up at will to the effect of one or of all. The process is easier with the ear than with the eye. The optical fusion is more complete, more difficult to analyse. But it may be made easier if we endeavour to fuse two surfaces of different colours in the stereoscope. Here there is not complete mixing of the colours, but the colour sensation is now that of one, now that of the other
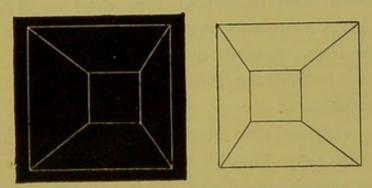
Fig. 90.—Diagram to illustrate causation of sensation of luminosity.

colour, the varying effect being probably due to changes in the activity of the two retinæ.

Estimation of Distance.—The foregoing considerations on the perception of solidity will assist us in answering the more general question as to the estimation of *space or distance.* We have seen that the muscular effort at convergence is greater for near than for remote objects, and the greater the effort experienced the nearer do we judge the object to be. But accompanying the effort at convergence there is usually a muscular action of accommodation. The pupil contracts to shut off divergent rays of light which would cause blurring of the image, and the ciliary muscle contracts in order to lengthen the focal distance of the eye

for the nearer object. Each of these muscular efforts must add its quantum to the general sum of muscular sensation. Objects at the point of sight are seen in clear detail, while those which are nearer or farther off are seen indistinctly, and we unconsciously judge of differing distances by varying efforts of accommodation. The dimness of bodies within the near point of vision is due to the impossibility of focussing the object. Far-distant objects are dimly seen because of the aerial perspective. The atmosphere not being perfectly transparent and colourless, small details are blotted out, and variety of colour lost in a bluish haze. The distant parts of a landscape are conceived to be nearer and smaller when seen in wet weather than in dry, for dust-laden air gives a more marked aerial perspective than that which has been washed by rain; and again, in misty weather the half-hidden forms of men may seem far away and of supernatural size.

Again, varying convergence assists our estimation of distance, not only through the muscular effort involved, but also by variation of the *angle of convergence* of the visual axes upon the object. For objects of similar size it is evident that the angle of convergence must be greater for near than for remote objects. We learn through the other senses, as well as through sight, to know the comparative sizes of objects, and by noting and comparing the apparent size of objects we arrive at a judgment as to their distance, the seemingly smaller, of course, being considered the more distant. Persons who have lost the use of one eye, and therefore the valuable aid of convergence, cannot judge accurately of the distance of near objects. If asked to touch an object quickly they are apt to fall short, as experience tells them they may misjudge and strike it roughly if they attempt to reach the full apparent distance.

Estimation of distance is likewise assisted by observation

of the distance of the background over which a body near to the eye seems to move when the relative positions of the eye and the body are changed.

In Fig. 91, I. the eye E moves while the body B is stationary, in II. the body moves from B to B′ while the eye is stationary. The apparent distance moved by B upon XY is only *ab*, while upon X′Y′ it is the much larger distance *a′b′*. The distance over which the body seems to pass gives an indication of the relative distances of the planes XY, X′Y′ from the observer.

We are also able to give a more accurate estimate of
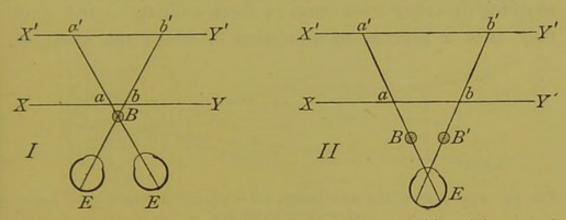
FIG. 91.—Estimation of distance from change in relative position of the eye and of an object observed.

the distance between two points when several objects intervene. We take a series of mental leaps, as it were, from point to point, the effort of which is greater than that of passing over the whole distance at one effort. The distance between A and B (Fig. 92) seems greater than that between B and C on account of the intervening dots, but it is the same. Children often amuse themselves with the

FIG. 92.

following experiment. A boy, after looking at a landscape in an erect posture, will turn, stoop down, and view it between his legs, and all objects will seem farther off, as, from the unaccustomed posture and the proximity of the

head to the ground, objects in the foreground, formerly dis-regarded, are now more dwelt upon.   Similarly, the sky seems nearer us at the zenith than at the horizon, and a landsman has great difficulty of judging distances at sea. The eye projects the image of the object viewed outwards, but if it be at any great distance, the lines of projection from the two eyes are practically parallel, and judgments as to size guide the judgment as to distance.   It is interesting to note, in this regard, that persons who have been born blind and have by an operation gained the power of vision, seem at first to see all objects close to the eye or almost touching it—they "see men as trees walking"—and it is only after a process of education in which the sense of
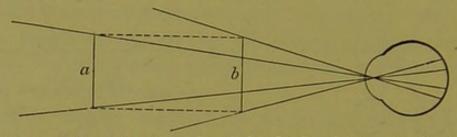
Fig. 93.—*a* and *b* are of the same length, but *b* subtends a greater visual angle, being nearer to the eye.
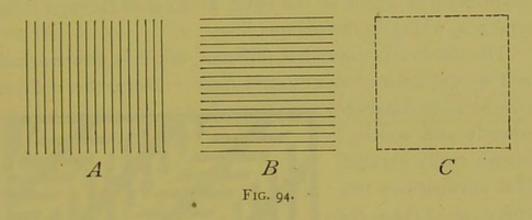
touch has much to do that they are able to form a proper estimate of externality or distance through vision.

Estimation of Size.—Closely connected with our estimate of distance is that of *size*. This primarily depends on the size of the retinal image, or in other words, of the *visual angle* subtended by the object.   In Fig. 72, p. 146, X is the visual angle subtended by the lines *c*, *d*, and *e*, and since these objects make a retinal image of the same size it is evident that, in estimating size, it is necessary to have at least an approximate idea of the distance of the object from the eye.   The moon subtends a larger visual angle than the stars because it is so much nearer to us, not because of its greater size.

We learn by experience, more especially by the com-

bination of touch and vision, that if two objects of different sizes subtend the same visual angle, the nearer of the two is the smaller; and the young artist measures the comparative length and breadth of distant objects by holding his pencil at arm's length between his eye and the thing sketched.

The *degree of convergence of the visual axes* is also of much importance in the estimation of size. For by experience we know that an object of known size will subtend a certain *visual angle* at a given distance, and that the nearer the object is to the eye the greater will be the angle subtended, as in Fig. 93. Then, of all bodies which subtend the *same*

A   *B*   *C*

Fig. 94.
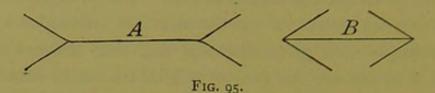
visual angle, that one must be the largest which requires the least convergence.

Thus, too, the intervention of bodies of known size gives an idea as to the size of the more remote object. The sun seen on the horizon behind trees seems larger than when in mid-heaven, because we have a better estimate of its distance and of the visual angle it should thus subtend. Few people agree in their estimate of the apparent diameter of the full moon, and in Fig. 94, B seems to have the greatest height from a mental summation of the horizontal spaces, A the greatest breadth, and C to be the smallest. Yet all are of the same area. In this case the three figures are of the same size, and must give rise to retinal .images of the same size, but the basis on which we form our judgment as

to the area of each being different, we judge them of different size. The judgment errs, not the organs of vision.

This *error of judgment* is perhaps even more marked in the case of Fig. 95, where the line A seems longer than B, although in reality of the same length. In A there is

FIG. 95.

insensibly divergence of the optic axes, in B there is convergence, owing to the oblique lines.

The illusion is somewhat different, but it is also marked in Fig. 96, known as *Zöllner's lines.* Here the oblique lines seem to converge towards one another, though really parallel. The unconscious tendency to follow the short lines till they would intersect leads to an impression that the oblique lines would meet if produced in the opposite direction.

Allied to this illusion of vision is that produced by drawing
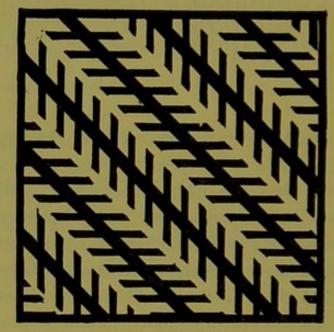
FIG. 96.—Zöllner's lines.

a thin line to intersect a broad line obliquely. In Fig. 97, EF, not CD, is in the same straight line as AB.

Illusions of Vision also arise when we look for a short time at a body in motion and then turn our eyes upon one at rest. It seems to move in the opposite direction,

whether that has been one of rotation or of movement in a straight line. Thus if we gaze for about a minute at a wheel revolving rapidly on a fixed axis, and then turn our eyes to the ground, a similar area seems to rotate in an opposite direction round the centre of vision. Similarly, as stated on p. 155, when upon the deck of a ship in motion, if we look for a time on the water and then at the deck, some of the boards seem to creep forwards relatively to those adjoining them. In looking at the water we instinctively try to fix our eyes upon points in the seemingly moving surface, and so the eyes have a backward movement. Owing to the persistence on the retina of visual impressions, we continue unconsciously to seek back towards the previously vanishing point; and in doing so the new image created by the body, stationary with regard
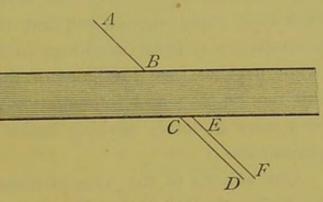
FIG. 97.—For description, see text.

to ourselves, seems to be that of a body in motion in the opposite direction.

Vision assists in the *perception oj motion* mainly by the change of position of the retinal image of the moving body, relatively to the fixed position of the image of the rest of the visual field. If the eyes follow the moving body, then its image is fixed on the retina, while the rest of the visual field changes its position. By the rapidity of movement of eye, head, or body, we judge as to the rate of movement of the object. We can form no idea, through vision, as to the *direction* of motion, unless we have this relative movement of the various parts of the field. Sitting in a railway train in motion, there is a change of position of near objects as

O

regards ourselves and the background, which is so rapid that we almost imagine them to be in motion. If another train passes us going in the opposite direction, it seems to be going with great velocity, because we assume the compartment in which we sit to be stationary, and the velocity of our own movement is added to that of the other train. Similarly, if two trains are standing side by side at a station, and the one adjoining us begins to move, we imagine that it is the train in which we sit that is moving in the opposite direction, because we are by habit led to believe that the station with all its contents is fixed, while our train is the only movable body. We can thus enjoy the sensation of somewhat rapid motion without the jarring that usually accompanies railway travelling, until, the other train having swept past, we see the sides of the station beyond silent and motionless ; and immediately we are brought to rest by a more smoothly working brake than has yet come into general use.

Our notions of the *form* of objects are based partly on the fusion of stimuli of different parts of the retina, giving rise to a sense of continuity, and partly from movements of the eyes from point to point. The body may be a plane figure in which, owing to the mode of construction, we may at will imagine different shapes to be represented. Fig. 98, for example, may be conceived at will to represent either "a staircase against a wall, or an overhanging portion of a wall, the lower part of which has been removed, and whose under surface has taken the form of steps."[1] In the former case, we regard *ab* as running backwards from *a*, the nearer point ; in the latter, we suppose *b* to be the nearer point, and *a* the more remote, and run the eye along *ab* in the direction from *b* to *a*.

In the perception of solidity of bodies, the possession, as

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[1] Bernstein, *The Five Senses*, p. 160.

we have seen, of binocular vision is of marked advantage.
The movements of accommodation and convergence, the
wider movements of the whole
eye from point to point and
from plane to plane, the play
of light and shade, the relation
to surrounding bodies — all
these are factors which in-
fluence the mind in its judg-
ment as to solidity. Nay,
further, in certain disordered
conditions of the brain, old
impressions may be renewed
and recombined, and the
surrounding space becomes
peopled with fantastic forms,
lovely or terrible, according
to mood—forms as real and
substantial to the disturbed
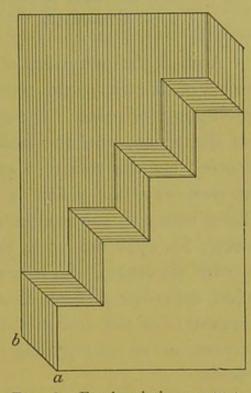
FIG. 98.—For description, see text.
(After Bernstein.)

mind as those which appear in ordinary vision. How
forcibly has this been painted in the dagger scene in
Macbeth—

Is this a dagger which I see before me,
The handle toward my hand? Come, let me clutch thee.
I have thee not, and yet I see thee still.
Art thou not, fatal vision, sensible
To feeling as to sight? *or art thou but*
A dagger of the mind, a false creation,
Proceeding from the heat-oppressed brain?
I see thee yet, in form as palpable
As this which now I draw.
Thou marshall'st me the way that I was going ;
And such an instrument I was to use.
Mine eyes are made the fools o' the other senses,
Or else worth all the rest ; I see thee still,

And on thy blade and dudgeon gouts of blood,
Which was not so before. *There's no such thing:*
It is the bloody business which informs
Thus to mine eyes.[1]

And as the perturbed mind may wander in an illusory world of its own, so the abstracted mind may disregard the promptings of sense. The eye is open, the image is painted on the retina, and the nerve currents pass to the visual centre; but the centre is preoccupied, the mind goes on its own way, the vision is unheeded. Such is the condition with the somnambulist. He rises and walks in his sleep; his eyes are open, but he sees only that which fits in with his dream. So it is with the mesmerised man. His mind, otherwise a blank, is moved this way and that at the suggestion of the operator, and in a stick he sees a hissing serpent, or an empty table becomes covered with choicest viands.

Again, as vision is only possible so far as the visual apparatus is perfect, and since we find the organ of vision in every stage of advancement, from the colour spot of the invertebrate up to the complete binocular vision of man, so we may infer that the higher intelligence of man is intimately associated with the perfection of the eye. Crystalline in its transparency, sensitive in receptivity, delicate in its adjustments, quick in its motions, the eye is a fitting servant for the eager soul, and, at times, the truest interpreter between man and man of the spirit's inmost workings. The rainbow's vivid hues and the pallor of the lily, the fair creations of art and the glance of mutual affection, all are

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[1] *Macbeth*, Act II. Scene i. In this scene, also, the great dramatist pictures, with profound psychological insight, the struggle between the delusions of the mind, as projected into space, and their correct appreciation by the reasoning faculties. The words indicating the application of the reason are printed in italics.

pictured in its translucent depths, and transformed and glorified by the mind within. Banish vision, and the material universe shrinks for us to that which we may touch ; sight alone sets us free to pierce the limitless abyss of space.

SOUND AND HEARING

THE organ of hearing is the ear ; but the human ear is a
much more complicated apparatus than most people suppose.
The really sensitive part of the ear, the part in which the
auditory nerve terminates, and where physical give rise to
physiological changes, is buried deep out of sight in the
bones of the cranium, and the external ear, that which is
seen upon the outside of the head, forms a part only of an
elaborate arrangement whereby sound waves may be trans-
mitted inwards to the true end organ of hearing. But while
this is the case in man, in many of the lower organisms we
find an ear which closely resembles the human ear in prin-
ciple, though much simplified in detail, and situated upon or
immediately below the surface.   In its simplest form the
ear consists of a set of cells to which we find attached
delicate hairs or rod-like structures, which are thrown into
vibration by sound waves.   These cells are connected, or
are in apposition, with the terminal fibrils of the auditory
nerve ; and when agitated by sound they produce a nerve
impulse, which in turn excites the central nerve cells,
and sound is heard.   The first step in complexity of organ-
isation of the ear is that the hair cells are no longer on the
free surface, but line in part a membranous sac containing
fluid, the cells having sunk down into the substance of the
animal's body, and being thus better protected from injury

(Fig. 99). The sac may be of a simple globular shape, or, in highly developed animals, it may assume a very complicated form ; so much is this the case in man, that it is known as the *membranous labyrinth*. The structure of the labyrinth is, as we shall see, of a most delicate and elaborate nature, and though in the embryonic condition it is near the surface of the head, in the adult it is at least $1\frac{1}{4}$ inch from the surface, and enclosed in bone so hard that it is called the petrous or stony bone. The osseous covering coincides to a great extent with the membranous bag inside, but a small amount of fluid separates the sac from its walls, and protects it from rude shocks transmitted through the bone. The auditory cells are situated in certain parts of this sac, and the auditory nerve passes to them through channels in the bone. There are also two
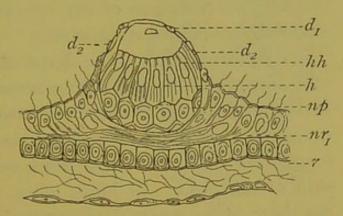
Fig. 99.—Auditory vesicle of *Phialidium*. d_1, d_2, Epithelium covering the sac ; h, auditory cells, with hh auditory hairs ; np, nervous cushion for the auditory cells, connected with nr_1, the lower nerve ring. (Hertwig and Lankester.)

openings by which changes of pressure may be transmitted from without to the fluid surrounding, and that contained by, the membranous labyrinth. But these openings cannot be seen from the outside. They communicate with a chamber known as the middle part of the ear, or simply the *middle ear*, or *tympanum*, or *drum*, a chamber containing air and opening by a tube passing forwards and inwards into the throat— the *Eustachian tube*. The middle ear is separated from the passage leading to the auricle, or visible ear, by a membrane, known as the *membrana tympani* (or *drum-head*), which vibrates in response to sounds, and whose move-

ments are communicated to a chain of bones, and by this chain to the inner ear. The membrana tympani closes the passage leading inwards from the outer ear or auricle. There are thus an outer and middle ear for the collection and transmission of sounds, and an inner ear for their reception as stimuli of sensation. By this arrangement the ear becomes more sensitive, for the middle ear acts as a drum giving resonance and strength to delicate sounds (Fig. 101).

In order to obtain a complete understanding of the manner in which sound affects the ear, we must consider carefully the structure of the ear, and how it is fitted to respond to sonorous vibrations.
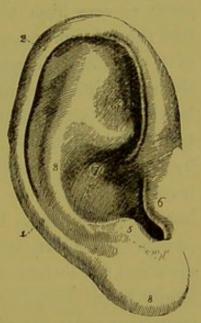
1. **External Ear.**—The shape of the external ear varies to a remarkable degree, and in some of the lower forms of vertebrates it may be entirely absent. In the frog, for example, there is no external ear, the tympanic membrane being seen as a disc on a level, and continuous with the skin of the head. In birds, again, the auricle is absent, but there is an external auditory canal or meatus leading down to a membrana tympani. The middle and internal ears are more highly developed in birds than in reptiles, but still fall far short of the human ear in complexity. In mammals, the auricle is of very varied size and shape, and it may be either stiff and erect from the presence of an elastic cartilage, as in the ear of the horse or man, or it may be soft and yielding, as in the elephant. The surface is usually convoluted and funnel or trumpet shaped, so as to gather the waves of sound to the best advantage, and many animals have the power of moving the opening of the auricle, by means of voluntary muscles, in the direction from which the sound comes. Thus the horse pricks up its ears when it hears a sound, and no doubt its appreciation of the direction of sounds is thereby assisted. In the human ear there are similar voluntary muscles, but man has, for the most

part, ceased to have the power of moving the auricle in response to sounds from varying sources apart from movements of the head as a whole. No doubt, by attention and practice, a man may acquire the power of moving the auricle slightly, and the great German physiologist, Müller, was proud of being able to do so. But, at best, these movements are small as compared with those of the lower animals. Special names have been given to the various depressions and protuberances of the auricle (for which see description of Fig. 100).

If we pass the finger round the border of the ear we will feel near the upper part a small nodule, which is interesting, according to the comparative anatomists, as being homologous with the tip of the pointed ear of many animals.

The general effect of the convolutions of the surface of the auricle is to collect and transmit to the external auditory canal, and that to the best advantage, sound waves falling upon the surface of the ear. For just as waves of light falling upon a

FIG. 100.—Outer surface of the right auricle. 1, Helix; 2, fossa of helix; 3, antihelix; 4, fossa of the antihelix; 5, antitragus; 6, tragus; 7, concha; 8, lobule. (Arnold.)

transparent body are partly reflected and partly transmitted, so sound waves striking the auricle are partly concerned in giving rise to corresponding vibrations in the substance of the auricle, and partly reflected, and the more the waves are sent to the inner ear the more intense will be the sound. The phenomenon familiar to every one, of the echo, is an example of this reflection of sound on a large scale in nature. We hear first the sounds transmitted directly to the ear, then those reflected from more

or less distant bodies. In the whispering gallery of St. Paul's Cathedral in London, or in the ducal mausoleum at Hamilton, faint sounds can be heard at a considerable distance from the point at which they originate, as they are reflected in such a way as to be focussed at a special point. So the shape of the auricle, by focussing sounds, helps the ear to hear sounds of low intensity. It would appear also that the form and size of the depressions of the concha strengthen tones of very high pitch, such as occur in hissing sounds, like the noise of waves breaking on a shingle beach, or that of a waterfall. Thus a very slight change in these depressions will affect the musical quality of tones. If the irregularities of the surface are filled with wax, sounds are not heard so loudly, and, conversely, we increase our receptivity by putting the hand to the ear, and turning the head sideways to the sound. If the auricle is entirely removed, hearing is, however, but little diminished. The collecting power of the auricles assists in the determination of the direction from which a sound comes ; the sound being more loudly heard in one ear than the other, we conclude that it comes towards that side of the head on which the louder sound is heard.

2. **Meatus or Passage.**—From the pinna or auricle, the *external auditory meatus*, or passage to the middle ear, passes inwards and slightly forwards, being inclined at first upwards and then bending downwards. The passage is almost circular in cross section, but the outer end is flattened a little from before backwards, while the inner part is broadest in the horizontal plane. The meatus is closed internally by the *tympanic membrane*, or *drum-head* (see Fig. 101, 17), which lies obliquely to the direction of the lumen of the tube, the lower margin being farther in than the upper, and the floor of the passage is thus longer than the roof.

The wall of the outer part of the meatus consists of cartilage which is continuous with that of the auricle, but round the deeper part of the tube the cartilage is absent, and the lining of skin which passes inwards from without is in close contact with the bone through which the tube
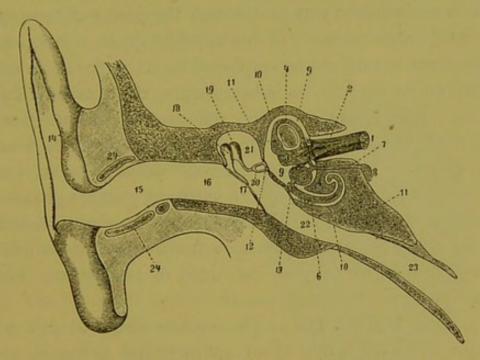
FIG. 101.—Diagram of the ear; natural size. 1, Auditory nerve; 2, internal auditory meatus closed by the cribriform plate of bone through the perforations of which the branches of the auditory nerve pass to the ear; 3-8, membranous labyrinth composed of 3, utricle, 4, semicircular canals, 5, saccule, 6, duct of the cochlea (the coils not entirely shown), 7, endolymphatic duct with, 8, its saccule lying inside of the cranial cavity; 9, lymphatic space surrounding the membranous labyrinth; 10, osseous labyrinth of compact bone lying in the more spongy substance of the petrous bone, 11, 11; 12, the oval window, filled by the foot-plate of the stirrup-bone; 13, the round window, across which is stretched the internal tympanic membrane; 14, auricle; 15, 16, external auditory meatus; 15, its cartilaginous, and, 16, its bony part; 17, tympanic membrane; 18-20, auditory ossicles; 18, hammer; 19, anvil; 20, stirrup; 21, middle ear; 22, osseous, and, 23, cartilaginous portion of the Eustachian tube; 24, cartilages of external auditory meatus. (Schwalbe.)

passes. Towards the inner part of the meatus the skin is very thin, and this is especially the case where it is continued as an epidermic covering over the fibrous tympanic membrane. At the outer part the skin is thicker, and from it spring fine hairs slanting outwards. It is well lubricated

by numerous small glands, of the nature of sweat glands much modified, which secrete a waxy substance known as *cerumen*. This material has a brownish colour and a bitter taste. The form of the canal is such as to facilitate the passage outwards of the wax, but sometimes it may accumulate in such quantity as to diminish the power of hearing to a considerable extent. If this should happen, a sharp hard instrument should not be employed for its removal, as much injury might thereby be inflicted upon the tympanic membrane. It is better to soften the wax with an alkaline or oily fluid, and then to syringe the meatus gently to remove the debris. The outward-pointing hairs and the bitter adhesive wax form together a valuable guard against the entrance of foreign bodies, animate or inanimate, into the cavity of the meatus, a provision similar to what we find in many flowers to prevent the store of honey from being plundered by marauding insects.

3. **The Middle Ear.**—The *middle ear*, *drum*, or *tympanum* is, in the adult, about an inch and a quarter from the free surface, and is thus embedded deeply in the substance of the temporal bone. Across this space passes the chain of bones from the drum-head to the internal ear, by means of which the movements of the membrane are transmitted to the labyrinth and variations of pressure effected. It receives air at atmospheric pressure through the Eustachian tube. The cavity is irregularly wedge-shaped, being wider at the top than at the bottom, and is larger from before backwards than from side to side. It is separated from the cranial cavity above by a thin layer of hard bone, and communicates behind with a set of spaces, which also contain air, lying in the part of the bone which can be felt as a prominence behind the external ear, and known as the mastoid process. The outer boundary of the middle ear is largely composed of the tympanic membrane, although it is

to be noted that the cavity extends upwards into the bone above the membrane, while in front of the membrane is a fissure in the bone, known as the *fissure of Glaser*, from its discoverer, through which pass a nerve (the *chorda tympani*) and a muscle (the *laxator tympani*), and in which, as in a socket, is fixed one of the processes by which the chain of bones is suspended. The membrane itself is firmly fixed in a groove, which can be readily seen in a macerated bone with the naked eye, and, though very thin and semi-transparent, it consists of firm fibrous tissue lined on one side by skin, on the other by mucous membrane. Fig. 102 represents the appearance of the tympanic membrane of the left ear as seen from without, and Fig. 101 shows how it is inclined obliquely to the axis of the meatus, both transversely, and from above downwards. The fibres of the membrane consist of ordinary connective, and a very
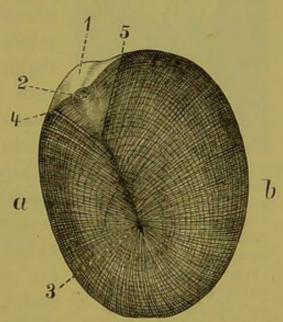
FIG. 102.--Left tympanic membrane showing the arrangement of its fibres. *a* anterior, *b* posterior border; 1, flaccid part of the membrane; 2, short process of the malleus; 3, umbo of the membrane; between 2 and 3, the handle of the malleus; 4, anterior and, 5, posterior end of the tympanic groove, between which are seen circular fibres attached to the short process, 2. (Schwalbe.)

small amount of elastic, tissue, and are disposed in a two-fold manner, some of them radiating from a point, the *umbo*, slightly below the centre of the membrane to the circumference, while others are arranged concentrically around the same point. The outer surface of the membrane is covered by a very thin layer of skin, while its inner tympanic surface is lined by ciliated epithelium. The first of

the chain of bones is firmly attached to the fibrous part of the membrane in such a way that the central part of the membrane is drawn inwards towards the tympanum, form-ing the umbo (or boss of a shield), and thus the disc is not flat, but slightly conical, and, owing to the circular fibres, the surface towards the meatus is convex. This cur-vature of the membrane, though slight, is of considerable import-ance in connection with the re-sponse of the membrane to sonorous vibrations. The sound waves fall on the convex surfaces of the radiating fibres. These keep the membrane stretched tightly, except at the fore and upper part, where the groove of attachment is de-ficient, and the membrane is looser, thicker, and more freely supplied with nerves and blood-vessels.

FIG. 103. — Horizontal section through the labyrinth, tym-panum, and part of the external auditory meatus of the left ear. Between *d* and *e*, the *tympanic membrane*, in the centre of which is seen the handle of the *malleus* cut across; *e*, anterior wall of the tympanum; *f*, in the tympanum above the *stapes*, whose base is inserted into the *fenestra ovalis*; *q*, the *stapedius* muscle; *h*, por-tion of facial nerve; *i, tensor tympani* muscle; *k*, vestibular division, and, *l*, cochlear divi-sion of the auditory nerve lying in the *internal auditory meatus*; *m*, cochlea; *n*, nerve going to ampullæ of semi-circular canals; *o*, section of utricle; *p*, section of sac-cule; *r*, section of semicircular canals. (Rüdinger.)

The inner wall of the tympanum, opposite the membrane, is irregular in shape, and perforated by two apertures. The upper of these, the *fenestra ovalis*, or *oval window*, is of an ovoid or kidney shape, and has the inner end of the ossicles of the ear fastened into it by means of a ligamentous tissue. The fenestra ovalis opens from the middle ear into the vestibule of the labyrinth. Lower down there is a smaller and more rounded aperture, the *fenestra rotunda*, or *round window*, leading into the front part of the labyrinth,

known as the cochlea, but closed during life by a thin membrane like the membrana tympani—that is to say, composed of fibrous structure, with an epithelial lining upon either side, and having a slight concavity towards the tympanum (Fig. 101, 13).

Between and in front of the above-mentioned apertures is a rounded elevation called the *promontory*, which corresponds to the first turn of the cochlea (p. 228). Behind the oval window is a very small process of bone perforated to allow the passage of a minute tendon, which gives attachment to the stapes (p. 211) of a small muscle, the *stapedius*, the belly of which lies in a space behind the tympanum (Fig. 103, *q*).

The passage leading away from the front of the tym-
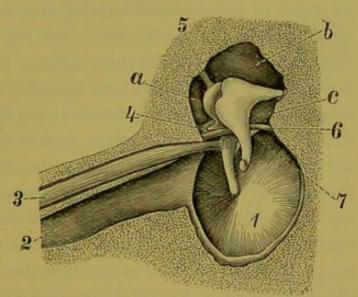
Fig. 104.—Incus and malleus of the right side seen in their natural position in the tympanum. 1, Tympanic membrane; 2, Eustachian tube; 3, tensor tympani muscle seen attached to the malleus; 4, anterior ligament of the malleus attached to the processus gracilis; 5, superior ligament of the malleus; 6, chorda tympani nerve; *a*, *b*, *c*, sinuses or spaces connected with the tympanum in which the ossicles move freely. (Schwalbe.)

panum is divided into two parts by a little ledge of bone, known as the *processus cochleariformis*, the upper part containing the fleshy part of a muscle, the *tensor tympani*, whose tendon crosses the tympanum to be inserted into the malleus, the lower going forwards as the Eustachian tube (Fig. 103, *i*).

The Eustachian Tube.—The mucous membrane of the Eustachian tube is continuous behind with that of the

tympanum, in front with the pharynx or upper part of the throat.   When, under certain conditions, this mucous membrane becomes swollen, the lumen of the tube may be blocked, and air does not pass readily to and fro between the throat and the middle ear.   Then the pressures upon opposite sides of the membrane becoming different, the membrane is too much stretched, does not respond so well as usual to sonorous vibrations, and one becomes slightly deaf.   It is commonly held that the Eustachian tube is open only during swallowing, and the positive and negative experiments of Valsalva are brought forward in proof of this.   The positive experiment is performed as follows : Close the mouth and nostrils, and then, while making the movements of a forced expiration, swallow.   The air in the pharynx is at more than atmospheric pressure, but does not force its way into the tympanum until the tube is opened during swallowing.   Then the condensed air penetrates into the middle ear, raises the pressure there, and the drum-head is forced slightly outwards and made more taut. The tightening of the membrane gives rise to a peculiar sensation referred to the region of the ears, and similar to what is sometimes felt after yawning.

We may directly observe this movement by inspection of the membrane during the act.   The principle of the negative experiment is much the same.   Instead, however, of making a forced expiration, we close the mouth and nostrils, raise the chest as in forced inspiration, and swallow. The air in the throat being at less than atmospheric pressure, when the Eustachian tube is opened the pressure in the middle ear is reduced, and the tympanic membrane moves inwards by the atmospheric pressure in the meatus. We have also met with a gentleman who had the voluntary control of the tube, so that he could open or close it at pleasure.   The advantage of having the tube closed at all

times, except when we swallow, lies in this, that were it always open there would be too much reverberation caused in our ears by the sound of our own voice. This, however, cannot affect the ears during swallowing, because then the lower part of the pharynx is cut off from the openings to the nose and ears by the meeting of opposite muscles, and the lifting of the uvula and soft palate. From all this it follows that one, and probably the most important, function of the Eustachian tube is to equalise atmospheric pressure on the two sides of the drum-head.

The Chain of Bones.—Across the cavity of the tympanum stretches the chain of little bones or ossicles (Fig. 104), to which frequent reference has already been made. This corresponds to the single bone in the frog's ear, which stretches from the tympanic membrane to the entrance to the inner ear, but, as we shall see, the chain confers considerable mechanical advantage. It consists from without inwards of the *malleus* or hammer bone, the *incus* or anvil bone, and the *stapes* or stirrup bone.

The body or head of the *malleus* (Fig. 105) is situated above the level of the tympanic membrane, and it gives off
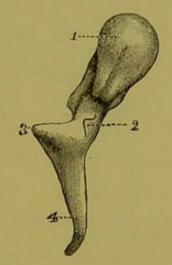
FIG. 105.—The malleus or hammer bone seen from in front. 1, The head ; 2, the processus gracilis foreshortened ; 3, the short process ; 4, the manubrium inserted into the tympanic membrane. The surface of the joint with the incus is not seen, as it faces backwards. (Schwalbe.)

downwards a comparatively strong process, the *handle of the hammer*, which is firmly affixed to the fibrous layer of the membrane. And just as a flattened beam will bear a greater downward pressure when placed edgewise than when laid flat, so the handle of the malleus, being flattened, is placed edgewise towards the tympanic membrane, thus combining lightness with power. Another process, the *pro-*

cessus gracilis more slender and elongated than the handle, passes forwards from the junction of the head with the handle, and is firmly fixed by ligaments to the little fissure in the bone in front of the tympanic membrane. This process is of interest as constituting one end of the axis upon which the chain of bones rotates. The head of the malleus is rounded, and attached to the roof of the tympanum by a small ligament. It bears upon its posterior aspect a smooth surface for articulation with the incus. The head is connected with the handle by a constricted neck, immediately below which we find, on the inner side of the handle, the point of attachment of the tensor tympani muscle, and on the outer part a small bony prominence which, impinging upon the tympanic membrane, causes a projection outwards of the membrane at that point. The laxator tympani muscle passes backwards from the fissure of Glaser, to be attached to the neck of the malleus, just above the origin of the processus gracilis.

FIG. 106.—Right incus or anvil bone, × 4. 1, Body; 2, joint surface for malleus; 3, projection that locks with malleus to prevent over movement; 4, short process for posterior attachment of the bone; 5, elliptic area on median side of short process; 6, long process ending in lenticular knob; 7, entrance of nutrient blood-vessel. (Schwalbe.)

The *incus*, or anvil-shaped bone (Fig. 106), lies behind the malleus, and is jointed to it by a saddle-shaped surface. A short process, pointing backwards, and fixed to the posterior wall of the tympanum by ligaments, forms the posterior end of the axis of rotation of the chain of bones. A longer process, corresponding to the conical projection of an anvil, points almost vertically downwards, but, at its lower extremity, bends inwards and ends as a little flattened knob, the *lenticular process*, which in early life is a separate bone, the lenticular bone. A small eminence,

immediately below the surface of articulation with the malleus, should be noted, as it fits into a corresponding depression in the malleus and prevents undue rotation.

The *stapes*, or stirrup-shaped bone (Fig. 107), is fixed in a horizontal plane, and at right angles to the descending process of the incus. The head of the stirrup is jointed to the lenticular process of the incus. Inwards from the head is a slight constriction, the neck, and from this arise the two arms of the stirrup. These are fixed at their inner end into an oval-shaped plate of bone, the base of the stirrup, which again fits into the oval window. The stirrup could move outwards and inwards freely but for the firm short fibres which unite its base to the margins of the aperture. The space between the arms is filled during life by a thin membrane, the arms being grooved to receive it. By this arrangement, lightness and strength are secured in the same way as we make wheels with spokes instead of solid discs. The tendon of the stapedius muscle is attached to the back part of the neck of the stapes.
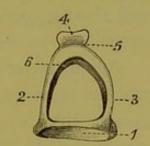
FIG. 107.—Stapes or stirrup bone seen from above, × 4. 1, Base; 2 anterior, 3 posterior limb; 4, head; 5, neck; 6, groove into which membrane is fixed which fills the opening. (Schwalbe.)

Movements of the Bones.—The malleus and incus rotate almost as one bone on a horizontal axis, passing fore and aft between the attachments of the slender process of the malleus in front, and the short process of the incus behind. The plane of rotation is consequently at right angles to that of the tympanic membrane, or across the cavity of the tympanum. When, then, the handle of the malleus is pushed inwards towards the mesial plane of the head, the head of the malleus moves outwards, carrying with it the body of the incus, any excess of movement being prevented by the suspensory ligament of the malleus. The
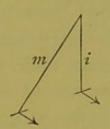
body of the incus rotating outwards, its descending process moves inwards synchronously with, and parallel to, the handle of the malleus, and the tip of the process is thus moved inwards and slightly upwards, and pushes the base of the stapes into the fenestra ovalis. There is also a slight rotation of the stapes in a vertical plane, and the upper border of the base of the stapes has a somewhat greater movement than the under side. We see, then, that when, by compression of the air in the external meatus, the tympanic membrane is forced inwards, the base of the stapes will also be forced inwards, and the pressure on the internal ear will be increased.

Again, when the air of the external meatus is rarefied, and the pressure on the inner side of the membrane becomes greater than on the outside, the membrane is forced outwards, carrying with it the handle of the malleus. Then the head of the malleus above the axis rotates inwards, carrying with it the body of the incus, and the long process of the incus, moving away from the mesial plane, carries the stapes with it, and pressure on the internal ear is diminished. The distance through which the base of the stapes can move is very small, and hence it might happen that a very loud sound, causing the tympanic membrane to vibrate through a comparatively large distance, might tear the stapes from its attachments. This, however, is guarded against in several ways. In the first place, a somewhat dense ligament passes from the upper part of the external wall of the tympanum to the head of the malleus, and this receives the impact of the head of the malleus as upon an elastic cushion, and may, when the head of the malleus tends to move too far inwards, restrain it from moving too freely. Secondly, the process below the upper joint of the incus fits into a depression in the malleus, and when the handle of the malleus tends to move too far inwards, this

projection locks into the opposing socket like the tooth of a cog-wheel, and prevents too great movement inwards. On the other hand, if the handle of the malleus rotates outwards excessively the tooth is withdrawn, and the saddle-shaped joint coming into play, the lower part of the joint tends to gape, and the incus does not move so far outwards as the malleus.

Further, the chain of bones acts like a bent lever, the arm of the incus being only two-thirds of the length of the malleus. When the lower end of the handle of the malleus, fixed in the umbo of the tympanic membrane, moves through a given distance, the stapes fixed to the lower end of the process of the incus will only move through two-thirds of this dis-tance. But while the excursion distance is diminished, we know from the principle of the lever that the force with which it moves must be increased by one-half. There is thus diminished amplitude of movement, but increase of power. This is a distinct advantage, considering the small power that sound waves have of moving the tympanic

FIG. 108.—Diagram illustrating the leverage action of the malleus and incus; *m*, handle of malleus; *i*, long process of the incus.

membrane, and the firmness with which the base of the stapes is fixed. This increase of power is augmented by the fact that the tympanic membrane has roughly an area twenty times as great as the base of the stapes. Thus the tym-panic membrane concentrates its power upon an area only one-twentieth of its size, and this, increased by the shorter arm of the lever (of the incus), must give a force at least thirty times as great as that with which the handle of the malleus is moved at the umbo of the tympanum. Another reason why the stapes cannot move far is found in the firm-ness of the fibres of the membrana tympani, and of its attachment to the handle of the malleus; extensive move-

ment of the membrane is thus prevented. Lastly, where the membrane might move too freely, we have the action of the tensor tympani muscle coming into play. By the pull inwards of this muscle upon the handle of the malleus, the tension of the membrane is increased, and its extent of vibration correspondingly diminished. But this brings us to a consideration of the manner in which membranes respond to sonorous vibrations.

Response of the Tympanic Membrane to Sound Waves. —The physical cause of the sensation of sound is the rapid vibration to and fro of the molecules of an elastic medium when these have been set in motion by a sudden shock. The particles, when disturbed, vibrate to and fro till they regain their former equilibrium. Such vibration may be transmitted from molecule to molecule through solids, liquids, or gases. Thus the arm of a tuning-fork, when set in vibration, causes an alternate condensation and rarefaction of the air in the space through which it moves. With each successive to and fro movement of the fork another alternation of change of density is set up, and this is propagated outwards in all directions from the fork as a centre. The direction of movement of the particles in a sound wave is not transverse to the direction in which the wave is moving, but in the same direction. Hence they are said to be longitudinal waves, as distinguished from the transverse movements characteristic of waves of light, or of waves moving on the surface of water. Such longitudinal waves can readily be set up in solids, as, for example, in a wooden rod by friction, and on account of the closeness to one another of the molecules in solids such vibrations are transmitted with great rapidity. But rods, strings, or membranes may be caused to vibrate transversely to their length or plane, as when a violin string is pulled aside by the bow, or a drum is beaten. If these vibrations be in quick

succession, they will give rise to sound waves in air. In this case it will be noticed that while the particles of the solid body are moving transversely to the length of the rod or string, or the plane of the membrane, their direction of vibration is still longitudinal in so far as the direction of the transmission of sound is concerned.

The impulses given to the air by a vibrating string are of a complex type, for while it may vibrate as a whole, and give forth a series of waves, which combining excite the sensation of a sound or tone, this fundamental tone is always modified by the presence of overtones produced by the simultaneous vibration of segments of the string (Fig. 109). In the case of a rod or string these segments are respectively a half, a third, a fourth, and so on, of the length of the whole rod or string, and the numbers of vibrations given forth by these segments are respectively twice, three times, four times, and so on, that of the fundamental tone. In the case of plates or membranes, the number and character of the overtones are more difficult to determine, being dependent on the form and elasticity of the plates, the manner in which they are
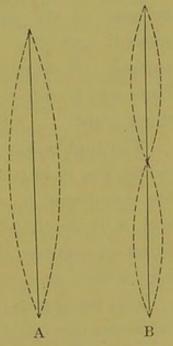
FIG. 109. — Diagram of string vibrating so as to give forth its fundamental tone (A), and its first upper partial tone or octave (B).

set vibrating, and the number of vibrations. The smaller and the more tightly stretched a membrane is, the faster will be its rate of vibration and the higher the pitch of the sound thereby caused. On a large vibrating membrane the surface is, as it were, subdivided into many portions of varying sizes, some small, some large, each vibrating at a rate peculiar to itself, and thus giving rise to a complicated set

of aerial vibrations. Conversely, if the air is vibrating at any of the rates at which the membrane, or parts of it, may vibrate, the membrane will begin to vibrate in response. Suppose two violin strings, or two tuning-forks, are tuned to the same pitch and placed close to one another ; if one of these be set vibrating the other will also begin to vibrate at the same rate ; but strings or rods will not respond so readily as membranes to a variety of tones. Membranes respond more readily to aerial vibrations than plates do, because of the smaller mass of matter requiring to be moved, and the consequently greater flexibility of the surface. A drum-head will move freely to and fro under a blow which will cause almost no apparent result upon a thick plate.

The application of these facts to the action of the tympanic membrane in hearing is not far to seek. In the first place, the membrane is small, very thin, its fibres are inelastic, and it is firmly but not evenly stretched in all its parts. From its thinness it can respond to aerial impulses of very faint kinetic energy.

This receptivity we have seen may be interfered with by the accumulation of hardened wax upon the membrane.

The peculiar arrangement of the fibres of the membrane makes it respond to sounds of widely-varying pitch. The fibres radiating from the umbo to their varying points of attachment in the tympanic groove constitute, as it were, a vast number of strings of varying lengths, each of which will respond most readily to its own particular tone. Again, the concentric circular fibres may be regarded as surrounding a series of nearly circular discs of gradually increasing size, and therefore of different vibratile capacities. Further, von Helmholtz has shown that the shallow conical form of the membrane, the slight outward convexity of its fibres, renders it less liable to have a fundamental tone only, and

increases its receptivity for all varieties of sounds. It has been found that if a handle be attached to a flat disc, and the disc be then curved like the tympanic membrane, it ceases to have a fundamental tone. This property of the drum-head is of paramount importance in hearing, as it leaves the ear free from the disadvantage of having all tones but one overburdened by a preponderating fundamental tone. Almost every ear will respond to tones having as low a frequency as 30 vibrations per second, while certain acute ears may hear tones caused by 40,000 vibrations per second.

The receptivity of the tympanic membrane for sounds of high pitch, that is to say, sounds due to a large number of vibrations per second, is enhanced by the action of the tensor tympani muscle (Fig. 104). When this muscle contracts it pulls the handle of the malleus, and with it the tympanic membrane, inwards, and thus tightens the membrane just as a drum-head is made more tense when it is braced up. The fibres being tighter, their play is diminished, and they respond more readily to vibrations following in quick succession. On the other hand, by the action of the laxator tympani, the membrane becomes more flaccid and responds better to sounds of low pitch.

It has been suggested that the power which many trained musicians have of recognising the absolute pitch of a note may depend to some extent upon the sense of muscular effort arising from varying degrees of contraction of the tensor tympani. In such cases long practice in the determination of the pitch of notes gives rise to such delicacy of judgment that there seems to be an intuitive and direct recognition of pitch, and not only may the pitch of a sound heard by the musician be named by him, but he may sing a note of any given pitch that he desires without the aid of tuning-fork or instrument. For the performance of this latter act, it is

not unlikely that the parts unconsciously assume the necessary degree of tension before the sound is uttered, just as we are apt to make involuntary contortions of the facial and other muscles when performing complicated or difficult actions.

One important factor in the regulation of the tympanic membrane has still to be mentioned.   If we strike the keys of a piano and hold them down so as to prevent the dampers touching the strings, the vibration of the strings will go on for a considerable time ; but when we release the keys, and the dampers touch the strings, the vibration stops.   In the ear the handle of the malleus attached to the tympanic membrane acts as a damper.   If the membrane went on vibrating after the sound wave had ceased, there might be interference with other succeeding sounds, but the duration of the vibration is cut short by the resistance offered by the chain of bones.   The development of overtones in the membrane is likewise prevented, and the ear is rendered more acute in the discrimination of different sounds following one another in rapid succession, and each tone is heard pure, and not interfered with by those which have immediately preceded it.   There is a further provision in the structure of the internal ear for differentiation of sounds, but this we will refer to afterwards.

Transmission of Vibration by the Auditory Ossicles.— We have next to consider how auditory vibrations are conveyed to the internal ear.   It has been experimentally determined that sound is mainly transmitted through the middle ear by the movement, as a whole, of the chain of bones.   No doubt where these are absent, or have been rendered immovable by disease, a person may still be able to hear, but the acuteness of hearing will be largely interfered with.   As to the nature of the movement of the bones there is a common consensus of opinion.   It will be readily

understood that the movement of a solid body may be the resultant of many constituent elements. The earth rotates upon its axis whilst it moves round the sun. In a red-hot cannon ball projected through the air, the molecules of the metal are in a state of extremely rapid movement with reference to each other, as well as in transmission through space. In a tense string set into transverse vibration there must be a continual lengthening and shortening of the string, or in other words, a change in position of the molecules relatively to one another and in the direction of the length of the string as well as the transverse movement of the string as a whole. The longitudinal movement of the particles is invisible, the transverse movement is visible, to the naked eye. The former we call *molecular*, the latter *molar* movement. Probably there is some molecular movement of the ossicles of the ear, but the presence of joints must largely interfere with this, and the movement is mainly of the bones as a whole, that is to say, a molar movement, a movement that may be seen with the eye. While this is so, we must be careful to distinguish between the amount of movement of the bones and the length of the sound wave. The length of a sound wave is dependent not upon the amplitude of movement of the sounding body— that determines the intensity or loudness of the sound— but upon the number of vibrations made in a given time by the sounding body. In Fig. 110, p. 220, A represents a long wave of small amplitude of movement, B short waves with greater amplitude. The length of the wave is measured by the interval between two successive points in like phase relatively to one another. Thus in A, we must move from *a* to *c* in order to get two particles in like condition of velocity and direction of movement, so we say that *ac* is the length of the wave. Now the distance through which a sound wave will pass in any medium in a

given time depends upon the elasticity and density of the body in question. Through air, sound waves pass, on an average, at the rate of 1120 feet per second. If, then, a body makes a complete to and fro vibration only once each second, the first movement must have passed 1020 feet before the second begins, or in other words, the wavelength is 1120 feet. If the body performs a complete vibration twice in a second the distance between two points of like condensation and rarefaction will only be one-half of 1120 feet, or 560 feet. The more rapid the rate of vibration, the faster will wave succeed wave, and the shorter will the wave be. The ear can readily distinguish as a musical tone sounds due to vibrations following each
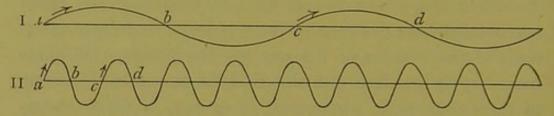
FIG. 110.—Diagram illustrating (I.) long waves of small amplitude, and (II.) short waves of greater proportional amplitude.

other thirty times in a second. The wave-length in such a case would be $1120 \div 30 = 37$ feet approximately, while certain ears can hear a sound due to 40,000 vibrations per second, in which case the wave-length will be 1120 feet $\div$ 40,000, or approximately $\frac{1}{3}$ of an inch. But in either case it will be seen that the bones of the ear cannot move through the "length of the wave," but rather that the *time* of recurrence of like condition of condensation or rarefaction at the drum-head gives rise to our appreciation of differences of pitch. Regularly succeeding stimuli going to the auditory nerve at the rate of say thirty times a second will give rise to a sensation of a sound of low pitch, and if at the rate of say 4000, to a sensation of a sound of high pitch. The length of the wave is of importance in regulat-

ing the number of times per second the drum-head will vibrate, taking into account the rate of the transmission of sound waves through air ; but the breadth of the ear, and even of the whole head, may only form a very small part of the length of the wave. A tuning-fork bowed gently will give a sound of the same pitch as the same fork bowed strongly. In the one case we cannot see any movement in the limbs of the fork ; in the latter the sharp outline of the limbs is lost, and we can see at once that the limbs are in motion. Similarly in the ear. With weak sounds the drum-head hardly moves, and the ossicles seem to be at rest, but if the sound is loud, the drum-head and the bones may be seen in motion.[1] With very loud sounds, when many molecules of air have been suddenly compressed into a small space, the pressure upon, and consequent movement of, the tympanic membrane is very great, and the force may even be so excessive as to cause rupture of the membrane, just as windows are sometimes shattered by a violent and consequently loud explosion.

While in ordinary circumstances the tympanic membrane is usually thrown into vibration through the medium of the air in the external meatus, it should be borne in mind that it may be set in motion also by transmission of vibrations through the bones of the skull.

If a tuning-fork is struck, and its handle pressed against the teeth, a molecular movement is transmitted to the membrane with such energy as to set the membrane and ossicles into visible molar movement. We can illustrate

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[1] A preparation can be made of the ear of a dead cat. The middle ear is laid open by removing a small portion of its wall. After lightly dusting the interior with lycopodium powder, it is strongly illuminated and examined with a microscope of moderate power. When the vibrations of an organ pipe, sounding loudly, are directed into the external ear, little brilliant specks of lycopodium powder may be seen to vibrate.

this by placing a number of marbles in a row, and touching one another.   If a smart tap be given to the marble at one end of the row, it will not apparently move, nor will the intervening members of the series, but the last marble of the row will fly off as if directly struck.   The energy of the blow is, in this case, transmitted through the molecules of the marbles, and is sufficient to give rise to visible movement in the last member of the series.   So the movement transmitted through the bones of the skull gives rise to free movement of the tympanic membrane, and through it to the internal ear.   Trial, however, will show that the tympanic membrane responds better to the vibrations of the air in the meatus than to those transmitted through the head.   If a tuning-fork be struck, and its handle held between the teeth till the sound has apparently ceased, and if then the fork be held opposite the ear, the sound will be distinctly heard again.   We may attribute this to the greater mobility of the molecules of air in the meatus than that of the molecules of the bones of the head.   They move more freely to and fro, and under a feebler stimulus, than the molecules of the bones, and thus the membrane responds more readily to the tuning-fork held to the ear. Still, although both membranes be absent, the ear is quite capable of hearing and of distinguishing musical sounds by the direct stimulation of the internal ear, and its appreciation of pitch cannot be affected, inasmuch as this is due to the physical fact of a recurrence of stimuli at definite intervals of time.   The intensity of the sound will, however, be diminished, because, as we have seen, the arrangement of membrane and ossicles gives a mechanical advantage in the way of increased power.

THE INTERNAL EAR

We have already said that the internal ear consists of a closed sac formed by an invagination of part of the skin at a very early period of life, and that the nerve of hearing ends in this sac. We have now to consider the form of the internal ear, the mode of ending of the auditory nerve in it, and the manner in which its structure is adapted to the function of hearing. And, in the first place, let it be noted that modern research tends to confirm a conjecture made long ago that the front part of the internal ear, the cochlea, has to perform an entirely different function from the posterior part. In correspondence with this, the auditory nerve has been shown to consist of two nerves (Fig. 103, *k*, *l*) which, arising in different parts of the brain, are united by connective tissue in the greater part of their course, but separate again as they
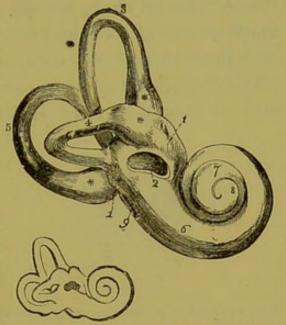
FIG. 111.—Right bony labyrinth viewed from the outside (× 2½, and natural size). The more spongy material of the petrous bone has been separated from the dense bony wall of the labyrinth. 1, The vestibule; 2, fenestra ovalis or oval window; 3, superior semicircular canal; 4, horizontal or external semicircular canal; 5, posterior semicircular canal; * * * ampullæ or dilatations of semicircular canals; 6, first coil of the cochlea; 7, second coil; 8, apex; 9, fenestra rotunda or round window. (Sömmerring.)

approach their termination, and end in organs which differ widely in appearance from each other.

The posterior portion of the sac is contained in the bony cavity known as the *vestibule* and *semicircular canals*.

We may imagine the canals as having been cut off from the main body of the sac by the meeting and agglutination of opposite parts of the original cavity, just as if, were we to press together between thumb and finger the opposite sides of a bag near one of its corners, we would form a canal or passage communicating at each end with the main cavity of the bag (Fig. 112). This main cavity in the ear is known as the *utricle* (Fig. 113); it is oblong in shape, being about one-fourth of an inch long, and communicates behind and above with three semicircular canals (Fig. 111, 3, 4, 5) which lie respectively in three planes, one horizontal and two vertical, and all exactly at right angles to each other like three
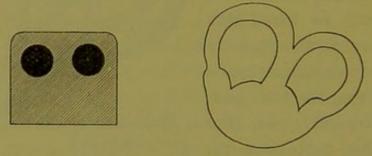
FIG. 112.—Diagrammatic representation of the manner in which the semicircular canals are formed from a primary cavity. (See text.)
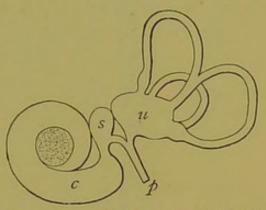
adjacent sides of a cube. From the direction in which the curves are inclined, the canals are named respectively the horizontal or external, the antero-posterior, or simply the posterior and the transverse or superior canals. Each canal has one of its openings into the utricle dilated to form what is known as an *ampulla* (Fig. 111), the other end passing into the utricle without enlargement, and the undilated ends of the canals in the vertical planes unite with one another before passing to the utricle, so that there are only five openings for the canals into the utricle, three of which are provided with ampullæ.

The *utricle* lies in the vestibule. Below, and in close apposition to, the utricle, and, like it, contained in the

vestibule, we have the *saccule* (Fig. 113), a smaller and more rounded space than the utricle. These two cavities are formed by a constriction of the primary vesicle, and even in adult life are in connection with each other by a long narrow tube of a Y shape, the *ductus endolymphaticus* (Fig. 113), one part of which actually penetrates through the bone into the cavity of the skull, and lies enclosed by the membranes surrounding the brain. The saccule, by a narrow tube, the *canalis reuniens* (Fig. 113), communicates with the long finger-like projection, the *canal of the cochlea,*

which is packed away in small space by being wound two and a half times round a central supporting pillar of bone, the *modiolus* (Fig. 117).
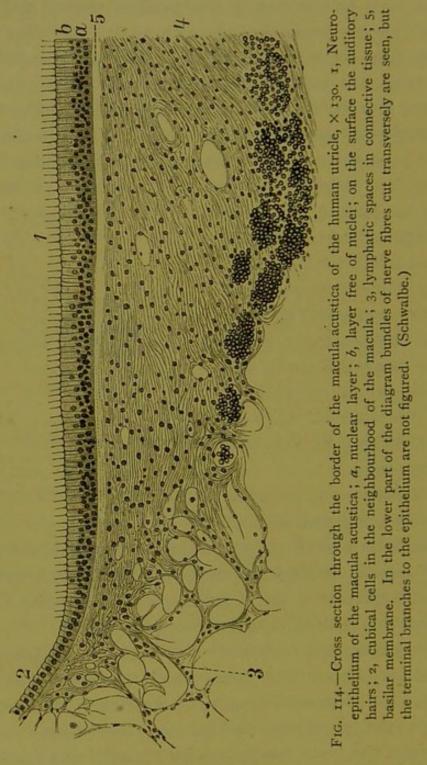
The *auditory nerve*, entering the bone containing the internal ear by a passage called the *internal auditory meatus*, divides, as it enters the bony labyrinth, into two main divisions, one going to the cochlea, and the other to

FIG. 113. — Membranous labyrinth (diagrammatic). *c*, Cochlea ; *s*, saccule united by *p*, the ductus endolymphaticus, with *u*, the utricle, arising from which are seen the three semicircular canals.

the vestibular part of the membranous labyrinth, the latter branch quickly dividing further so as to supply a terminal branch to the utricle, the saccule, and the ampullæ of the semicircular canals, and to these parts alone.

The *membranous labyrinth* has for its outer coating a layer of connective tissue from which numerous processes pass to the fibrous lining of the bone. The spaces between the processes, similar to other lymph spaces throughout the body, are lined with flat cells and filled with a somewhat viscous fluid. The connective tissue is homologous with the true skin, and like it contains blood-vessels.

Q

The inner lining of the sac, except where the nerves end, consists of a single layer of flattened cells. In one portion

FIG. 114.—Cross section through the border of the macula acustica of the human utricle, × 130. 1, Neuro-epithelium of the macula acustica; *a*, nuclear layer; *b*, layer free of nuclei; on the surface the auditory hairs; 2, cubical cells in the neighbourhood of the macula; 3, lymphatic spaces in connective tissue; 5, basilar membrane. In the lower part of the diagram bundles of nerve fibres cut transversely are seen, but the terminal branches to the epithelium are not figured. (Schwalbe.)

of the utricle and of the saccule lies a small oval spot, or *macula*, and in the ampulla of each canal a ridge or *crista*

which, since they contain the termination of the vestibular nerves, are known respectively as a *macula* or *crista acustica*. Over these the epithelium is stratified, being mainly made up of thread-like columnar cells (Fig. 115), having a well-marked nucleus, and supporting another set of nucleated cylindrical cells, whose free surfaces bear bunches of stiff rod-like hairs which are often adherent one to another, and are known as the *auditory hairs*. Some observers have described the hairs as passing through a membrane similar to that found in the cochlea (p. 236) ; but this has been disputed. The terminal twigs of the auditory nerve, passing through the connective tissue which forms the main substance of the prominence or ridge, lose their outer sheaths and pass as naked axis-
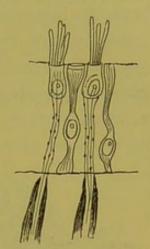
FIG. 115.—Epithelial cells from macula acustica of the utricle.

cylinders into the epithelium, where their mode of termination is not definitely known. Some suppose that they end in the cells, others that they simply surround them with a nest of fine fibrils ; but, from analogy with the other sense

FIG. 116.—Otoconia from the cupula above the human *macula acustica.*

organs, we may conjecture that they are at least stimulated by the agitation of the hair-cells. The free ends of the auditory hairs are embedded in a soft mucous material, the *cupula*, in which are often found small crystals consisting largely of carbonate of lime, called *otoconia*, or *otoliths* (Fig. 116). The function of this covering is unknown, though it has been supposed to act as a damper to the vibration of the auditory hairs. It may possibly be driven mechanically against the points of the hairs by vibrations of sound, and thus increase the sensitiveness of the hairs to such vibrations.

The Cochlea.—We come now to consider the structure of the cochlea (Gr. *cochlias*, a snail with spiral shell), which is a tubular cavity coiled in a spiral manner round a central pillar called the *modiolus*. The part of the membranous labyrinth which it contains is much smaller in cross section than the bony space, and is known as the *canalis cochlearis*. It is fixed in the whole of its course, except at its closed end, to either side of the cochlea, having a broad surface of attachment on the outside, but a very narrow one towards the median column. Indeed, we find
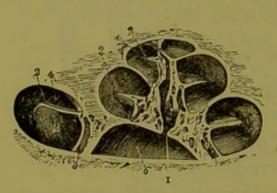
FIG. 117.—The osseous cochlea divided through the middle, × 5. 1, Central canal of the modiolus in which lies the cochlear nerve; 2, the spiral osseous lamina; 3, scala tympani; 4, scala vestibuli; 5, spongy bone of modiolus near the spiral canal, 8. (Arnold.)

here that the cochlear canal is only attached on its inner aspect to the free edge of a shelf which winds round the central pillar, projects outwards into the lumen of the cochlea, and is known as the *lamina spiralis ossea*, or spiral plate of bone. It really consists of a double plate of bone, between the surfaces of which the nerves pass out from the central column to enter the cochlear canal. In a section made transversely through one of the whorls of the cochlea, we see then three spaces represented in Fig. 118. The upper space, containing perilymph, is in connection, at its beginning, with the vestibule, and, as it winds round towards the apex of the cochlea, it is known as the stairway from the vestibule or *scala vestibuli*. At the summit of the cone it bends round the closed end of the cochlear canal and the free hook-like end or *hamulus* of the *lamina spiralis*, by a little passage called the *helicotrema*, and communicates with a descending space which, winding

round the modiolus, ends at the *fenestra rotunda*, whose
membrane closes the opening into the middle ear. This
lower space is known as the *scala tympani*. The two
scalæ are lined with a connective tissue membrane which
is thickened on the outer wall to form the *spiral ligament*,
first described by Bowman, and the free surface of the
membrane is covered with a single layer of flattened cells.
The scalæ being in connection with each other at the top
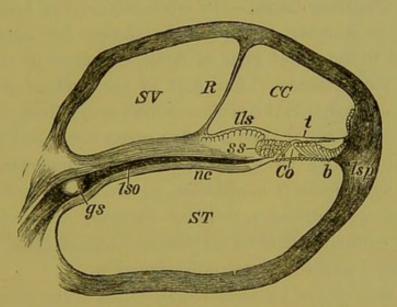
FIG. 118.—Section through one of the coils of the cochlea (diagrammatic). SV,
Scala vestibuli; ST, scala tympani; CC, canal of the cochlea; *lso*, lamina
spiralis ossea, or spiral plate of bone; *lls*, limbus of the spiral lamina; R,
Reissner's membrane; *ss*, spiral sulcus or groove; *t*, tectorial membrane;
CO, organ of Corti; *b*, basilar membrane; *lsp*, spiral ligament; *nc*, cochlear
nerve; *gs*, spiral ganglion in course of cochlear nerve. (After Henle.)

of the whorl, and being filled with perilymph, the pressure
of the fluid in the two spaces must be the same when the
ear is at rest. If, by the movement of the stapes, the
pressure of the fluid in the vestibule be increased or
diminished, there must be a corresponding change of
pressure transmitted from the scala vestibuli to the scala
tympani, and this may be effected either directly through
the cochlear canal or through the helicotrema. The fluids
of the ear being practically incompressible there must be a

corresponding movement of the membrane closing the fenestra rotunda.

Upon the upper surface of the spiral bony shelf, and near its free border, is a thickening of the connective tissue known as the *limbus*. This thins away as it covers the free edge of the shelf, and a groove is formed—the *sulcus spiralis* (Fig. 118)—whose free borders are known respectively as the vestibular and tympanic lips.

The Cochlear Canal.—In cross section, the canal of the cochlea is roughly triangular in shape, the apex being attached to the spiral plate of bone, the base to the outer wall of the cochlea. That part of the wall of the canal which looks towards the scala vestibuli arises from the upper surface of the spiral shelf a little nearer the modiolus than the limbus, and stretches as a thin fibrous membrane, known as *Reissner's membrane*, to the outer wall. It is lined on its vestibular side by flattened cells, while the internal surface is clothed with more cubical cells, some of which have probably a secretory function.

The wall of the cochlear canal, which takes part in the formation of the scala tympani, stretches from the tympanic lip of the spiral lamina to the spiral ligament, and is known as the *lamina spiralis membranacea*, or basilar membrane. It is indistinctly fibrous towards its inner attachment, but in its outer two-thirds shows a radial fibrillation as of rod-like fibres embedded in a homogeneous matrix. This part of the structure is, as we shall see, probably of considerable importance in the appreciation of the pitch of sounds.

The tympanic surface is lined with cells, often of a spindle shape, which lie transversely to the fibres above them, and, at one part immediately below the organ of Corti about to be described, we find a small blood-vessel, the *vas spirale*, which ensures a good blood supply to the superjacent structures.

The Organ of Corti.—The epithelium upon the upper, or, with reference to its position in the head, anterior surface of
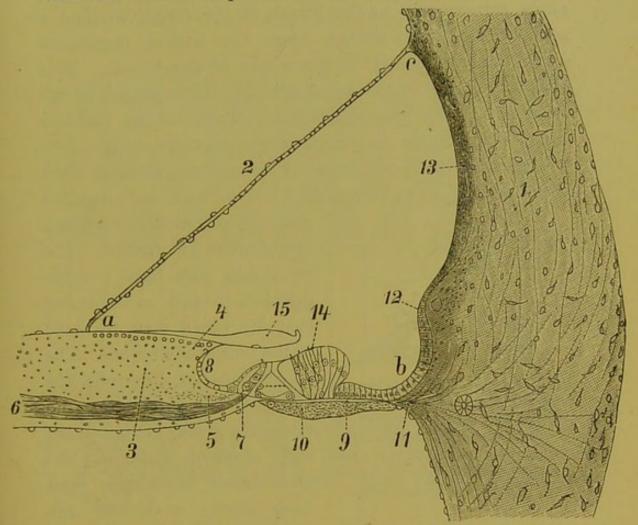
FIG. 119.—Cross section of the human cochlear duct at the junction of the first and second turns of the cochlea, × 100. 1, Outer wall (part of the spiral ligament) reaching from *b* to *c*; 2, vestibular wall, or Reissner's membrane, from *a* to *c*; tympanic wall from *a* to *b*; 3, lamina of bone; 4, its vestibular lip; 5, its tympanic lip; 6, nerves of hearing passing to epithelium at 7; 8, internal spiral groove with flattened epithelium; 9, basilar membrane; 10, its tympanic covering; 11, basilar crest of spiral ligament; 12, prominence of spiral ligament with blood-vessel; between 11 and 12, the external spiral groove; 13, vascular layer; 14, spiral papilla (epithelium of Corti's organ); near 14, the outer hair-cells and Deiter's cells; further inwards the rods of Corti covering the tunnel; internal to this the inner row of hair-cells; 15, the tectorial membrane. (After Retzius.)

the basilar membrane is of a highly specialised type, and more especially that part which rests upon the inner half of the membrane. This part is commonly known as the *organ*

of Corti, from the Italian Marquis of that name who first gave a detailed description of it. When we examine sections made transversely to the length of the canal, we find a peculiar structure resting upon the basilar membrane immediately adjoining its inner line of attachment. This consists of a set of elongated rod-like cells arranged in two rows throughout almost the whole length of the cochlear canal, and known as the *outer* and *inner rods of Corti.* These rod-cells, rising from the membrane, meet at their upper ends like the beams of a sloping roof, and, together with the membrane, enclose a space called the *tunnel*. The individual rods have a cylindrical form and an expanded base, by which they are fixed to the basilar membrane. The upper ends of the rods are enlarged, but flattened at the sides, where they are in contact with adjoining rods, and the inner heads have upon their outer aspect a socket into
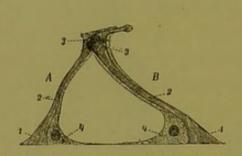
FIG. 120.—Inner and outer rods of Corti from the cochlea of a guinea-pig, × 275. A, Inner rod-cell; B, outer rod-cell. In both are seen—1, the foot piece; 2, the body; and, 3, upper end of rods; 4, nucleus and protoplasm. (Schwalbe.)

which fit the rounded heads of the outer row of rods. From the head of each rod there projects outwards a flattened process, those of the inner row overlapping those of the outer. The inner rods are about a half more numerous than the outer, so that two outer rods fit into three of the inner row. At the base of each rod we find a nucleus and granular protoplasmic material, while the main substance of the rod exhibits no structure, or merely a faint longitudinal striation. The rods being placed in line, and all the head-plates being similar in size and appearance, they present, when seen from above, a remarkable resemblance to the key-board of a piano.

Fibres of the auditory nerve pass between the rods and across the tunnel, which, during life, contains also a colourless jelly-like intercellular substance (Fig. 121).
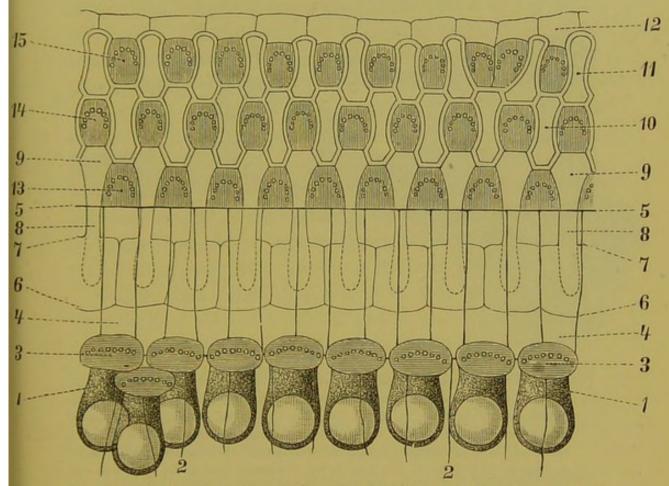
FIG. 121.—Surface view of the spiral papilla of Corti's organ from the topmost coil of a rabbit's cochlea, from the inner hair-cells to the cells of Deiter. (After Retzius.) Highly magnified. 1, Inner row of hair-cells; 2, boundary line of their surface; 3, cuticle of the inner hair-cells, each showing eight hairs; to the left an extra inner cell is present; 4, flattened tops of the inner rods of Corti; 5, outer border of these plates; these completely cover the tops of the outer row of rods, seen between 6 and 7; at 6 is seen the inner border line of attachment of the heads of the outer rods. From the tops of the outer rods are seen at 7 the processes to the phalangæ, narrow at 8, and widening at 9 to form part of the lamina reticularis. 10, Phalangæ of the first row. 11, Phalangæ of the second row. 10-12 are the cuticular end plates of the three rows of Deiter's cells. In the interspaces between these appear three rows of outer hair-cells, each showing eight hairs, arranged in horse-shoe shape, projecting from their free cuticular surface.

The Inner Hair-Cells.—Just to the inner side of the rods of Corti we find a row of columnar cells whose free

surface is on a level with the head of the inner rods upon
which they rest.   Each of these columnar cells has project-
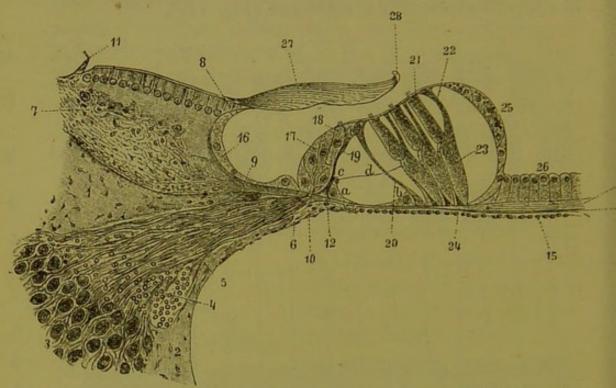
FIG. 122.—Radial section through the tympanic wall of the middle of the cochlear
duct of the guinea-pig, × 212.   1 and 2, Upper and lower plates of the
osseous spiral lamina ; 3, spiral ganglion ; 4, spiral bundle of medullated
nerve fibres ; 5, medullated nerve fibres radiating outwards between the bony
plates of the spiral lamina ; 6, thin connective tissue lining bone (periosteum) ;
7, limbus of the spiral lamina ; 8, its vestibular lip ; 9, its tympanic lip,
through which at 10 the nerve fibres, losing their medullary sheath, pass to
the epithelium ; 11, beginning of Reissner's membrane ; 12, union of tympanic
lip with basilar membrane ; 13, nucleated transparent layer of the basilar
membrane ; 14, layer of basilar fibres ; 15, cellular lining of basilar mem-
brane ; 16, epithelium of internal spiral groove ; 17, inner supporting cells,
below which the nerves emerge ; 18, inner hair-cells ; 19, inner rod of Corti,
a, nucleus and protoplasm ; 20, outer rod of Corti with, b, its nucleus and pro-
toplasm ; c, cross section of spiral bundle of nerve fibres winding up with the
tunnel ; from it the nerve fibres, d, pass outwards between the outer rods of
Corti to the outer hair-cells ; 21, outer hair-cells in three rows alternating
with phalangar processes, 22, of Deiter's cells, 23 ; 24, supporting fibres
of Deiter's cells ; 25, cells of Hensen ; 26, cells of Claudius ; 27, membrana
tectoria ; 28, its marginal thickening.   (Schwalbe.)

ing from its free surface from fifteen to twenty short stiff
hairs arranged in a crescentic line, whose convexity faces
outwards.   The attached ends of the hair-cells are conical

in shape, and do not come down to the basilar membrane, but are connected with, or closely invested by, terminal fibrils of the auditory nerve. There may also be seen around and below the lower ends of the hair-cells a number of nuclei. These belong to elongated filamentous cells, which, arising from the beginning of the basilar membrane, pass to the surface between, and to the inside of, the hair-cells, and, in all probability, act like the rods of Corti as supporting structures. From the inner row of hair-cells epithelial cells, at first columnar, then more cubical or even flattened, line the spiral groove already referred to, but the overhanging part of the vestibular lip of the limbus is devoid of epithelium, and is broken up by slight radial markings into a set of projections known as the *auditory teeth*.

Outer Hair-Cells.—To the outer side of the rods of Corti we find rows of hair-cells and supporting cells similar in many ways to the row found to the inside of the rods. In the human ear there are usually four rows of hair-cells, but there may be only three, or as many as five, rows in certain parts of the canal. In the ears of lower mammals there are seldom so many rows as in man.

The hair-cells of the outer row are likewise columnar, have short stiff hairs arranged in a semicircular or horse-shoe shape—convexity outwards—on their free surface, a nucleus surrounded by granular protoplasm, and nearer their free border a dark pigmented spot known as *Hensen's spot*. The lower ends of the hair-cells do not pass down to the basilar membrane, but, like the inner row of hair-cells, are in contact with the terminal fibrils of the auditory nerve. Closely apposed to the outside of each of the hair-cells in the outer rows is a supporting structure, known as *Deiter's cell* (see Fig. 122), which, arising by a thicker nucleated part from the basilar membrane, gradually becomes narrower and passes, as a small cylindrical process, to the free

surface. Here the Deiterian cells are fixed to fiddle-shaped plates—*phalangæ*—which, uniting with adjoining plates, and with the processes from the heads of the rods of Corti, form a *fenestrated* or *reticulated membrane*, in the meshes of which lie the free ends of the hair-cells. Each hair-cell is thus fixed to and supported by a structure, which is itself inserted at either end into a membrane, and thus the component cells are firmly held in their respective places, and we can see that any movement of the basilar membrane must be at once communicated to the hair-cells through the medium of Deiter's cells.

Outside of the rows of hair-cells we find, for a short distance, a row of columnar cells, devoid of hairs, and having no direct connection with the auditory nerve. They are known as *Hensen's cells*, and they soon merge into a layer of cubical cells, the *cells of Claudius*, which cover the outer third of the basilar membrane, and are continued over the spiral ligament and that part of the cochlear canal which is in contact with the outer cochlear wall.

The *spiral ligament* into which the basilar membrane is fixed, consists in the main of connective tissue, but spindle-shaped cells have been described as existing in it, which, as first suggested by Bowman, are supposed to be muscular, and whose function would be to tighten the basilar membrane, and adapt it for variations of pitch. The spiral ligament is vascular, and at one part a slight elevation (*vas prominens*) is made by a vein (Fig. 119).

It will be seen that the neuro-epithelium of the cochlea resembles, in many respects, that found in the vestibular part of the internal ear. This likeness is further increased by the fact that we find, lying in the cochlear canal, fixed at one end to the vestibular lip of the limbus, and at the other free or attached to the outer part of the organ of

Corti, a thickish layer of fibrous tissue known as the *membrana tectoria*. This may, as conjectured in the case of the cupula, act as a damper when resting on the hair-cells, but its action is not known.

Innervation of the Cochlea.—The cochlea is supplied by a branch of the auditory nerve. The modiolus or central column, round which the cochlea is coiled, is hollowed out in a conical fashion, the space being filled by the cochlear nerve, which, comparatively thick at first, soon lessens in diameter by giving off numerous branches which pass out into the bony spiral shelf. Before reaching their ultimate destination, however, the fibres pass into a mass of ganglionic nerve-cells of a spindle or bi-polar form, which form a continuous spiral from the base to nearly the apex of the cochlea, known as the *spiral ganglion* (Fig. 122). From this the fibres emerge in bundles which coalesce to form finer bundles. These passing radially outwards, between the opposing surfaces of the spiral lamina, emerge in little furrows or canals at the tympanic lip, called *foramina nervina*, and, losing here their primitive sheath and white medullary substance, pass as bare axis-cylinders into the neuro-epithelium of Corti's organ.

The nerve fibres do not seem to pass directly after emerging from the bony plate to the hair-cells opposite. They seem rather to bend round and run in the direction of the cochlear spiral, some below the inner row of hair-cells, some, after entering the tunnel, through interstices between the rods of Corti, and some in spaces between each row of the Deiter's cells supporting the outer row of hair-cells. There are thus an inner spiral strand, a spiral strand of the tunnel, and three or four outer spiral strands. From these spirals are given off the ultimate fibrils which proceed to the hair-cells. Whether they pass into these, or simply into contact with them, is not definitely known. We may,

however, feel assured, both from analogy and from careful study of the structure, that the hair-cells are the true terminal organs of the auditory nerve, that they alone can respond to auditory vibrations, and set up sensory impulses in the auditory nerve, and that the other cells of Corti's organ are merely accessory in function. In birds, for instance, the cochlea is very rudimentary, consisting of a small protuberance from the saccule, and containing only hair-cells on a basilar membrane and no rods of Corti. It may seem strange that in birds, even in the sweetest songsters, the part of the ear which seems specially devoted to the appreciation of musical tones should be ill developed ; but it must be remembered that the quality and variety of tones of the bird's song are vastly inferior to those of the human voice, nor has the brain of the bird the development necessary for the due recognition of the variety of sounds which the human brain can differentiate. In the human ear itself, the structure of Corti's organ varies as we pass from the beginning to the end of the canal. At first, where it unites with the canalis reuniens (p. 225), it is lined with ordinary epithelium. Then the organ of Corti has at first only three rows of hair-cells ; farther on, four rows appear, and in some ears five. At the closed end of the canal, the neuro-epithelium is again awanting, and gives place to a simple squamous epithelium.

Observations are still required with regard to the comparative powers of ears as regards the appreciation of varying sounds according to the number of hair-cells which may be present. While the general principle of formation of Corti's organ remains the same throughout the whole length of the cochlea, the grouping of the supporting cells, and more especially those of Hensen, gives different appearances at different levels of the spiral. It is also noteworthy that the basilar membrane varies in breadth, not, as was at one

time supposed, narrowing from base to apex, but actually increasing from .21 mm. ($\frac{1}{125}$ inch) to .36 mm. (nearly $\frac{2}{125}$ inch) (Retzius) in breadth as it ascends. Thus, if we regard its radial fibres as corresponding to the strings of a musical instrument, such as the harp, those fibres which lie at the base of the cochlea, and consequently nearest the vestibule, would compare with the short strings of the harp, which vibrate rapidly, and give forth sounds of high pitch, while those at the apex of the cochlea correspond to the long strings which emit a bass note. If, as has been supposed, this analogy is not a merely fanciful one, it is manifest that we have in this arrangement the greatest mechanical advantage, tones of short wave - length obtaining immediate response, while those of greater wave-length must travel
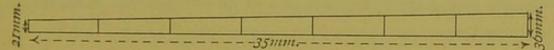
FIG. 123.—Diagram illustrating change in breadth of the basilar membrane from base to apex of cochlea ; the length of the diagram is about twice, the breadth about ten times, the actual dimensions ; the numbers in the diagram indicate in millimetres the size of the structure in the ear, not the lengths of the lines.

farther. The basilar membrane being, according to Retzius, about 35 mm. ($1\frac{2}{5}$th inch) in length, the accompanying diagram (Fig. 123) represents on an enlarged scale the comparative breadth of the membrane in different parts in relationship to each other, and to the length of the canal. The actual difference in the length of the fibres is, as will be seen, very little, and it should further be noticed that the distinct fibrillation of the membrane is well marked only in the outer side of the membrane, between the outer rows of hair-cells and the attachment of the membrane to the spiral ligament. If this part alone be considered, we find that the ratio is somewhat altered—namely, from .075 mm. at the base to .126 mm. at the apex, or nearly 1 : 2 instead of 3.5. The difference in absolute size may seem very little,

but we must always bear in mind the exceeding minuteness of all the parts involved, and the extreme delicacy with which so small an organ must be constructed in order to give such complex and varied results as does the human ear. The presence of what seem to be contractile cells in the spiral ligament lends colour to the supposition that, in the length and tension of the fibres of the basilar membrane, we are to look for the mechanism for the appreciation of pitch. We have said that possibly, in the cultivated musical ear, the training of the muscles attached to the drum-head, or rather the recognition of the muscular sensation caused by varying degrees of contraction of these muscles, may play a large part. It may now be added that this sensation may be strengthened by the feeling of tension in the spiral ligament ; but at present this is merely a conjecture.

AUDITORY SENSATIONS

Physiological Characters of Sounds.—We have already referred briefly to the physical causation of sound, and we shall now consider how the physiological variations arise in connection therewith. When we seek to analyse the effect produced in consciousness by the stimulation of the auditory mechanism, we find that all sounds may be roughly divided, in the first place, into such as we designate *noises*, and those recognised as *musical tones*. The sounds of a peal of thunder, of the rending of silk, of the creaking of a door on dry hinges—these we call noises ; but when a tuning-fork vibrates, or a note on the piano is sounded, we call the effect produced upon the ear musical. The difference, however, between a noise and a musical sound is not of a hard and fast kind. One may merge insensibly into the other. The tuning of musical instruments by an orchestra gives us

a noise as result, but the noise is made up of musical tones, and many sounds usually dismissed as noises, such as street calls, the barking of dogs, or the blast of a fog-horn, contain a distinctly musical element. When aerial vibrations agitate the ear in regular recurrence, when equal periods of time elapse between each stimulation, the sound produced is musical; but in the example mentioned above, of the sound produced when an orchestra tunes its instruments, the musical tones from the different players come at irregular intervals, and at rates which interfere with one another in such a way as to produce a harsh or unmusical sound. On the other hand, sounds professedly musical are sometimes noises of the most disagreeable nature. As a combination of musical tones may produce a noise, we will best arrive at a clear comprehension of auditory sensations in general by the study in the main of musical sounds.

Apart from the emotional feelings which may be aroused by music, there are certain sensations produced in the mind on hearing a musical tone. These sensations may be divided under three heads—first, of *pitch*; second, of *intensity*; and third, a sensation of a special *quality* of the sound, dependent upon whether it is one simple sound, or a combination of simple sounds. In practice, we seldom hear simple musical tones, such as are produced by a tuning-fork. The sounds produced by such musical instruments as the piano, violin, or flute, are not simple tones, but sounds in which many simple tones are blended into one so as to give a sound with a special quality, timbre, or klang, by which we can recognise the kind of instrument that has given it forth. But, given the pitch, intensity, and quality of a sound, we can, with proper instruments, reproduce any variety of tone we please. We shall consider, then, in the first place, the nature of pitch and of intensity or loudness, and then how tones of varying pitch

and intensity combine to give rise to a sensation of quality in a musical tone.

1. **Pitch.**—The pitch of a tone depends upon the frequency of the vibrations in a given time ; or, to put it in another way, since the wave-length is shorter in direct proportion to the rapidity of recurrence, the pitch depends upon the length of the waves which go to produce the sound.   If the vibrations come too slowly or too rapidly, no musical sound is perceived, and while ears may hear musical tones produced by vibrations at rates varying from about 30 to 40,000 per second, the range of the tones employed in music lies between 30 and 4000 per second.

The fact that pitch depends upon frequency of vibration can be easily demonstrated by means of an instrument called the *syren*.   This, in its simplest form, is a thin metal plate revolving upon an axle at a rate which can be exactly regulated.   The plate is perforated by a set of holes at equal distances from the axle and from one another.   The wheel is first caused to rotate slowly, and a current of air is blown against the plate, so that it will pass through the holes when they pass a certain point.   At first a series of puffs is heard, but, as the speed of rotation is gradually increased, the puffs begin to coalesce, and when they recur at from 20 to 30 times a second, a low buzzing or droning sound is heard.   The faster the plate revolves, the more numerous the puffs become, and the higher will be the pitch, until at last the sound grows faint and ceases to be audible.   When the pitch of a sound is very high, the effect produced upon the listener is unpleasant.   It is as if a thin metallic blade or needle were piercing the ears, or it may be compared to the shimmering effect of sunlight reflected by the ripplets on the surface of water agitated by a light breeze.   If the plate be made to rotate quickly and at constant speed, the pitch of the note will remain the same.

Von Helmholtz has devised a double syren, with which many interesting experiments can be performed as to the nature
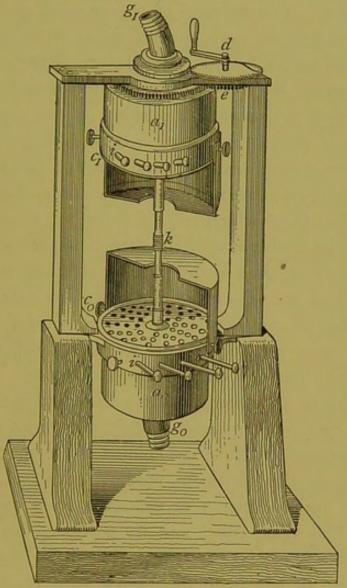
FIG. 124.—Double Syren of von Helmholtz. a_0, a_1, Brass wind-chests communicating by tubes, g_0, g_1, with bellows; the opposite ends of the cylinders are closed by brass plates perforated with holes corresponding to those seen in the disk, c_0; the disks, c_0, c_1, rotate on a common axis, k, provided with a screw for the counting apparatus, which is omitted here. The upper cylinder, a, can be rotated on a vertical axis in either direction by toothed wheel, e, with handle, d; the four rows of holes may be opened or shut by means of studs, i, i; there are 8, 10, 12, and 18 holes respectively in the four rows of holes in the lower disk, and 9, 12, 15, and 16 in the upper (not seen in diagram).

of pitch. It consists (Fig. 124) of two boxes, supplied by bellows with air, which, emerging through the lids of the

boxes by holes, the number of which can be varied, causes a plate close to, and in a parallel plane with, the lid of each box to rotate. The rotation of the parallel plates allows the air to escape through several series of holes in them, just as in the simple syren. The beauty of the mechanism lies in the power it gives us of regulating exactly the number of impulses per second, of reading off the number upon a dial, and of permitting us to note the effects produced when the two syrens are emitting tones of different pitch. It is thus most valuable in studying concords, discords, and beats, the nature of which will be described shortly. One point which invariably arrests the attention when the syren is heard for the first time is the peculiar effect of the gradual rise in pitch as the velocity of rotation is accelerated. We may say that at one moment it is giving forth many impulses, say, 200 per second; at another a different number, say, 201; but the change from 200 to 201 is through an infinite fractional series; and so with regard to the sound; it does not rise by leaps and bounds, but glides up in continuous transition. Just as the colours of the spectrum vary through an infinite series, in passing from one colour to another, so do the sounds in changing from one pitch to another. The same effect can be produced on the violin by sliding the finger up the string while it is being bowed. And, further, as has been mentioned with regard to perception of colour, as some eyes are insensible to the red, and others to the violet end of the spectrum, so some ears are insensitive to sounds of low pitch, others to those of high pitch. As might naturally be expected, the sensibility to pitch varies more in the higher than in the lower parts of the scale, and we find people who suppose their powers of hearing to be perfectly normal, who yet fail to hear sounds due to more than 6000 vibrations. Test of power in this respect may be made by means of a set of short-

steel cylinders, made by König, which, when suspended by threads to a wooden frame, and struck with a metallic instrument, emit tones to upwards of 40,000 vibrations per second. The same result may be attained by using short-limbed or heavy tuning-forks.

Within the range of musical pitch, too, we find that people vary much in their capability of distinguishing a tone of one pitch from another nearly the same. This likewise holds good in respect of colour. Orientals distinguish many shades of colours which seem the same to us. While most people can detect a difference of a semitone in two notes sounding together when of medium pitch, some acute ears can detect as small a difference as $\frac{1}{64}$th of a semitone. It becomes more and more difficult to detect the difference as we pass to the upper or lower limits of hearing—a fact one may readily prove for oneself by striking adjoining keys, now in the centre, now at either end of the key-board of a piano. We have already indicated that the power of detecting variations in pitch can be increased by exercise and training, and have suggested a possible explanation as to how this is so. On the other hand, there are some people who are unable to discriminate more than a very few tones, and who find it utterly impossible to sing any complicated tune. The pitch of the ordinary human voice in singing, it may be mentioned in passing, may be as low as fa_1 (87 vibrations per second), or as high in a good soprano as sol_4 (768 vibrations per second); or, in other words, it is comprised within a range of a little more than three octaves. There have been a few exceptional singers who have been able to sing pure musical notes beyond these limits. Thus Gaspard Forster, a basso, passed from fa_{-1} (42 vibrations) to la_3 (435 vibrations); it is said that Nilsson, in *Il Flauto Magico*, can take fa_5 (1365 vibrations); and Mozart states that in Parma, in 1770, a soprano,

Lucrezia Ajugari, ranged from sol_2 (192 vibrations) to do_6 (2048 vibrations). The latter is the most highly pitched voice in musical literature, an octave and a half above the highest ordinary soprano. The extreme range of the human voice, then, taking into account the extraordinary voices above alluded to, is from fa_{-1} (42 vibrations) to do_6 (2048 vibrations), or about six octaves, while the range of the human ear for musical tones is from do_{-1} (32 vibrations) to do_{10} (nearly 40,000 vibrations), or about eleven octaves.

2. **Intensity or Loudness.**—The second character of a musical tone which we notice is its intensity or loudness. This varies with the amplitude of vibration of the sounding body. Thus a tuning-fork bowed gently will give out a faint sound, while the same fork bowed strongly will give a note of the same pitch as the former, but sounding much louder.

In the case where the particles of the wave move at right angles to the direction in which the wave is advancing, as, for instance, a wave on the surface of water, one can readily understand what is meant by the height or amplitude of the wave. But this is not so easy in connection with a wave of sound where the particles are moving in the same direction as the wave, and we are apt to confuse the amplitude with the length of the wave, which, as we have seen, is invariable in any given medium for any given note, and determines pitch, not intensity. We can probably realise the meaning of amplitude best in connection with sound waves by thinking of what happens when a large tuning-fork is vibrating feebly or strongly. In the one case, the excursion of the limbs is so small that, to the unaided eye, the fork seems to be motionless ; in the other, there is a perceptible movement through space, and though the pitch of the note remains the same, it has a louder, stronger

effect upon the ear. The fork makes exactly the same number of vibrations in each case, but in the latter its limbs move through a greater distance. Hence more molecules of air must at one moment be crowded into a given space, at another there must be a more complete rarefaction of the air. There must then be a greater difference in the degree of pressure upon the drum-head of the ear; at one time a greater increase, at the next a greater diminution. Corresponding to this, there will be greater movement of the tympanic ossicles, and more variation in the pressure on the internal ear, and disturbance of the nervous arrangements. The contrast of loud and faint sounds can be readily made by holding to the ear a vibrating tuning-fork, and turning it round between finger and thumb, now this way, now that. It will be found—and this bears out the statement just made as to amplitude—that the sound is loudest when the plane in which the limbs are vibrating is at right angles to the side of the head, for here the air is disturbed with the greatest energy. The same experiment also shows the gradual transition in intensities just as in the case of pitch. The more the energy of vibration, or, in other words, the greater the number of molecules packed into a given space in a given time, the greater will be the loudness—a phenomenon comparable to the sensation of varying brightness of light.

3. **Quality, Timbre, Klang**.—The quality of a musical sound enables us, after a due amount of training, to know, from the effect produced upon the ear, what is the instrument by which the sound has been produced. We readily distinguish, for example, a musical note produced upon the piano from that of the violin, or either of these from the tones of the human voice, or of a wind instrument such as the flute. Each kind of instrument produces a set of

characteristic wave-forms, and the musician can tell by the effect produced what kind of instrument is sounding.

The simplest form of vibration which gives rise to the sensation of a musical tone is that of a body vibrating in simple harmonic motion. Suppose a disturbance to be made in the perfectly smooth and level surface of a sheet of water. A concentric series of waves will spread outwards from the point of disturbance in ever-widening circles. But while the wave-forms move outwards, the particles which go to form the waves have only a vertical motion, up to the crest of the wave above, or down into the trough below, the ordinary water-level; and after a series of gradually diminishing oscillations, they come to rest exactly in the position from which they started. If the waves were all of equal size the particles would move up and down in simple harmonic motion. Similarly, when a tuning-fork is vibrating so as to give forth a pure tone, its various parts move in approximately simple harmonic motion.[1]

If we attach a stylet to the limb of a tuning-fork, set the fork vibrating, and allow the stylet to write upon a sheet of paper drawn in the direction of the length of the fork, a curved line will be traced upon the paper similar to the curve from d_0 to δ in Fig. 125. The shape of the tracing will depend upon the rate at which the paper moves. If the paper moves slowly the waves will be short and steep; if quickly, they will be elongated. Such a series of vibrations reaching the ear gives rise to a sensation which, lacking

[1] A simple harmonic motion is thus mathematically defined by Thomson and Tait, *Elements of Nat. Phil.* Part I. p. 19 : '' When a point Q moves uniformly in a circle, the perpendicular QP drawn from its position at any instant to a fixed diameter AA of the circle, intersects the diameter in a point P, whose position changes by a simple harmonic motion.''

brilliancy and variety, soon palls on the ear. The one continuous tone has a dull uniformity ; it is monotonous in every sense of the word.

In the next place, suppose we have two tuning-forks vibrating at the same time but at different rates, and for the sake of simplicity let one of them vibrate twice as quickly as the other. We can now attend at will to the tone given forth by either fork, or to a new third sensation
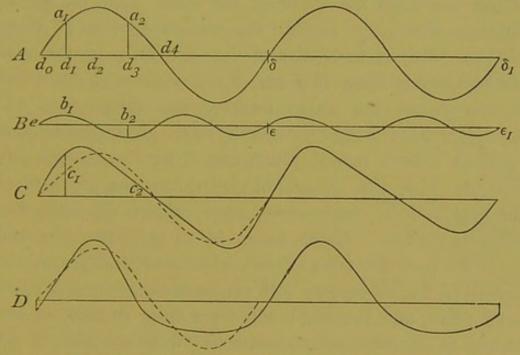
FIG. 125.—Pendular vibrational curves A and B. C, Vibrational curve obtained by superimposing B on A, so that the point e is on d_0 ; D, vibrational curve obtained by superimposing B on A, with the point e on d_1 of A. (Von Helmholtz.)

produced by the combination of the two tones. If the waves of condensation begin at exactly the same instant, the combined effect may be graphically represented by the continuous line in C, Fig. 125. When both forks produce condensation or rarefaction of the air at the drum-head at the same time, the effect will be that of the sum of the two. If one tend to produce condensation, while the other causes rarefaction, the combined effect will be equal to the

difference of the two. Thus the height of the continuous curve C (Fig. 125) at the perpendicular c_1 is equal to the sum of the height a_1 d_1 of wave A, and of the height of the crest at b_1 in curve B. At d_2 no effect is produced by B as the crest is changing to the trough. At a_2 d_3, A is still producing condensation, while B is producing rarefaction, the resultant effect being that at this phase the continuous line c falls below the dotted line between c_1 c_2, and so on. If the crests do not occur at the same moment, but at different times, as in D, the resultant form of wave will be different from that of C. Similarly in the case of the smooth sheet of water, if the surface be disturbed at two points the waves meeting and intersecting will have increased height or depth when crest meets crest or when trough meets trough, but if the crest of the one coincide with the trough of the other, the measure of the amplitude of the resultant wave will be the difference between the two. If the waves be of the same size and meet so that the crest of one exactly coincides with the trough of the other, they will counterbalance or neutralise each other, and the result will be a level surface for the water, or in the case of sonorous vibrations rest of the molecules and silence. And now let us suppose that we have an indefinite number of sets of vibrations, whose period or time of vibration is such that the primary or fundamental series is always a multiple of the smaller or more rapid sets, then the resultant curves, as graphically represented, may assume an infinite variety of forms, but these being repeated at regular intervals, the effect upon the ear will be that of a musical note. What complicated forms the wave may take can be readily imagined if we think of the effect produced on the surface of the sea by a gale of wind. The great rollers have their crests buffeted and broken by conflicting gusts, their surfaces roughened

by a thousand waves and ripplets. No two great waves seem exactly alike. Such a disturbance of the atmosphere affecting the ear would give rise simply to a noise, but let the great waves, irregular as they may be, succeed each other as exact copies one of the other, then we will have the musical tone, whose pitch or fundamental tone is that of the largest waves, but whose quality is determined by the combination of waves and wavelets into one.

Resonators.—We can easily prove that the musical notes of most instruments are compounded of a fundamental and upper partial or overtones by using the resonators of von Helmholtz. These are hollow spheres of brass or glass with apertures to either side, as seen in Fig. 126, or tubes shaped somewhat like a bottle without a bottom. The air in these instruments vibrates at a given rate, or in other words, with a certain pitch determined by the size of the resonator (the larger the resonator the lower the pitch), and most loudly when a note of the same pitch is sounded in the vicinity
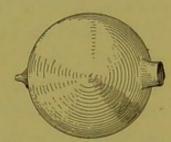
Fig. 126.— Resonator of von Helmholtz.

of the resonator. When the smaller aperture is inserted into the external ear the special tone is heard to the exclusion of all others, the amplitude of the vibration being largely increased in the resonator. The principle by which this is brought about is the same as that which comes into play when any periodic motion is increased in amplitude by slight successive increments. For instance, suppose we wish to cause a person sitting on a swing to rise to a considerable height, or, in scientific terms, to cause the swing to move in vibrations of large amplitude. We first push the swing from the vertical, and thereby cause it to rise a slight distance above its lowest position. Under the influence of gravity the swing falls back to its position of

rest, but acquiring momentum as it falls it passes the vertical line and rises on the other side until stopped by gravity, the friction of the rope, and the resistance offered by the air to the movement of the body through it.   If, further, we ourselves interpose, we can readily prevent the rise and bring the swing to rest.   But suppose we wait till the swing, having risen as high as possible, stops and begins to fall again and now give another slight push in the same direction as formerly.   The new force added to the old, which has not yet entirely died away, causes the swing to rise a little higher than at first, and the return rise is also higher.   Again, when it begins to fall we give a slight push, and so on, till at last the swing sweeps to and fro in wide oscillations and with great momentum.   The periodic application of a slight force has given rise by summation of effect to a great force and extensive movement.   So is it with the resonator.   Vibrations of small amplitude in the external air set the molecules of air in the resonator into oscillation, and the successive impulses are given just at the moment when they will increase the amplitude of vibration. Thus atmospheric vibrations which, when diffused freely through the air, have insufficient energy to give rise to a sensation, will, acting upon the air in the resonator, set up a sympathetic resonance, which enables the ear to detect their presence even amid a multitude of louder sounds.   But if the pitch of the external note is sharpened or flattened, the vibrations clash, and the resonator is silent.

Analysis of Compound Tones by Resonators. — To satisfy ourselves that the sound produced by most musical instruments is compounded of many simple tones, we have simply to sound a note upon the instrument in question, and listen with a series of resonators.   We will have, firstly, resonance for the fundamental tone, and then for a set of tones of higher pitch whose vibrational numbers are

multiples of that of the fundamental tone. We might have, for example, a set of overtones or partials or harmonics of the following relationship :—

	Fundamental Tone.	Upper Partials or Harmonics.								
Note . .	do^1	do^2	sol^2	do^3	mi^3	sol^3	$si\flat^3$	do^4	re^4	mi^4
Partial tones	1	2	3	4	5	6	7	8	9	10
Number of vibrations	33	66	99	132	165	198	231	264	297	330

Instead of applying a series of resonators to the ear, and so detecting the presence of various simple tones by hearing, we may analyse the compound note, and demonstrate optically the presence of the partial tones by means of an apparatus devised by König. This consists of a series of resonators mounted on a frame. The apertures of the resonators, which are usually inserted into the ear, are connected by elastic tubing with a set of small boxes. Coal-gas is led into the boxes, but prevented from passing to the resonators by closure of the entrance to the tubes with a thin india-rubber membrane. The gas passes from the boxes to a corresponding set of small burners, which give long pointed flames. When the air in one of the resonators is set in vibration, the membrane shutting off the resonator from the gas-box vibrates in sympathy, causing a variation in the pressure of the gas, and of the size of the flame. With all musical tones, however, the number of vibrations per second is so great that, from persistence of the retinal impression, we are unable with the naked eye to see the change in size of the flame. To obviate this difficulty, the rays of light from the flame are reflected to the eye from the surface of a cubical mirror rotating upon an upright axis. If the flame is burning steadily, the series of reflections of the light sent from the rotating mirror are blended into one smooth edged band of light ; but if the

resonator is in action, the smooth band gives place to one with teeth on its upper border. Each tooth represents an increase of pressure from the resonator, each notch a diminution. When a note containing the overtones to which these resonators respond is sounded, the flame picture in the mirror will declare their presence. The adaptation to organ
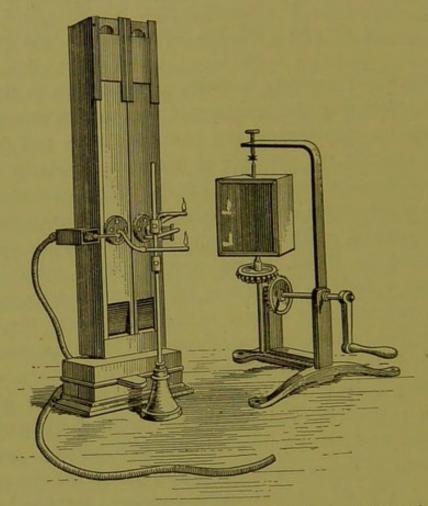
FIG. 127.—König's apparatus for studying optically the vibration of air in organ-pipes.

pipes of the same kind of apparatus, viz. the gas-box, and the light of the flame reflected from a rotating mirror, is shown in Fig. 127, where we have the means of studying the vibration of air in organ pipes. By such an arrangement, for example, we may see that with two organ pipes sounding, the one an octave higher than the other, the

flame picture on the mirror for the upper note will have twice as many elevations as that of the lower.

In the absence of von Helmholtz's resonators, a simple means of analysing a compound note, or at least of detecting its most important partial tones, is to cause the note to sound beside a piano. If we gently depress the key corresponding in pitch to that of the note sounded, so as to remove the damper, we will hear quite distinctly the sound of the piano-string vibrating in sympathetic resonance. Next depress the key of the octave above, and we will hear it sounding, but more faintly than the fundamental note. Again, if we press down the key of the fifth (sol) in the second octave, and so on with the various harmonic overtones, we will hear the resonance, but always becoming weaker. It will, as a rule, be found that the sound obtained from any note other than those in the harmonic series is by no means so distinctly heard, although we may have inharmonic upper tones due to a note being not purely musical in character, but accompanied in its production or propagation by noises.

For the notes sounded by almost all musical instruments, then, we may conclude that each note is compounded of a series of simple tones, each of which may be made to produce its effect upon the ear as if the others were absent, and the total effect is due to a summation of the effects and a combination thereof to give a new sensation.

We can imitate the notes of instruments having special overtones by combining pure partial tones, and in the organ some of the stops are so designed as to make sets of pipes sound together whose pitch is such as to give the effect of some other instrument, such as the flute, the clarinet, or even the human voice (the *vox humana*).

As a result of a careful series of observations on the quality of different musical tones, the particulars of which

are detailed in his book *On the Sensations of Tone,*[1] von Helmholtz arrives at the following conclusions :—

" 1. Simple tones, like those of tuning-forks applied to resonance chambers, and wide stopped organ pipes, have a very soft pleasant sound, free from roughness, but wanting in power, and dull at low pitches.

" 2. Musical tones, which are accompanied by a moderately loud series of the lower upper partial tones up to about the sixth partial, are more harmonious and musical. Compared with simple tones they are rich and splendid, while they are at the same time perfectly sweet and soft if the higher upper partials are absent. To these belong the musical tones produced by the pianoforte, open organ pipes, the softer piano tones of the human voice, and of the French horn. The last-named tones form the transition to musical tones with high upper partials ; while the tones of flutes, and of pipes on the flute stops of organs, with a low pressure of wind, approach to simple tones.

" 3. If only the *uneven* partials are present (as in narrow stopped organ pipes, pianoforte strings struck in their middle points, and clarinets) the quality of tone is *hollow*, and, when a large number of such upper partials is present, *nasal.* When the prime tone predominates, the quality of tone is rich and full ; but when the prime tone is not sufficiently superior in strength to the upper partials, the quality of tone is *poor* or *empty*. Thus the quality of tone in the wider open organ pipes is fuller than that in the narrower ; strings struck with pianoforte hammers give tones of a fuller quality than when struck by a stick, or pulled by the finger ; the tones of reed pipes, with suitable resonance chambers, have a fuller quality than those without resonance chambers.

" 4. When partial tones higher than the sixth or seventh

[1] Von Helmholtz, *Sensations of Tone,* pp. 172, 173.

are very distinct, the quality of tone is *cutting* and *rough*. The reason for this lies in the dissonances which they form with one another. The degree of harshness may be very different. When their force is inconsiderable, the higher upper partials do not essentially detract from the musical applicability of the compound tones ; on the contrary, they are useful in giving character and expression to the music. The most important musical tones of this description are those of bowed instruments, and of most reed pipes, oboe (hautbois), bassoon (fagot), physharmonica (harmonium, concertina, accordion), and the human voice. The rough braying tones of brass instruments are extremely penetrating, and hence are better adapted to give the impression of great power than similar tones of a softer quality. They are consequently little suitable for artistic music when used alone, but produce great effect in an orchestra."

It has been stated that the quality of a tone is dependent upon the *form* of the wave which produces it. We have seen that the graphic representation of a complex tone reveals a series of very different forms of waves, according to the phase or period of combination of the partial tones. The question then arises : Does the ear appreciate these differences of phase in the combinations of partial tones ? For a given set of combined partial tones, do the different resultant wave-forms give rise to sensations of different quality ? To this question conflicting answers have been given. On the one hand, it is maintained by von Helmholtz that "the quality of the musical portion of a compound tone depends solely on the number and relative strength of its partial simple tones, and in no respect on their differences of phase." The difference of wave-forms C and D in Fig. 125, according to von Helmholtz, makes no difference in the sensation of the quality of the resultant complex tone. The ear has the power of resolving the complex vibrations

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into series of simple vibrations, and of hearing the pure tones corresponding to these sets of vibrations. As according to mathematical demonstration, however different the wave-forms for any given combinational tone may be, varying with phase of combination, these forms can only be resolved into one definite set of partial tones, the ear must always recognise the same set of partials, and we combine them again to give rise to a tone of the same quality. On the other hand, it is asserted that the different forms, representing as they do real differences in pressure on the drum-head of the ear, give rise to sensations of different quality. The curve D, for example, in Fig. 125, may be taken as representing short periods of increased pressure and long periods of diminished pressure upon the tympanic membrane, while, by slightly altering the phase of the component parts, we could give rise to alternate long periods of increased pressure and short periods of diminished pressure. In the one case, the general condition is one of diminished pressure on the sensory apparatus with brief change to high pressure ; in the other, the sensory apparatus is subject in the main to higher pressure than usual, but with short periods of low pressure intervening. The pitch and intensity are, of course, unaffected, because the rate of vibration and amplitude of the waves are the same. The decision between the opposing opinions can be made only by personal trial, for, theoretically, we have no knowledge as to the way in which variations of pressure in the internal ear affect the sensory apparatus, nor, again, how changes in the end organ are transmuted into conscious sensation. As a matter of fact, the differences of quality, if any do arise, are very slight, and only to be appreciated by a highly-trained ear, and with simple binary compounds. For the notes of ordinary musical instruments, or for combinations of numerous partials into

complex tones, it is practically impossible to detect differences of phase, so that the statement holds good in the main that the quality depends, as von Helmholtz asserts, upon the number and relative strength of the partial tones. This holds for all perfect harmonies, at least those in which the vibrations are strictly periodic and resolvable into series of partial tones—the *period* of the fundamental tone being a multiple of those of the partial tones.

Beats.—When two simple tones of exactly the same pitch are sounded together, if some arrangement be made by which the phase of vibration of each coincides, the result of their combination will be increased amplitude of vibration of the drum-head, and increased intensity of sound, but if the phase of one series of vibrations differ by a half wave-length from the other, the one will neutralise or interfere with the other, and there will be silence. Suppose, now, that we have two simple tones sounding together of the same intensity, and of *nearly* the same pitch—say, for example, that one is due to 200 the other to 201 vibrations per second—and suppose that the vibrations are in the same phase to begin with, it is evident that, since one falls behind the other to the extent of one wave-length in a second, it must fall one-half of a wave-length behind in half a second; near the beginning and near the end of the second the vibrations are nearly in the same phase, and combine to intensify the effect; but in the middle of the second, being in opposite phases, they tend to counteract each other, and there will be a diminution of intensity even to momentary silence. There will thus be an increase of volume followed by a diminution of volume of the sound every second, and we have an unevenness in the sound, or a succession of what have been called *beats*. The number of beats per second will depend upon, and be equal to, the difference of rate of vibration of the two partial tones. We

have seen that a difference of one vibration per second gives one beat per second. If the simple tones differ by two vibrations per second, there must be two beats per second ; for, since the one set falls two wave-lengths behind the other in a second, they must be one wave-length behind in half a second, and a half wave-length behind in a quarter of a second. There is increase of sound about the beginning of the first and third quarters, and diminution about the beginning of the second and fourth quarters, or, as we have said, two beats per second. Beats, then, can arise only when the vibrational number of one set is not a multiple of the other ; if the period of one is a multiple of the period of the other, there can be no beat. When there are not more than five or six beats per second, the ear can easily note the gradual rise and fall in intensity, and the effect is not unpleasant. When the beats come more quickly we lose the power of paying attention to the rise and fall of each beat, although we can still for a time recognise the beats as arising and differing from the continuous tones. The effect is that of a whirring harsh sound ; it is called *dissonance.* According to von Helmholtz, by gradually increasing the frequency of the beats, we may have as many as 132 per minute, and yet recognise the dissonant character of the sound and the presence of beats. Beyond this number the regular recurrence of the beats leads to a secondary fusion, and the starting of a new tone arising from the beats—a beat-tone. The ear fails to recognise a strictly musical character in beat-tones even when the beats are much more numerous than the vibrations required for an ordinary musical tone. This we may possibly explain by the fact that the development of beats is due not so much to a variation of pitch as of intensity. The higher tone continues to sound at exactly the same pitch as before, and there is merely a periodical variation in the amplitude of the vibrations which give rise

to it. We have, then, in the production of beats, a condition analogous to the variations of pressure experienced in the sense of touch, in which, as stated (p. 58), we are able to discriminate the individual stimuli much longer than we can either with visual or ordinary auditory stimuli. There may be no fusion by the sense of touch of as many as 500 stimuli per second ; whereas, if the stimuli to the eye come faster than 10 per second, or by the ear 30 per second, there is a fusion in sensation. In the phenomena of beats, then, we seem to find a link between the sensation of touch and that of hearing, the *tactile* element (variation of amplitude) being superposed upon the *auditory* element (constancy of pitch). The unpleasantness of the sensation excited when the beats come at about 35 per second, when carefully investigated, is found to be similar in kind to that experienced when the senses of sight and touch are stimulated too rapidly for the bestowal of attention on each stimulus, and yet too slowly to give rise to central sensory fusion. A flickering light has a similar effect. The mind seeks, as it were, to maintain order in the reception of the messages of sense, to give to each sensation its due recognition, and yet to subordinate it to general relationships and conscious sequence. But the stimuli come on the border-line between what may be grasped and what may not. Before the sensorium has had time to give full effect to one stimulus another has come upon it, and finds it partly ready but not quite, or, from the physical point of view, the sensory centre has not had time to recover completely from the disintegrating effect of one shock before it has to endure another. Something is being impressed upon the receptive centres which tends to force the mind from the path in which it seeks to move, and which is itself followed by another and another claimant for notice, till we become irritated at the disturbance and weary of the repeated dis-

traction.   All this, of course, takes place in a semi-uncon-
scious way, since it is not, as a rule, the beat in the sound
or the flicker in the light to which we wish to pay attention ;
the pure musical sound with which the beat interferes, or
the thing seen, now clearly, now dimly, in the changing light,
is the object of mental effort.   Without analysing the nature
of the disturbing element, we feel that it is there, and to
this must in the main be attributed the disagreeable effect
produced.

Yet while this holds true of long-prolonged tones roughened
by fast-repeated beats, it must be remembered that in ordi-
nary orchestral music we rarely hear notes entirely free from
beats.   While the various notes of a chord struck upon a
piano may be of such pitch as not to generate beats, the
overtones of these interacting on one another most prob-
ably will.   Certain chords, no doubt, are freer from such
roughness, and it is no uncommon thing to heighten the
effect of a pure harmonious note by causing it to be preceded
by a discord.   Contrast in sound, as in colour, heightens
the effect on the sensorium.   The eye fatigued by looking
at a red colour will, when turned to a green surface, see it
of intenser hue ; the ear has a keener appreciation of pure
harmony when the harsh note has ceased to jar.

Noise.—When auditory stimuli are non-periodic in char-
acter the resultant sensation is that of a noise.   A single
variation of pressure upon the tympanum might be sufficient
to set the mechanism of hearing in action, but the resultant
sound could not be musical in character.   It has been held
by some that two impulses exactly alike, and the one quickly
following the other, may give rise to a musical sensation,
but the probability is that the musical effect is in this
instance due to overtones, and to such a sound it is not
possible to assign a definite pitch.   The ear can easily distin-
guish as separate noises the effect upon it of impulses coming

at the rate of less than 16 per second. When the noise is due to vibrations coming at the rate of more than about 16 per second, there is a certain amount of fusion in sensation, and the noise has for us a certain pitch. Where there is an initial shock, as in a thunder-peal, with echoing and re-echoing at somewhat prolonged intervals, we have a deep, rumbling sound ; if the vibrations succeed one another very quickly we have sounds or noises of high pitch, which we describe as crackling, whistling, rustling, shrieking, creaking, and so on. The wind sweeping through a forest sets up an infinite number of intermittent variations of aerial pressure as it sways branches and leaves to and fro, and a low rustling sound is heard ; but when it agitates tense structures, such as the cordage of a ship's rigging or the strings of an Æolian harp, the sound becomes more distinctly musical, and especially if the wind blows with a fairly constant force. The harsh nature of the sound educed from a violin by an unskilled performer is due to inequalities of pressure upon the strings with the bow, while the master hand, by maintaining steady continuous pressure for longer or shorter intervals, and thus eliminating discordant overtones, will draw forth pure melodious sounds.

General Mode of Action of the Ear.—Having considered the structure of the ear and the physical nature of sound, we have next to see how the one is adapted to the other, how the ear responds to auditory stimuli. Much may be learned from the study of pure physics as to the beauty of the mechanical adaptations, but this merely brings us to the threshold of sensation. The changes in the auditory nerves and nerve centres which accompany or give rise to the sensation of sound are almost entirely unknown. Even with regard to the mode of action of the internal ear there is still much uncertainty.

The *external ear*, we have seen, acts mainly as a collector of sound waves, and the external meatus, closed internally by the drum-head, helps, like von Helmholtz's resonators, to increase the energy with which the membrane is agitated.

The *middle ear* is so constructed as to diminish as little as possible the power of the aerial vibrations in their transmission to the sensory terminals. When vibrations pass directly from air to solids or liquids, much of their energy is lost. If a membrane intervenes between the air and a liquid, the energy is not lost to so great an extent. There is, therefore, mechanical advantage in the separation of the fluids of the internal ear from the air by the membranes closing the round and oval windows. But these membranes are small of size, tense in texture, and in apposition upon one side with fluid in an enclosed space. They have thus little amplitude of movement. This is compensated for by the drum-head. Being larger than the membrane of the oval window, and having air upon both sides, it vibrates freely, and being firmly attached to the tympanic ring and tense in the greater part of it, its vibrations are readily transmitted to the attached chain of bones, and by them, with little if any loss of power, to the foot of the stirrup-bone with its membranous attachment to the circumference of the oval window, and so to the perilymph. Nay, there may be an actual gain from the lever action of the chain of bones and the greater size of the drum-head (p. 213). The chain of bones, working freely in the middle ear, gives, as we have seen, a greater amplitude of movement than would be available if the internal ear were simply buried deeply in the cranial bones. Still, the ligamentous connection of the bones with the membranes and the walls of the tympanum hinders over-movement, and enables them to act as dampers, preventing unnecessary oscillation of the drum-head. The tenseness of the membrane and, consequently, its power of

responding to sounds of different pitch and intensity are likewise regulated by the intrinsic muscles of the middle ear, and more especially by the *tensor tympani* muscle, while the entrance of air by the Eustachian tube maintains equality of atmospheric pressure upon the two sides of the drum-head.

Vibrations then may reach the *internal ear* either through its osseous walls or through the membranes of the oval and round windows. In the vestibule and semicircular canals these vibrations are further transmitted to the membranous labyrinth through the perilymph, for the connection of this part of the auditory sac, with its surrounding walls, is by no means so close as in the case of the cochlear canal. Through the membranous sac the vibrations reach the endolymph, and so come to the terminations of the vestibular portion of the auditory nerve in the *maculæ* of the utricle and saccule, and in the *cristæ* of the ampullæ of the semicircular canals. The effect may be enhanced by the otoconia (p. 227) in the endolymph, and by the rods projecting from the auditory epithelial cells; for, as has been pointed out, the hand thrust into water may be incapable of detecting the presence of sound waves passing through the water, but will easily do so if grasping a rod. This will be readily understood if we consider that the rod will act as a lever, and so increase the effect of the sound waves on the hand.

That the auditory hairs do actually sway to and fro under the influence of sonorous vibrations may be taken as proved, for Hensen has seen with low microscopic powers the auditory hairs of *Mysis* (the opossum shrimp) vibrating in response to the notes of a keyed horn. The auditory hair-cells are either the terminations of the auditory nerve fibres, or are in close apposition with them, and, on receipt of the vibrational stimulus, an impulse is given to the nerve; but at this point we are arrested, for we do not know whether

or not the nerve current corresponds in rate of intermission with the variation of pressure due to sound, whether vibrations are transmitted along the nerve, or whether we have to do with an entire change of physiological phenomena in the development of the nerve current.

In the case of the cochlea, the vibrations may be transmitted by the perilymph, and through the membrane of Reissner and the cochlear endolymph, or through the basilar membrane to the endings of the cochlear branch of the auditory nerve in Corti's organ, or sonorous vibrations of the bones of the skull may, through the medium of the spiral osseous lamina and Bowman's spiral ligament, be directly transmitted to the basilar membrane and its superjacent structures.

From noting the mode of termination of the cochlear nerve in or round the hair-cells of Corti's organ, and from the analogy of the nerve-endings in hair-cells in the case of the other special senses, we cannot but infer that the hair-cells in the organ of Corti form the peripheral sensory terminals, while the rods of Corti and the supporting cells of Deiter, with their phalangeal connections, serve mainly to transmit to the hair-cells the vibrations set up in the basilar membrane.

In all parts of the fluid of the internal ear changes of pressure due to movements of the chain of bones must be experienced, and as the fluid is incompressible, there must be an outward or inward movement of the membrane of the round window corresponding respectively to every inward or outward movement of the stapes. The question therefore arises : Do all parts of the internal ear, or at least, do all the terminations of the auditory nerve, respond alike to the sound ; or does each nerve-ending have a special duty to perform, have a special response to a special element of the sound, be it pitch, intensity, or quality ?

The semicircular canals in relation to movements. —Considered merely from an anatomical point of view, we should expect a difference in function corresponding to the structural differences between the *maculæ, cristæ,* and *organ of Corti,* between the vestibular and cochlear divisions of the auditory nerve, and the different nerve centres to which they pass. It has even been suggested that the vestibular nerve and its terminals have nothing to do with the sense of hearing, but have to do with the sense of equilibrium or of the position of the head in space, while the appreciation of sound is relegated to the cochlea alone. In support of this view it has been pointed out that the *semicircular canals,* with their *cristæ acusticæ,* may be destroyed without impairment of the sense of hearing. At the same time, the animal begins to perform peculiar movements which vary according to the canal destroyed. If either of the canals in the vertical plane is injured, the animal rotates its head round a horizontal axis at right angles to the plane of the canal ; and, if the horizontal canal be injured, rotation takes place round a vertical axis.

These rotary movements being similar to those produced by lesions of the cerebellum, and being apparently associated with a disturbance of the power of co-ordinating muscular movement—a power which depends largely upon the sense of equilibrium—it was held that the canals have to do with this sense, or, as suggested by Cyon in 1872, with sensation as to the position of the head in space. As Crum Brown has shown, the canals of the opposite sides of the head may be divided into three sets of two each in nearly identical planes, and so related as to be nearly at right angles to each other. When the head is moved in any direction, the fluid in the canals tends to move in the opposite direction, or at least to lag behind the moving walls of the canals, just as when we rotate a vessel contain-

ing water the inertia of the water prevents its moving so quickly as the vessel at first, and of stopping so quickly when once set in motion. As the volume of fluid in the canals is constant, the fluid must, however, move with the head. It cannot lag behind, but there will be variation of pressure due to inertia. Thus, according to Crum Brown, "in each of the three pairs of canals (right and left horizontal, right superior and left posterior, right posterior and left superior) the two canals are so placed that when rotation takes place about the axis to which they are perpendicular, one of the two canals moves with its ampulla preceding the canal, so that the flow or tendency to flow (or pressure) is from ampulla to canal, while in the other the ampulla follows the canal, and the flow or tendency to flow (or pressure) is from canal to ampulla. If, then, we suppose that flow from ampulla to canal—or adopting Mach's view, increase of *pressure* in the ampulla—alone stimulates the hair-cells, while no effect is produced by flow in the opposite direction—or by *diminution* of pressure in the ampulla—we have in the six canals a mechanical system capable of giving us an accurate notion of the axis about which rotation of the head takes place and of the sense of rotation."[1] It has been further urged that the *maculæ* of the utricle and saccule have to do respectively with the sense of movement in a vertical or horizontal straight line, just as the cushions of the ampullæ respond to rotation.

On the other hand, it is alleged that even when the auditory nerve is destroyed and the body rotated, a sensation of rotation comes on as usual. If this be so, the canals cannot be essential to the sense of position. Again, it is held that we cannot dissociate the vestibular nerve from

[1] A. Crum Brown, "Cyon's Researches on the Ear," *Nature*, 1878. See also M'Kendrick's *Text-Book of Physiology*, vol. ii. p. 694.

auditory sensation, since animals which can undoubtedly hear well may have a very rudimentary cochlea.

On the whole, it seems probable that the vestibular nerve can respond to auditory stimuli. It may act under the stimulus of sound, and it may respond to differences of intensity of sound, but can it lead to the appreciation of differences in the *pitch* of sound? To this question we must probably give a negative answer. No doubt, in the case of crustaceans, Hensen has found that auditory hairs of different lengths respond to certain notes better than to others, but no such difference of length in the *auditory hairs* of the *maculæ* or *cristæ* can be seen in the human ear, nor any difference that could lead us to imagine that one cell should respond differently from another. The hairs on the hair-cells of Corti's organ are still shorter, so that we cannot conceive that they have any differentiating action as regard the appreciation of pitch. They seem to act rather, as suggested above, as minute levers by means of which the auditory cells are rendered sensitive to even the slightest movements in the fluid that bathes their free surfaces.

Analytic Power of the Ear.—Has the ear, then, any mechanism which enables it to appreciate differences of pitch, or to analyse a compound tone into its constituent partial tones? There is a fusion of all partial series of vibrations in the air of the external ear. The tympanic membrane vibrates as a whole, and responds to the compound summational wave, however complex its form may be—that is to say, however quickly it changes, and proportionally in extent to the variations of atmospheric pressure. With the drum-head moves the chain of bones, and with it again the perilymph and the endolymph. Yet, in the sensorium, we can appreciate either the quality of the complex tone, or we can attend to its constituent parts. Wherein

comes the power of analysis? Is it the case, as Rutherford holds, that the hairs of all the auditory cells vibrate to every tone, just as the drum of the ear does, and that there is no analysis of complex vibrations in the cochlea or elsewhere in the peripheral mechanism of the ear; that the hair-cells transform sound vibrations into nerve vibrations, similar in frequency and amplitude to the sound vibrations; that simple and complex vibrations of nerve molecules arrive in the sensory cells of the brain, and there produce not sound again, of course, but the sensation of sound, the nature of which depends, not upon the stimulation of different sensory cells, but on the frequency, amplitude, and form of the vibrations coming into the cells, probably through all the fibres of the auditory nerve?[1]

Upon this theory the whole internal ear vibrates in unison with the drum-head, and the auditory nerve in unison with both, just as the receiving plate of a telephone moves in unison with the transmitting plate. Analysis must then be a mental act dependent upon the powers of the central nerve cells, but how it is to be exercised we are not informed.

Or does the power of analysis lie with the cochlea? This is the theory which von Helmholtz first stated and explained with consummate skill. We have seen (p. 255) that when a compound tone is sounded before a piano with uplifted dampers, the strings of the piano which are in tune with the partial tones of the compound tone will vibrate. Similarly, von Helmholtz conceived that the cochlea has the power of analysing compound tones into simple pendular vibrations, and that different parts of the cochlea respond each to the particular partial to which it is attuned. At first, he supposed the rods of Corti's organ were the structures which, varying in size and shape, took up each its own tone, and,

[1] Rutherford, "On the Sense of Hearing," *The Lancet*, January 1887.

by striking upon or otherwise exciting the hair-cells with which they were connected by means of the phalanges, caused sensory stimuli to be sent by the nerve fibres attached to the hair-cells to corresponding nerve cells in the sensorium. He did not, however, suppose that the nerve current resembled physically in any way the vibration which roused the auditory cell. The resulting sensation was simply due to the specific power of the cell in the brain, to give rise to a sensation of a sound of a certain pitch when stimulated by its proper tone.

Various considerations, however, induced him to modify his theory. In the first place, the rods of Corti vary very little in form and size, as we pass from the base to the apex of the cochlea. Again, there are only about 3000 of them altogether, and yet we can distinguish differences of pitch in sounds varying in their number of vibrations from 30 to 40,000 per second. Further, we have good grounds to believe that birds can distinguish the pitch of tones, and yet the rods of Corti are entirely absent from their cochleas which have the hair-cells in contact with the basilar membrane, and are very rudimentary in other respects. For these and similar reasons, von Helmholtz supposed that the real analysers, in respect of pitch, are the fibrils in the outer part of the basilar membrane, and that the rods of Corti simply serve to pick up and transmit their vibrations to the hair-cells. This view is supported by the fact that the basilar membrane is stretched firmly in the direction of these fibrils, but is loose in the direction of the canal. The fibres are easily separated from one another, but are not readily torn across. The membrane will not vibrate, as a whole, like one in which the tension is alike in all directions, but it is made up of strings or fibres, each of which may vibrate independently of the other.

There are about 24,000 of these fibrils in the basilar

membrane—a number much larger than that of the rods of Corti, although less than the number of sounds between which we can make a distinction of pitch. Von Helmholtz supposed, then, that these fibrils, varying in length and possibly in tension, may respond in sympathetic vibration each to its proper tone, and that these vibrations are transmitted to the hair-cells by their supporting structures. If a tone falls upon the ear which does not correspond exactly in vibrational frequency with that of any of the fibrils, von Helmholtz suggested that two or more adjacent fibrils might respond in various degrees, that being strongest which approximated most nearly to the stimulus, the others more feebly. By a mental combination and comparison of the different stimuli the true pitch of the note would be arrived at. Thus each fibril has, according to him, one proper tone to which it answers strongly, while to all others it is less responsive. Similarly, in the case of the stimulation of the auditory hairs of *Mysis*, it was found that different hairs responded strongly to different tones. One, for example, vibrated strongly to $d\sharp$ and $d'\sharp$, more weakly to g, and very weakly to G. Another hair answered strongly to $a\sharp$ and adjacent tones, more weakly to $d\sharp$ and A$\sharp$. For some tones, then, the cerebral cells are directly tuned, but not for others ; for all others there must be a comparison of several tones and appreciation of pitch through the means of an average. As von Helmholtz does not suppose that the nerve current in any way corresponds in number of vibrations to that of the exciting cause, each nerve cell depends on its own inherent power of response in giving rise to a sensation of a special pitch. But, further, it has been computed that there are only about 15,000 hair-cells, and if it be the case that each of these is connected with one nerve fibre and its special brain cell, and that each hair-cell corresponds only to one tone, the number of special tones to be directly recognised

in the brain is considerably less than the number of fibrils of the basilar membrane would lead us to expect. On the other hand, if the cell may respond to more than one tone, and give rise to sensations of different tones in the sensorium, we must have some difference in the nerve currents transmitted at different times from periphery to centre by the same nerve, and this would probably correspond to different rates of vibration of the basilar fibrils.

Now, it is just possible that there may be a greater power of response in the basilar membrane to sounds of varying pitch than von Helmholtz supposes. If at any particular moment there is no fibril attuned to the pitch of the incoming sound, it may be that the tension of part of the membrane may be varied to suit the exigencies of the case. We have seen that Bowman's ligament, by which the basilar membrane is attached to the outer wall, contains spindle cells which may be regarded as muscular, and by the contraction of which the pull upon the fibrils may be varied, and their tension increased or diminished. A similar result might follow a change in the amount of blood circulating in the spiral ligament, giving more or less turgidity to this structure. Thus if each fibril of the basilar membrane in its normal condition of length and tension is tuned approximately to a special tone, and if by variation of its length or tension it may be rendered responsive to tones of slightly higher or lower pitch, as we may tune a violin by tightening or slackening the strings, we have in the ear a complete analysing mechanism for the pitch of all musical sounds. Such an hypothesis renders it possible likewise that we may have a complete series of tones from the lowest to the highest, melting one into the other by imperceptible change— an ear, in fact, that can appreciate the pitch of any possible tone between the lowest and the highest limits, a capacity which experience shows to be possible in the human ear,

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and that directly for all tones, and not indirectly for some, as von Helmholtz holds.

If, further, it is the case, as Rutherford suggests, that the sensation varies in the central cell according to the rate at which the peripheral end of the nerve fibre or the hair-cell is stimulated, we arrive at a view which is free from objections that may be urged to the theories both of Rutherford and von Helmholtz. Rutherford's theory is unsatisfactory in so far as it entirely disregards the elaborate structure and wonderful complexity of the cochlea, deprives the ear of any analysing power, and relegates that function to the brain, among whose cells we can find nothing in any way suitable, from a morphological point of view, to lead to a perception of variation of pitch. The physical basis for analysis must be either in the ear or the brain ; but if all parts of the ear, and all the fibres of the auditory nerve, and all the auditory nerve cells, respond together and vibrate alike, we have no such basis. To have the power of selecting one or other partial tone, and of devoting attention to it alone while others are still affecting the sensory mechanism, it seems to us that there must be several structures in vibration or molecular change at different rates. If the auditory centre is in vibration or molecular action as a whole, and similarly in all its parts, it is impossible to understand how a mere effort of will can enable us to note constituent parts of a complex tone. We can pay attention to one or other partial tone in a complex sound, just as we can fix our regard upon one part of the field of vision to the exclusion of all the rest, but how can this be done if all parts of the auditory centre are affected alike ? To each part of the retina there is a corresponding part in the cortex of the brain ; there is probably a similar relationship between different parts of the cochlea and the auditory centre.

On the other hand, the main objections to von Helm-

holtz's theory are the limited number of structures compared with the known capacity of the ear and the supposition that each brain cell is concerned only with the perception of one tone in different degrees of power. All are agreed that the cerebral centres can appreciate variations in strength of stimulus. In all the special senses the strength of the sensation varies with the strength of the stimulus. Now, this does not necessarily imply in regard to the auditory nerve that the actual vibration of the endolymph is transmitted as a vibration that might be seen passing along the auditory nerve as we might see a wave of vibration passing along a tensely-stretched rope when it is struck, but it does imply a greater molecular movement in one case than in another, and a greater or less effect upon the protoplasm of the receptive nerve centre. There may be no real to-and-fro vibration of the nerve corresponding to that of the internal ear, but there must be a variation in the nerve current in respect of *amount* of movement. If the nerve cell can respond to variations in intensity, there is no greater difficulty in supposing that a cell whose function is to give rise to a sensation of pitch may give slightly different sensations corresponding to slight variations in the rate of stimulation.[1] If it be urged that this again relegates distinction of pitch to the brain, and that we might as well suppose each auditory cell to have the power of discriminating between all degrees of pitch, we would answer that the multiplication of centres, each having slightly different receptive powers, affords an anatomical basis for the simultaneous reception of many stimuli differing from one another

[1] See also the remarks on the modified theory of colour vision recently propounded by von Helmholtz (p. 169). This distinctly favours the view that terminal organs, such as the rods and cones of the eye (and why not the delicate mechanism of the internal ear ?), may respond to different rates of vibration.

only it may be in the matter of pitch, while by allowing that each little centre may give slightly different pitch-sensation with variation in the rate of stimulus we avoid the difficulty into which von Helmholtz's theory plunges us. But, it may be asked, can a nerve fibre respond in this way to different numbers of stimuli per second? There is not the least doubt that it can. The number of stimuli sent along a nerve to a muscle may be largely varied with varying effect on the muscle in the way of contraction. In the case of insects, for example, the wings may vibrate as often as 352 times per second (Rutherford), and each movement must be due to at least one separate nerve impulse. A nerve removed from the body may be inserted in a tele-phonic circuit, and it will conduct the electric current and transmit the delicate variations of electrical intensity neces-sary for telephonic communication. We do not assert that the ordinary nerve current is electrical in character, but if the nerve can transmit variations so delicate as those of the telephone must be, they may as readily be deemed capable of responding in rate to their normal auditory stimuli. Moreover, it must be borne in mind that the sensation of pitch is in no way comparable qualitatively with the phy-sical changes which give rise to it. We have no sensation of each individual variation in the stimulus. The sensorium fuses the impulses so as to give rise to a continuous tone. And again, we do not, as a rule, note the partial tones separately and respectively: indeed, until the time of Tar-tini they were not known to exist, and until the time of von Helmholtz were deemed of small importance. Their com-bination and appreciation, as a sound of determinate quality, is a purely mental act, combined, that is to say, by a mechanism higher than and different from the initial recep-tive auditory centres. It is only when, by conscious effort and using special aids, such as resonators, we pay attention

to the sensory effect that we note the constituent parts.
There must be higher mental centres in which fusion occurs,
or a unity of mind in which a synthesis of the partial sen-
sations is brought about.

The Psychical Elements in Auditory Sensations.—
When the auditory centres have been stimulated and the sen-
sation of sound receives due attention, certain mental effects
are produced which are superadded to the simple sensation
of sound.   We judge, for example, that the sound has been
produced outside or inside of the body, that it comes in a
certain direction and from a certain distance, or we may
recognise that it is purely of a subjective character, and
exists only in imagination.   In arriving at a decision upon
such points as these we are aided by the other senses
and by knowledge previously acquired.   Thus, when we
see a man at a distance from us lifting a gun to his shoulder
and a puff of smoke issuing from the muzzle, we know from
experience that we will shortly hear the sound of the detona-
tion.   We infer from the character of the sound, its loudness,
and the time that elapses before the report is heard, that
it comes from the gun and from no other source.

Externality of Sound.—The power which the mind
possesses of determining whether a sound originates out-
side or inside of the body seems to be in large measure
dependent upon whether the sonorous vibrations are com-
municated to the ear through the auditory meatus, the
drum-head, and the chain of bones, or directly through the
bones of the head.   We mentally project the source of the
sound outwards when the vibrations act mainly through the
meatus on the tympanum, but if the sounding body is
touching the head we may have the impression as if the
sound came from within the head.   Weber has pointed out
that if the meatus is filled with water the idea of externality is

destroyed, and that the sound seems to originate in the head. Even when the air in the meatus is vibrating freely in response to sonorous undulations, if the body emitting the sound touches the head, the idea of externality may disappear. Suppose two bodies giving out exactly similar sounds, as when two telephones, connected in one circuit, are held to the two ears and made to respond to one and the same sound. If the telephone to the right side be tightly applied, while the one to the left be held at some little distance from the ear, the sound will seem to originate in the right side of the head. If the one to the left is now pressed closely and that to the right withdrawn a little, the sound is heard in the left side of the head, but if both instruments are held tightly to the ears, the sound seems to originate *inside* of the head and towards the middle line, so that it will be described by one observer as seeming to be in the mouth, by another at the top of the head, and by a third at the nape of the neck. Lastly, by slight variations in the pressure on the head we can apparently make the sound move from side to side at pleasure. The sound of our own voice is heard as originating within the head, and certain disorders may give rise to sensations of sounds referred to the ears. Thus when the intracranial circulation has been disturbed, we may have a ringing in the ears, or may hear the throbbing of the pulse. An accumulation of cerumen or wax in the external meatus may give rise to unpleasant sounds by interfering with the vibration of the drum-head. Drugs, such as quinine or salicin, may cause hissing or whistling sounds, or even a sensation of deafness, by interfering with the nutrition of the auditory centres, and the insane often think they hear voices and sounds on account of disordered and abnormal stimuli in the diseased brain. So strong, indeed, is the power of imagination in the hallucinations of the insane that nothing

will persuade them that the voices are not actually coming from an external source, and it is to be remembered that the sensations are at least real to them, latent impressions being developed or obscure memories recalled by cerebral irritation. Nay more, we may ourselves under certain circumstances by an effort of the mind give rise to auditory hallucinations. Much pleasure may often be derived from the following experiment. If when in bed, lying perfectly quiet, and with no sounds breaking the stillness of the night, we think the music of a song, fixing our attention upon the music but not humming it, we may sometimes seem to hear it being sung an octave higher by a voice external to ourselves—a female voice apparently, from its delicacy, tenuity, and high pitch—and, strange to say, not exactly synchronous with but very slightly behind our own imaginary singing. When the hallucination is thoroughly established and we resign ourselves completely to it, the two voices may seem to go on without effort on our part, and we ourselves to be merely passive listeners. The least movement, however, or wandering of the thoughts to another subject, immediately dispels the illusion. In performing this experiment, it is most probable when the mind has all its faculties concentrated upon the endeavour to hear the faint sound that, in thinking the music, we actually give rise to slight variations in the tension of the auditory structures, and possibly stimulate the auditory centre through the auditory nerve, but to so small an extent as to be hardly perceptible to the senses, or it may be that with the concentration of the mind upon the expected sound the nutrition of the auditory centre is involved. It might even be that the auditory centre is stimulated from the parts which subserve volition, but this is mere conjecture, for which no experimental data can be adduced beyond the well-established fact that lower centres may be inhibited or

excited by influences coming from higher cerebral centres. As a monarch may summon his ministers and invoke their aid or dismiss them from his presence, so the conscious mind may call upon the senses for their testimony, or may bid them be silent, and the obsequious senses do sometimes seem to give that answer which their master desires, although they have no true warrant for so doing.

Direction of Sound.—We have seen (p. 200) that the determination of the direction in which a sound has come is largely due to the greater intensity of the sound in one ear than in the other owing to the sound waves striking more fully and directly upon one ear than the other. If, however, the source of sound is in a plane passing forward through the middle of the body it is impossible by means of this alone to say whether the sound comes from behind or in front. Judgment as to direction is made more accurate by moving the head so that the sound falls more intensely now on one side now on the other. If the apex of a hollow cone or the ear-piece of an ear-trumpet be inserted into the meatus and the instrument be moved forwards and backwards, the apparent direction of the sound may be largely modified, and we have a similar change if the auricle be flattened out backwards against the side of the head or brought forward with the hand.

In many cases, we judge the sound to come in a certain direction from knowing where it probably originates, as when we hear a bell rung in a steeple with whose position relatively to ourselves we are acquainted. It is easier to judge the direction of noises than of musical sounds, and that mainly because there is a slight difference in the quality of the sounds coming to the two ears, and noises having generally more partial tones than musical sounds, the difference is more easily noted and the judgment as to direction assisted.

Distance of the Source of Sound.—The ear has no direct power of estimating the distance from which a sound comes, since it only becomes cognisant of the sound when it reaches the ear. We can only form a rough estimate from knowing by previous experience that a given sound will presumably have a certain intensity when produced at a certain distance from us, and that, other things being equal, it will diminish to a certain extent the farther it is from the ear. Experimentally, it has been proved that when sound is transmitted through a fairly homogeneous medium, as through air or water, the intensity of the sound varies inversely as the square of the distance. For twice the distance, the intensity will be one-fourth; for three times the distance, one-ninth, and so on. But if we modify the conditions for the transmission of sound, our power of judgment soon fails us. If, for example, when sitting at a table we scratch it gently with the finger-nail, the arm being outstretched, we hear a sound of faint intensity, the distance of which we can estimate fairly well; but if the ear be applied to the table, the sound seems to be made at the ear, its intensity not having been materially diminished by transmission through the wood. Similarly, if the sound is transmitted through tubes, the law of diminution of intensity, according to the square of the distance, does not apply, and we hear people speaking through a long tube, as from top to basement of a house, as if they were close beside us. By gradually diminishing the intensity of a sound, it may be made to seem to come from a considerable distance when really being produced close at hand. Thus, when the operatic chorus leaves the stage, and disappears from view behind the scenes, by singing more and more softly, the performers can convey the impression that they have retired to a great distance. So the art of the ventriloquist lies in his power of speaking with almost no

facial movement, of changing rapidly the strength of his voice so as to give the impression of varying distance, and of conveying by gestures that the sound seems to come from a certain spot, whence he seems to hear it coming, just as we do ourselves. A slight variation in the quality of a sound likewise takes place as it recedes from us, certain partial tones becoming inaudible sooner than others ; this too may help our judgment as to distance.

Memory of Sound.—It is sometimes difficult for us to judge by the power of hearing when a sound has ceased to stimulate the ear. When, for example, a bell has been ringing for some time and then stops, the sound gradually dies away, and it is almost impossible for us to tell the exact moment when it has ceased. It may seem to have died away entirely, and we cease to strain the ear to catch its faint tones, but if we listen again we seem to hear it faintly. This may be due to different causes. It may be that the ear has become fatigued for the special sound, and that the momentary withdrawal of the attention has rested the ear, so that it can respond to tones previously inaudible. On the other hand, it may be due to a vivid form of memory. We cannot doubt that there is some physical change in the auditory centre when the sensation of sound is excited, and when the centre has once acted in a particular way it does so more easily when similar circumstances again arise, or even as the result of a mental effort. Sometimes it may require repeated attempts before we are able to recollect a sound, as, when after hearing a new song, we fail for a day or so to remember the music of it, but gradually note by note, and line by line, it returns, often without conscious effort, until we are able to piece it all together again, more or less correctly, according to acuteness of ear and receptivity for musical impressions.

Mental Receptivity for Sound.—This is a power which

varies much with the state of the mind and the nature of our environment. As a rule, we pay no attention to, and do not consciously hear, such customary sounds as the ticking of a clock, the noise of street traffic, and the like, although they must be constantly acting upon the ear. They, indeed, constitute for us our basis of silence, so to speak, for if the clock should stop, or if we pass to the solitude of the country, we seem to hear the silence which ensues. Again, just as some people are colour blind, so others may be deaf to the pitch of sounds. Some ears are adapted only for sounds of comparatively low pitch, others for high pitch; they are deaf to all others. If we take the lowest limit for pitch at 16 vibrations per second, and the highest at about 40,000, we have in all a range of about 11 octaves. The ear has thus a much wider range for pitch than the eye for colour, for it will be remembered that the lowest red rays of the spectrum have a vibrational frequency of 435 millions of millions per second, while those of the ultra violet are about 764 millions of millions—that is to say, less than twice the number at the lower end of the spectrum, or less than one complete octave.

But the power of distinguishing tones of varying pitch is, with some, so slight that they are quite unable to distinguish one tune from another, and others who can recognise the difference are unable to sing more than one or two notes of different pitch.

Binaural Audition.—Some persons have been found who seemed to have the two ears differently tuned, so that the same sound seemed to be of higher pitch to one ear than to the other. Under normal conditions, although from the position and shape of the ears the sound waves which fall upon the drum-head cannot be *exactly* the same in form nor in time of excitation, yet the resultant sensations in the auditory centre are mentally united, and

we hear one sound, not two. This is mainly to be accounted
for by the fact that the sensation lasts for a short time
after cessation of the stimulus, and the two sounds are so
slightly separate in time as to blend readily with one
another. Inasmuch as the two ears enable us to a cer-
tain extent to judge the distance of the sounding body,
binaural audition is, in a way, comparable to binocular
vision, which assists in the perception of solidity or distance
in space.

THE PHYSIOLOGICAL CONDITIONS OF SENSATION

IN the preceding sections we have given, in the first place, a general view of the mode of action of the nervous system, and then we have described each of the five senses in detail. We have seen that external agents, such as light or sound, act on special terminal organs, and that from these, nervous impulses are carried by the nerves of sense to the central nervous organs. In these central nervous organs molecular changes occur, which are related in some way to conscious states or sensations, and we then refer these sensations to the outer world, and to the agent which we believe to be their primary exciting cause. Further, we know that these sensations may give rise either to voluntary or involuntary movements, and that they may influence many organs of the body, causing, for example, the voluntary movement, the involuntary start, the blush of modesty, or the pallor of fear, the more rapid action of the heart, or the quickening or slowing of respiration. The functions of the central nervous organs and of the organs of sense are so closely related as to make it no easy matter to form a conception of the system working as a whole. The progress of discovery naturally tends to differentiation, and to attaching undue importance to one organ as compared with others, so that we are in danger

of losing sight of the solidarity of the whole nervous system.

During the profound unconsciousness of coma, or of deep sleep, the mind is at rest. There are no thoughts and no interpretation of messages from the sense organs. The higher centres of the brain are inactive, but lower centres, such as those governing the circulatory and respiratory mechanisms, may still be active, the heart continues to beat, and an onlooker sees the movements of respiration. During the waking and conscious state, however, the higher centres are active. They are not only the seat of molecular phenomena related to the conscious state, giving rise to the revivications of memory, the play of ideas, the rise of desires and impulses, and efforts of volition, but they now are momentarily receiving messages from the various sense organs. These messages affect the higher centres themselves, and, through them, lower centres and the body generally. Probably every nervous action, however delicate and evanescent, affects more or less the entire system, and thus, in addition to the impulses coming from the various organs of sense, there may be an undercurrent streaming into and out of the nerve-centres. This undercurrent may never give rise to distinctly conscious states, but, along with numerous interactions in the centres themselves, it contributes to, and partly accounts for, the apparent continuity of conscious experience.

No one doubts that *consciousness* has a material substratum, but the problem of the relation between the mental state and the molecular movements in nervous matter is as far from solution as in the days when little was known of the physiology of the nervous system. Consciousness has been driven step by step upwards until it now takes refuge in a few thousand nerve-cells in a portion of the gray matter in the cortex of the brain, or it may be

in the dense network of fine fibrils that abounds in gray matter. The ancients believed that the body participated in the feelings of the mind, and that the heart, liver, and reins (kidneys) were connected with the emotions, a view quite consistent with the familiar experience that these organs are often influenced by such mental states. As science advanced, consciousness was relegated to the brain, first to the medulla, and lastly to the cortex. But supposing we were able to understand all the phenomena— chemical, physical, physiological—of this intricate ganglionic mechanism, we would be no nearer a solution of the problem of the connection between the objective and subjective aspects of the phenomena. It is no solution to resolve a statement of the phenomena into mental terms or expressions, and to be content with an exclusively idealistic theory of cognition. Nor is it more satisfactory to translate all the phenomena of mind into terms describing physical conditions, as is done by those who support a purely materialistic hypothesis. A philosophy that recognises both sets of phenomena, mutually adjusted and ever interacting, recognises the facts of the case, and does not delude the mind by offering a solution which is in reality no solution at all. The difficulty is somewhat lessened if we assume that behind all physical and mental phenomena there is a metaphysical essence, conscious or unconscious, and that the phenomena we term physical and mental are only different sides of the same thing. Such an essence can never be known to science, and the discussion of the possibility of its existence and of its properties belongs to the province of philosophy.[1]

Apart from the ultimate question, however, there is the important one whether physiologists are right in relegating consciousness entirely to the gray matter of the brain. The

[1] Von Hartmann, *Philosophy of the Unconscious*, especially vol. iii.

facts of comparative physiology are against a view so exclusive, because we cannot deny consciousness to many animals having rudimentary nervous systems, or none at all. As already said, research in anatomy and physiology, and the observation of disease, have obliged physiologists to adopt the view that the brain is the seat of sensation, or, in other words, of consciousness. This is no doubt true in the sense that it receives all those nervous impulses that result in consciousness, but parts acted on by external physical agents (like the retina) and the parts transmitting the nervous impulse (like the optic nerve) are, in a sense, as much concerned in the production of conscious states as the brain itself. This view of the matter was urged by Cleland in 1870,[1] and is consistent with the facts of nervous physiology. It presents fewer difficulties than the one generally held which drives consciousness into the recesses of the nerve-cells in the cortex of the cerebral hemispheres. It keeps clear of the prevailing error in the philosophy of modern physiology, that of regarding the body, and even the nervous system, as a vast collection of almost independent organs, losing sight of community of function and interdependence of parts. At the same time it must be admitted that it approaches no nearer a final solution of the problem of the origin of consciousness ; it only states the conditions of consciousness with greater precision.

Let us now approach the question from another point of view. The simplest structural nervous unit is a **Cell**, which we may call **A**, with a fibre passing to it from a specialised cell, **B**, on the surface of the body, and another fibre passing from it to a contractile cell, **C**. A stimulus applied to **B** causes molecular changes in it, which result in the transmission of an impulse to **A**, in which molecular changes again occur, resulting in the transmission of an

[1] Cleland on *Evolution, Expression, and Sensation*, 1870.

impulse to **C**. This is the simplest form of a so-called reflex mechanism. Suppose the same kind and degree of stimulus be applied to **A** many thousand times in succession, and repeated not only in an individual, but in a line of individuals genealogically connected as parent and offspring, we can imagine that its molecular structure will become so modified that it will gradually become more and more responsive to stimuli of this kind, the simple mechanism having become attuned to the movements of the outer world. Here, then, we have a molecular condition associated with the dawn of consciousness, and the attuned condition of the structure may be regarded as the beginning of memory. No doubt it is impossible here, just as in dealing with a complex brain, to form any conception of the genesis of consciousness. It evidently cannot be the result, in any physical sense, of the molecular changes in the cell, because even although we were cognisant of all the molecular changes we could not detect a conscious state. So far as an outsider is concerned, the conscious state of the cell can only be recognised by some outward manifestation in the form of movement, and it is conceivable that the cell might be conscious, and yet not make any movement. Suppose a, b, c, d, e, etc., to represent links in the chain of physical phenomena between the irritation of the cell **B** and the movement of **C**, and that consciousness is an attribute of **A**, which we may denominate x, it will be impossible to find a place for x in the chain, in the same sense as the movement of **C** is the last link of the chain. It cannot come in between a and b, as a is the physical antecedent of b, nor, for a similar reason, between b and c, nor between c and d, d and e, etc. The condition x is therefore outside the physical chain ; and yet it is related to it so intimately as to lead to the illusion that x forms one of the links. This appears to prove that consciousness, x, is outside

any chain of related physical phenomena conceivable in the simplest nervous mechanism.

Nor do we get any farther towards clearing up the mystery if we suppose, as some have done, that even dead matter has in some way associated with it units of consciousness,[1] because it is equally impossible in this case to understand the nexus between the material particles and consciousness. The condition of the conscious state may therefore be represented by two parallel curves infinitely close together, the one representing the chain of physical phenomena, linked together as cause and effect, and the other the chain of conscious states. Any variation in the one coincides with a variation in the other, but no explanation can be given as to how the one influences the other. To assert that one is the cause of the other is simply to beg the question. If we say that the chain of physical phenomena is the cause of the conscious states, in the same sense as the physical phenomena in a cell of the liver is the cause of the secretion of bile, we introduce into the chain an immaterial something, and break the physical continuity of the various links ; and, on the other hand, if we try to escape the difficulty by translating the physical links themselves into states of consciousness, and deny any knowledge of the physical substratum, we are deceived by words and reach no solution.

Again, to regard consciousness as a *mode of energy* is unsatisfactory. Energy, in the physical sense, is nothing more than the power any material system has of doing work, owing to the relative position of its component parts. If the relative position of these parts be altered, the distribution of energy in the system will also be altered. It follows from this that energy may be manifested by various kinds of movements—heat, light, gravitation, etc.—and

[1] W. K. Clifford, *Lectures and Essays*, vol. ii. p. 31.

one form of energy may be resolved into another. But when motion produces heat, there is a quantitative conversion of energy from motion to heat, which is, in turn, another mode of motion. If we now assume molecular changes to be the cause of consciousness, these molecular changes also produce heat, molecular movements associated with chemical action, and perhaps movements on a larger scale; but the sum of these resultant forms of energy is equal to the energy at first existent in the physical system, which we assume to be also the seat of consciousness. Consequently consciousness does not come into the dynamical chain. It cannot be measured; it cannot be derived from the physical energies, nor can it be resolved into them. It is outside the chain. Movements of matter, therefore, cannot be resolved into consciousness, or, in other words, consciousness is not a form of energy.

We are thus face to face with an insoluble problem, even when we discuss it in its simplest form, and it becomes infinitely more complicated when we consider the manifold phases of consciousness connected with the mechanism of the brain. If, however, we begin with the structural unit of a simple reflex mechanism, along with its associated conscious state, we find that the complex functions of the fully-developed brain are aggregations of the simple mechanism we have considered, and that what we term consciousness is a condition which is the sum of the conscious states of the individual nerve cells, or aggregations of nervous matter, constituting the brain. We can form no conception of the nature of the consciousness of a nerve cell any more than we can of the consciousness of a sea-anemone or of a worm; but we must assume the existence of consciousness in a nerve cell, otherwise it is impossible to understand how consciousness is associated with an aggregation of such cells in a brain. To deny

consciousness to such a cell would be equivalent to deny-ing consciousness to the brain, which would be absurd. Whilst, therefore, we give up the explanation of the genesis of consciousness as an insoluble problem, it is possible to gain some insight into the general mode of action of brain as the recipient of sensory impressions.

Suppose, for example, we irritate the skin of the sole of the foot, an impulse is carried by nerves to cells in the posterior horns of gray matter in the spinal cord (see Fig. 7, p. 16), in which molecular processes are excited. From these, impulses are carried by fibres in the cord to cells in the anterior horn; in which, again, molecular processes occur, resulting in the transmission of nervous impulses along motor nerves to the muscles of the limb, and the limb will be drawn away by a sudden contraction of the muscles. This is a reflex movement, not in obedience to a volitional impulse, not associated with consciousness in the usual sense of the term (as implying activity of the brain), but, from the arguments already led, we may assume that these molecular changes in the cells of the cord are associated with a lower mode of consciousness, such as presumably exists in animals having a nervous system of this simple type. But the cells in the gray matter of the cord are connected with cells in the masses of gray matter in the upper centres, and, in particular, we have reason to believe that each unit area of sensitive surface of the body has a corresponding unit area in the cerebral cortex, that is to say, from each unit area (the size of which varies much in the different sense organs, from a minute area of retina to a much larger area of skin surface) nerve filaments pass which carry impressions to a corresponding unit area in the cortex (see remarks on the tactile field, p. 60, and on the visual field, p. 30 and p. 176). This does not mean that individual nerve fibres necessarily pass from unit area of sensory

surface to unit area of cortex, but that impressions are so related. If so, the irritation of the skin of the foot, in the experiment we are considering, may cause impressions to pass, not merely to the cord, but also to the higher centres in the brain, and the result may be a feeling of pain. This may be also explained by supposing that the *reflex* centre in the cord is intimately connected by fibres with the *conscious* centres in the cortex, a supposition strongly supported by the increasing mass of evidence as to the paths of transmission between the cord and the brain. The sensation of pain must be associated with molecular changes in the cells of the cortex, and, as a rule, these changes cause, by a kind of irradiation, the transmission of impulses outwards to other nerve centres, which in turn call forth various more or less complicated movements. Thus, for example, they may be carried to the cells in the gray matter of the medulla, which is the origin of the nerves governing the movements involved in crying, in the expression of pain by the muscles of the face, or they may reach the cells in the gray matter of the cord, calling forth the movements of the limb requisite for drawing the limb away from the irritation, or for defending it from further attack. Again, the irritation may call forth involuntary exclamations, in the form of words, expressive of pain, and in this case the centre for articulate speech has been involved. Impressions may also be carried from the sensory centre in the cortex to the parts of the brain concerned in volition, and the reflex and involuntary movements we have considered will be added to, or supplanted by, direct voluntary movements. Even voluntary movements, however, are essentially reflex in character, inasmuch as they are called forth by stimulations which have been applied to a sensory surface either immediately before the voluntary act, or which have been applied, it may be, long before.

In the latter case, the effects of the stimulation still remain in certain groups of nerve cells, as a kind of *memory*, so that when they are roused into activity, the voluntary act will follow, as it probably did on the first occasion when the stimulus was applied. Finally, the irritating body may be *seen*, and the effects of the image formed optically on the retina are carried by the optic nerve to the *corpora quadrigemina*, and from these to the visual centres in the cortex. Again, a *memory* of this impression may remain, and may be called into action by nervous influences coming from other parts of the brain, so that a *vision* of the irritating body may afterwards arise into consciousness, so vividly as to call forth movements similar in character, although, probably, not so intense, as those which occurred in the first instance. This revivication of old impressions is most likely to occur when the upper centres are somewhat in abeyance, as in the phenomena of hypnotism and somnambulism.

Sensory impressions, however, are not only carried to the cerebral cortex, there awakening consciousness, but they are also conveyed, and many of them in the first instance, to the cerebellum, and in this organ they set in action the physiological mechanism that results in *co-ordinated* movements. It is not improbable that the sensory areas of the body have corresponding areas in the gray matter on the surface of the cerebellar convolutions. Thus the cerebellum is the organ that gives a rhythmic character to certain movements of the body, as those of walking, flying, swimming, etc., and probably it is only when these movements become associated with sensation, or are voluntary, that the centres in the cerebral cortex come into play.

Again, if an external object acts at the same time on different organs of sense, as when we hold a rose in the

hand, admire its colour, and enjoy its delicious perfume, the various sensations thus related to molecular movements in different parts of the cortex are combined by the action of the numerous fibres passing from centre to centre, and the result is a conscious perception of the thing as a whole. These fibres may be called *fibres of association*, because they combine impressions that have reached various sensory cortical centres. It is evident that such a combination of impressions may also give rise to various movements of the limb, or of the muscles of expression, and that the impressions will be more or less vivid as the exciting causes are strong or weak. If they are vivid, or, in other words, if the molecular changes in the nerve cells of particular parts of the cortex of the brain are intense, they will have both a tendency to last after the exciting cause has been removed, and a tendency to be renewed by a slighter stimulus than was at first necessary to produce them. This is the physiological, or organic, foundation for *memory*, and also for the mental process known as the *association of ideas*. Further, if such molecular processes, by frequent repetition, stamp a certain character on particular parts of the cerebral cortex, so as to be transmitted according to the laws of heredity, then we have a physiological basis for innate tendencies or *intuitions*. The brain of one man differs from another in this respect. The greater the number and variety of impressions made on an individual, the greater will be the number and variety of the molecular movements in the cells of the cortex, and the greater the number and variety of resulting mental and reflex phenomena. So intense may these processes be that they may be called into action by a stimulus from another part of the brain, as when irritation of the *corpora quadrigemina* by Indian hemp awakens in the cells of the visual centres of the cortex those changes which are associated in the mind
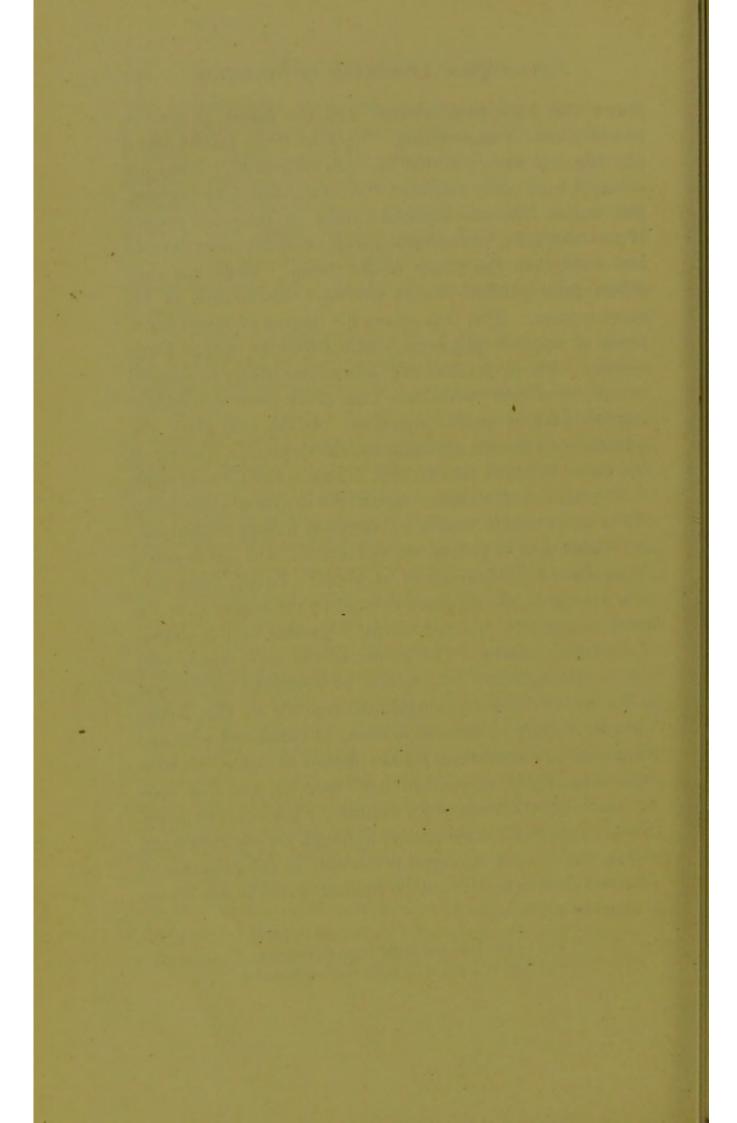
with long-forgotten visual impressions, and the person sees passing before him a phantasmagoria of brilliantly-coloured images. These may also arise spontaneously, but the apparent spontaneity, however, is dependent on a stimulus so feeble as to escape notice, as when the sight of an object suddenly and almost unconsciously awakens memories of past events, and brings before the mind's eye forms and colours that long before produced impressions on the organs of sense.

Many nervous phenomena are at first in a sense voluntary, and by and by they become more and more of a reflex character, and are less and less associated with the higher consciousness. Thus a child acquires powers of walking by repeated efforts involving volition, judgment, and perception of different impressions, but the same movements of locomotion may be unconsciously performed by an adult. Familiar examples also are seen in the unconscious dexterity of movement of a skilful performer on a musical instrument, or in the deft movements of a cunning artificer. So is it even with psychical operations involving the action of the brain, and the brain cortex may, as in *unconscious cerebration*, pass through molecular processes which result in the unconscious performance of actions that would be regarded as the result of mental processes, if the person were conscious. Many instinctive actions are probably in this sense of an unconscious character. There can be no doubt that even in men the brain may work unconsciously, and the product may suddenly start out into consciousness.

Facility of mental acquirement means a certain *receptiveness* for particular kinds of molecular action. Other personal factors come into operation, such as the *power of choice* of particular impressions, the *degree of attention* paid to them at the time (depending largely on strength of will), the *degree of stability* of the results of the molecular move-

ments that have been excited, and the *power of associa-tion* of different impressions. Each of these factors has a physiological basis peculiar to each individual. They are susceptible of being extended and strengthened by exercise, and just as muscular exercise causes an increased growth of muscular fibre, so regulated mental exercise must develop and strengthen the tissue of the brain. Thus one man differs from another in the primitive constitution of his nerve centres. This determines his degree of intelligence, power of accurate judgment, and aptitude for special kinds of work. These qualities are determined chiefly by *inherit-ance from ancestors* who have thus given their descendant a groundwork of mental character. In the next place, the influence of a man's environment develops to a greater or less extent this and that faculty. This is the rational basis of all educative processes. Again, the degree of excitability of the nerve centres varies considerably among individuals, and it also may be influenced by exercise. On this depends the *aptitude* for reflex acts of all kinds. Lastly, there may be a greater or less influence exerted by the higher over the lower centres, or, in other words, a greater or less degree of inhibitory power. The power of the *will*, which may also be strengthened by exercise, or weakened by yielding to disease, or by tame compliance, depends on this factor. Thus by a study of nervous actions, as connected with and stimulated by impressions on the organs of sense, we have constructed a *physiological basis of character*, and that with-out admitting the truth of an exclusively materialistic hypo-thesis. Behind all brain action, although closely connected with it, there is the strongest probability of the existence of an immaterial agent of which Spenser wrote in his *Hymn in Honour of Beauty :*

" For of the soul the body form doth take,
For soul is form, and doth the body make."

APPENDIX I

THE ACTION OF LIGHT ON THE RETINA

AT p. 150 reference is made to the electrical change that occurs when light falls on the living retina. A full description of this remarkable phenomenon was out of place at that part of the book, but inasmuch as it is the only example we have of a known physical process occurring in a terminal organ of sense, it merits here a further notice. For the detection of electrical currents in living tissues a sensitive galvanometer of high resistance must be employed. The currents are led off the living tissues by electrodes that are so constructed as to be unpolarisable—that is to say, they do not themselves generate any current, nor are they altered by the passage of even a feeble current through them, so as to give rise to any electrical action. They simply lead off to the galvanometer any current that may exist. Such electrodes are variously constructed ; but a convenient form is a trough of zinc, resting on insulating plates of vulcanite, amalgamated on the inner surface, and filled with a saturated solution of sulphate of zinc. A pad of blotting-paper, wet with the sulphate of zinc solution, is placed into each trough, and on the pad a bit of clay, moistened with saliva, is laid, so as to protect any animal tissues placed on the clay from the irritant action of the sulphate of zinc. The electrodes, so prepared, are connected with the galvanometer. A frog's eye is dissected out (after the animal has been decapitated, and all sensation has been lost), and is so placed on the pads of clay that one pad touches the middle of the surface of the cornea, and the other the posterior surface of the eyeball and the transverse section of the optic nerve. A current, which we may call the "resting-eye current," is shown by a deflection of the needle of the galvanometer. It can be shown that this current

passes from the corneal surface through the galvanometer and back to the posterior surface of the eyeball—that is to say, the eyeball acts like a little galvanic element, the positive pole of which is the cornea and the negative pole the transverse section of the optic nerve. The eye is now covered with a blackened box so as to keep it in the dark, and the box is provided with a shutter by which the light may be shut off or admitted at pleasure. When we open the shutter, and allow light to fall upon the eye, the needle of the galvanometer will be seen to swing in the direction that indicates an increase in the current. If light is allowed to act on the eye for a few minutes, the current diminishes, falls off in strength as the retina becomes fatigued, and soon becomes less than it was when light was allowed to fall on the eye. If the light is allowed to act sufficiently long, the current becomes less and less until it reaches zero. If, however, we remove the light by closing the shutter before the retina has become too fatigued, there is at once a second increase in the strength of the current again indicated by a swing of the galvanometer needle, then a rapid diminution, and soon the needle becomes almost stationary. These are the details of a single experiment ; and they show that light alters the electrical condition of the eye, the impact of light causing an increase, its continued action a diminution, and its removal another increase in the "resting-eye current."

It can be shown that the effect is due to the action of light on the *retina*, because if this structure be removed, light will produce no variation in any current that may be got from other structures. The effect is due to *light* and not to heat, because it is easy to absorb the heat rays, and still allow the light to pass, and *vice versâ*. In both cases it is only when light rays reach the retina that the effect is obtained. These variations have been seen in the eyes of invertebrates and vertebrates, and even in the eye of man himself. Further, by allowing the different rays of the spectrum to fall on the eye, we can show that the luminous yellow rays produce more effect than the less luminous green, red, blue, or violet rays, and that the sum of the effects of the different rays is almost that of white light. It can also be demonstrated that the effects of varying intensities of light agree with the laws formulating the relation between the strength of the stimulus and the strength of the resulting sensation referred to on p. 39. The importance of this observation is due to the indication it gives that the stimulus-sensation-ratio may be a function of the terminal organ as well as of the brain.

The electrical variations above described may be physical indications of chemical phenomena known to occur in the retina. This, however, has not been proved. It is conceivable, as an alternative hypothesis, that the rods and cones act as transforming structures, changing the waves of light into electrical variations that pass along the fibres of the optic nerve. Electrical variations are the only phenomena that have yet been demonstrated in a nerve fibre during the passage along it of a nervous impulse ; and if, as the physicists assert, light waves are only short electrical waves, the hypothesis suggested is not unreasonable.

These electrical changes in the retina, caused by the action of light, were independently discovered by Holmgren in Upsala, and by Dewar and M'Kendrick in Edinburgh, between 1870 and 1873.[1]

[1] Dewar and M'Kendrick, *Proceedings of Royal Society of Edinburgh*, 1874. Also M'Kendrick's *Text-Book of Physiology*, vol. ii. p. 627.

APPENDIX II

DERIVATIONS OF SCIENTIFIC TERMS

ABERRATION, L. *ab*, away ; *erro, erratum*, to wander
Actinic, Gr. *aktis*, a sunbeam
Acustica, Gr. *akouo*, to hear
Æsthesiometer, Gr. *æsthesis*, feeling ; *metron*, a measure
Afferent, L. *ad*, to ; *fero*, I carry
Alkaloid, Arab. *alkali* ; Gr. *eidos*, likeness
Allotropic, Gr. *allotropos*, of a different nature
Ametropia, Gr. *a*, not ; *metron*, measure ; *ops*, the eye
Amplitude, L. *amplitudo*, largeness
Ampulla, L. *ampulla*, a bottle
Anæsthesia, Gr. *a*, without ; *æsthesis*, perception
Analgesia, Gr. *a*, without ; *algos*, pain
Anode, Gr. *ana*, up ; *hodos*, a way
Anosmia, Gr. *a*, without ; *osme*, smell
Aqueous, L. *aqua*, water
Arborescent, L. *arboresco*, to become a tree
Astigmatism, Gr. *a*, without ; *stigma*, a point
Ataxia, Gr. *a*, without ; *taxis*, arrangement
Auditory, L. *audio, auditum*, to hear
Aura, Gr. *ao*, to breathe
Auricle, L. *auriculus*, dim. of *auris*, an ear
Automatic, Gr. *automatos*, of one's own accord

BASSOON, Gr. *basis*, base ; a wind instrument giving a low note
Biconvex, L. *bis*, twice ; *con*, together ; *veho, vectum*, to carry
Binary, L. *bina*, a pair

Binaural, L. *bis*, twice ; *audio*, I hear
Binocular, L. *bis*, twice ; *oculus*, the eye

CALLOSUM, L. *callosus*, thick-skinned
Camera, L. *camera*, a chamber
Capillary, L. *capillus*, a hair
Cardinal, L. *cardo*, a hinge
Cataract, Gr. *kata*, down ; *arasso*, to fall
Cerebellum, L. *cerebellum*, dim. of *cerebrum*, the little brain
Cerebrum, L. *cerebrum*, the brain
Cerumen, L. *cera*, wax
Choroid, Gr. *chorion*, skin ; *eidos*, likeness
Chromatic, Gr. *chroma*, colour
Ciliary, L. *cilium*, an eyelash
Cilium (*pl.* cilia), L. *cilium*, an eyelash
Circumvallate, L. *circum*, around ; *vallum*, a wall
Cochlea, Gr. *kochlias*, a snail with a shell
Coma, Gr. *koma*, drowsiness
Commissure, L. *com*, together ; *mitto, missum*, to send
Complementary, L. *com*, together ; *pleo*, to fill
Congenital, L. *congenitus*, born together with
Conjugate, L. *con*, together ; *jugum*, a yoke
Conjunctiva, L. *con*, together ; *jungo, junctum*, to join
Consciousness, L. *con*, together ; *scio*, I know
Convergence, L. *con*, together ; *vergo*, to bend
Convolution, L. *convolvo, convolutum*, to roll
Corium, Gr. *chorion*, skin
Cornea, L. *cornu*, a horn
Corona, L. *corona*, a crown
Corpus (*pl.* corpora), L. *corpus*, a body
Corpuscle, L. *corpusculus*, dim. of *corpus*, a body
Cortex, L. *cortex*, bark
Cranium, Gr. *kranion*, the skull
Cribriform, L. *cribrum*, a sieve ; *forma*, likeness
Crista, L. *crista*, a crest
Cuneus, L. *cuneus*, a wedge
Cupula, L. *cupula*, a small cup

DALTONISM, Dalton, a celebrated chemist who was colour-blind
Decussation, L. *decusso*, to place crosswise in the form of an X
Dental, L. *dens, dentis*, a tooth

Derma, Gr. *derma*, the skin
Diabetes, Gr. *dia*, through ; *baino*, to go
Diaphragm, Gr. *dia*, across ; *phrasso*, to fence
Dioptrics, Gr. *di*, through ; *horao*, I see
Dispersion, L. *dis*, asunder ; *spargo*, to scatter
Dissonance, L. *dis*, asunder ; *sonans*, sounding
Dynamical, Gr. *dynamis*, power

EFFERENT, L. *ex*, out ; *fero*, I carry
Electrode, Gr. *elektron*, amber ; *hodos*, a way
Electrolysis, Gr. *elektron*, amber ; *lysis*, a softening
Emmetropic, Gr. *en*, in ; *metron*, measure ; *ops*, the eye
Endolymph, Gr. *endon*, within ; *lympha*, water
Entoptic, Gr. *entos*, within ; *ops*, the eye
Epidermis, Gr. *epi*, upon ; *derma*, skin
Epiglottis, Gr. *epi*, upon ; *glotta*, a tongue
Erectile, L. *e*, out ; *recto*, to make straight
Ether, Gr. *aither*, the upper air
Ethmoid, Gr. *ethmos*, a sieve ; *eidos*, likeness

FAUCES, L. *fauces*, the gullet
Fenestra, L. *fenestra*, a window
Fibril, L. *fibra*, a filament
Filament, L. *filum*, a thread
Filiform, L. *filum*, a thread ; *forma*, form
Fluorescence, L. *fluo*, I flow
Focus, L. *focus*, a fireplace
Foliata, L. *folium*, a leaf
Follicle, L. *folliculus*, dim. of *follis*, a wind ball or bag
Foramina, L. *foro*, to bore
Formication, L. *formica*, an ant
Fornicatus, L. *fornicatus*, arched
Fovea, L. *fovea*, a small pit
Function, L. *fungor*, *functum*, to discharge an office
Fundus, L. *fundus*, the bottom
Fungiform, L. *fungus*, a mushroom ; *forma*, form
Fuscin, L. *fuscus*, tawny

GALVANOMETER, Galvani, the discoverer of certain electrical pheno-
     mena ; *metron*, a measure
Ganglion (*pl.* ganglia), Gr. *ganglion*, a tumour under the skin
Glosso-pharyngeal, Gr. *glossa*, the tongue ; *pharynx*, the throat

Gustatory, L. *gustatus*, tasted
Gyri, Gr. *gyros*, a circuit

HÆMORRHAGE, Gr. *haima*, blood ; *rheo*, to flow
Hamulus, L. dim. of *hamus*, a hook
Helicotrema, Gr. *helix*, a spiral ; *trema*, a perforation
Hemianæsthesia, Gr. *hemi*, half ; *a*, without ; *æsthesis*, feeling
Heteronomous, Gr. *heteros*, another ; *onoma*, a name
Hippocampus, Gr. *hippos*, a horse ; *kampos*, a sea-monster
Homologous, Gr. *homos*, the same ; *logos*, a discourse
Homonomous, Gr. *homos*, the same ; *onoma*, a name
Horopter, Gr. *horos*, a boundary ; *opter*, a spectator
Hyaloid, Gr. *hyalos*, glass ; *eidos*, a likeness
Hypermetropia, Gr. *hyper*, beyond ; *metron*, measure ; *ops*, the
      eye
Hypnotism, Gr. *hypnos*, sleep
Hypoglossal, Gr. *hypo*, under ; *glossa*, the tongue
Hypometropia, Gr. *hypo*, under ; *metron*, measure ; *ops*, the eye

ILLUSION, L. *in*, in ; *ludo, lusum*, to play
Incus, L. *incus*, an anvil
Index, L. *in*, in ; *dico*, to proclaim
Internuncial, L. *inter*, between ; *nuntius*, a messenger
Intuition, L. *intus*, within ; *itum*, to go
Iris, Gr. *iris*, the rainbow

JAUNDICE, Fr. *jaune*, yellow

KATHODE, Gr. *kata*, down ; *hodos*, a way
Klang, Ger. *klang*, the quality of a sound

LABYRINTH, Gr. *labyrinthos*, a labyrinth
Lachrymal, L. *lachryma*, a tear
Lamella, L. *lamella*, dim. of *lamina*, a small plate
Lamina, L. *lamina*, a small plate
Laxator, L. *laxo*, to loosen
Lens, L. *lens*, a lentil
Lenticular, L. dim. of *lens*, a small bean
Limbus, L. *limbus*, a border
Lingual, L. *lingua*, a tongue
Logarithm, Gr. *logos*, ratio ; *arithmos*, number

Lumen, L. *lumen*, light
Luminosity, L. *lumen*, light

MACERATE, L. *macero*, to waste away
Macula, L. *macula*, a spot
Malleus, L. *malleus*, a hammer
Mastoid, Gr. *mastos*, the breast
Meatus, L. *meo*, *meatum*, to pass
Medulla, L. *medulla*, the marrow ; *medius*, the middle
Melanin, Gr. *melan*, black
Meridional, L. *meridies*, midday
Mesentery, Gr. *mesos*, middle ; *enteros*, intestines
Minimum visibile, L. *minimum*, the least ; *visibile*, able to be
    seen
Modiolus, L. dim. of *modus*, a measure
Molecular, L. dim. of *moles*, a mass
Momentum, L. *moveo*, to move
Morphological, Gr. *morphe*, form ; *logos*, a discourse
Motor, L. *moveo*, *motum*, to move
Mucus, Gr. *muxa*, the mucus of the nostrils
Muscæ volitantes, L. *musca*, a fly ; *volitans*, flying
Myopia, Gr. *muo*, to close ; *ops*, the eye

NARES, L. *nares*, the nostrils
Neurilemma, Gr. *neuron*, a nerve ; *lemma*, a coat
Neuro-epithelium, Gr. *neuron*, a nerve ; *epi*, upon ; *tithemi*, to
    place
Neuroglia, Gr. *neuron*, a nerve ; *glia*, glue
Nexus, L. *necto*, to twine
Nodal, L. *nodus*, a knot
Nucleus, L. *nucleus*, the kernel

OCCIPITAL, L. *ob*, against ; *caput*, the head
Odoroscope, L. *odor*, odour ; Gr. *skopeo*, I see
Olfactory, L. *olfacio*, to smell
Operti, L. *opertus*, opened
Ophthalmic, Gr. *ophthalmos*, the eye
Ophthalmoscope, Gr. *ophthalmos*, the eye ; *skopeo*, I see
Orbit, L. *orbita*, an orbit
Organ, Gr. *organon*, an instrument
Organism, Gr. *organon*, an instrument

Ossicle, L. dim. of *os*, a bone
Otoconia, Gr. *ous*, *otos*, the ear ; *konis*, dust
Otolith, Gr. *ous*, *otos*, the ear ; *lithos*, a stone
Ozone, Gr. *ozo*, to smell

Pancreas, Gr. *pan*, all ; *kreas*, flesh
Papilla, L. *papilla*, a nipple
Parietal, L. *paries*, a wall
Pari passu, L. *par*, equal ; *passus*, step
Pathological, Gr. *pathos*, suffering ; *logos*, a discourse
Peduncle, L. *pedo*, having broad feet
Pellicle, L. *pellicula*, dim. of *pellis*, a skin
Period, Gr. *periodos*, a going round
Peripheral, Gr. *periphereia*, a periphery
Peritoneum, Gr. *peritonaios*, stretched over
Petrous, Gr. *petra*, a rock
Phakoscope, Gr. *phakos*, a lentil, the lens ; *skopeo*, I see
Phalangæ, Gr. *phalanx*, a block
Phantasmagoria, Gr. *phantazo*, to make appear ; *agora*, an assembly
Pharynx, Gr. *pharynx*, the throat
Phase, Gr. *phasis*, *phaino*, to show
Phenomenon, Gr. *phainomenon*, appearing
Photometrical, Gr. *phos*, light ; *metron*, a measure
Physharmonica, Gr. *physao*, to blow ; *harmonikos*, musical
Pigment, L. *pingo*, to paint
Pitch, A.S. *pycan*, to pick or strike with a pike
Pituita, L. *pituita*, phlegm
Plane, L. *planus*, smooth
Plexus, L. *plexus*, a network
Pons, L. *pons*, a bridge
Præcuneus, L. *præ*, before ; *cuneus*, a wedge
Presbyopia, Gr. *presbys*, old ; *ops*, the eye
Prism, Gr. *prisma*, from *prio*, to saw
Protoplasm, Gr. *protos*, first ; *plasma*, anything formed
Pseudoscope, Gr. *pseudos*, false ; *skopeo*, I see
Psychical, Gr. *psyche*, the soul
Pupil, L. *pupilla*, dim. of *pupa*, a puppet

QUADRIGEMINA, L. *quatuor*, four ; *gemini*, double
Quantum, L. *quantum*, how much

RECTUS, L. *rectus,* straight
Refraction, L. *re,* back ; *frango, fractum,* to break
Refrangible, L. *re,* back ; *frango,* to break
Resonator, L. *re,* again ; *sono,* to sound
Reticulated, L. *rete,* a net
Retina, L. *rete,* a net

SACCHARINE, L. *saccharum,* sugar
Saccule, L. dim. of *saccus,* a bag
Schematic, Gr. *schema,* form
Sclerotic, Gr. *skleros,* hard
Sebaceous, L. *sebum,* suet
Section, L. *seco, sectum,* to cut
Segment, L. *seco,* to cut
Sensorium, L. *sentio, sensum,* to feel
Septum, L. *sepes,* a hedge
Serous, L. *serum,* a watery fluid
Sine, L. *sinus,* a curve
Spectrum, L. *specio,* I see
Sphenoid, Gr. *sphen,* a wedge ; *eidos,* likeness
Sphincter, Gr. *sphingo,* I contract
Squamous, L. *squama,* the scale of a fish
Stapes, L. *stapes,* a stirrup
Stereoscope, Gr. *stereos,* solid ; *skopeo,* I see
Stimulus, L. *stimulus,* a goad
Striata, L. *striatum,* grooved
Stylet, Gr. *stylos,* a style or pencil
Sulcus, L. *sulcus,* a groove
Synchronous, Gr. *syn,* together ; *chronos,* time
Syren, L. *siren,* a singer of sweet music

TAPETUM, Gr. *tapes,* tapestry
Telestereoscope, Gr. *tele,* at a distance ; *stereos,* solid ; *skopeo,* I see
Temporo-sphenoidal, L. *tempora,* the temples ; Gr. *sphen,* a wedge ; *eidos,* likeness
Thalamus, Gr. *thalamos,* a couch
Thaumatrope, Gr. *thauma,* wonder ; *tropos,* a turning
Timbre, Fr. *timbre,* the sound of a bell, the voice
Translucent, L. *trans,* through ; *luceo,* to shine
Triturate, L. *tritus,* rubbed

Turbinated, L. *turbinatus*, pointed
Tympanum, Gr. *tympanon*, a drum

UMBO, L. *umbo*, the boss of a shield
Uncinate, L. *uncus*, a hook
Undulatory, L. *unda*, a wave
Utricle, L. dim. of *uter*, a leathern bag
Uvula, L. dim. of *uva*, a grape

VAS, L. *vas*, a vessel
Vertebrate, L. *verto*, I turn
Vestibule, L. *vestibulum*, a threshold
Vibration, L. *vibro*, to quiver
Vibrissæ, L. *vibro*, to quiver
Vidian, after Vidius, who described the Vidian nerve
Viscera, L. *viscera*, the bowels
Vitreous, L. *vitrum*, glass
Volatility, L. *volo*, *volatum*, to fly
Vorticosa, L. *verto*, to turn

ZERO, Arab. *tsaphara*, empty
Zonule, L. dim. of *zona*, a belt

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THE END

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