[NOVEMBER, 1908.]

BRAIN.

PART III., 1908.

Original Articles and Clinical Cases.

A HUMAN EXPERIMENT IN NERVE DIVISION.

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Chapter I.—History of the Case.

It had long been recognized that the consequences of injury to a peripheral nerve could not be adequately explained on any accepted theory of its structure and function. In 1901, Dr. Head and Mr. Sherren therefore determined to make a systematic examination of the patients attending the London Hospital for some nerve injury. The hospital patient is frequently an admirable subject for sensory experiments; at his best he answers "Yes" and "No" with certainty, and is commendably steady under the fatigue of control experiments. Moreover, the number of patients, who come to the London Hospital for such injuries, is so large that it is possible to eliminate entirely those who are found to be untrustworthy in consequence of misuse of alcohol or other causes.

Most of the main facts of nerve distribution and recovery of sensation can be elicited from a study of hospital patients by means of simple tests requiring no undue expenditure of time. But such patients can tell little or nothing of the nature of their sensations, and the time they are able, or willing, to give is insufficient for elaborate psycho-physical testing.

It soon became obvious that many observed facts would remain inexplicable without experimentation carried out more carefully and for a longer period than was possible with a patient, however willing, whose ultimate object in submitting himself to observation is the cure of his disease. For instance, an examination of the part played by heat- and cold-spots in the return of sensation was impossible under clinical conditions.

It is also unwise to demand any but the simplest introspection from patients, to whatever class they may belong. This side of the investigation was, therefore, almost entirely closed to Mr. Sherren and Dr. Head. From the early days of their research, Dr. Rivers had acted as their guide and counsellor. His interest lay rather in the psycho-physical aspect of the work, and he was impressed with the insecurity of this side of the investigation. Introspection could be made fruitful by the personal experiences of a trained observer only.

Lastly, we were anxious to investigate the functions of deep sensibility. Sherrington [25] had shown that muscular nerves contained a large number of afferent fibres. From the beginning of their research, Head and Sherren [17] had tried to determine the sensibility remaining after complete division of all cutaneous nerves without injury to the muscular branches. But accidental injuries of this kind are excessively

rare, and they were compelled to attack the problem by indirect and less satisfactory methods. As soon, therefore, as it was determined to make an experimental division of peripheral nerves, means were taken to ensure that the nature of these deep afferent fibres should come clearly to experimental investigation.

At the time of the experiment, H. was nearly 42 years of age and in perfect health. Since boyhood he had suffered from no illnesses, excepting as the consequence of wounds in the *post-mortem* room. None of these had attacked his left arm or hand, which were entirely free from scars or other deformities.

For two years before these experiments began he had given up smoking entirely. No alcohol was ever taken on the days during which he was under examination, and for some years he had abstained from alcohol except on holidays.

On April 25, 1903, the following operation was performed by Mr. Dean,[1] assisted by Mr. Sherren.

An incision 6½ in. (16·5 cm.) long was made in the outer bicipital fossa extending along the axial line of the left upper extremity; this wound was almost exactly bisected by the fold of the elbow. After turning back the skin, the supinator longus was hooked outwards, and the radial nerve (ramus superficialis nervi radialis) was divided at the point where it arises from the musculo-spiral (N. radialis). A small portion was excised, and the ends united with two fine silk sutures. The external cutaneous nerve (N. cutaneus antibrachii lateralis) was also divided where it perforates the fascia, above the point where its two branches are given off to supply the anterior and posterior aspects of the pre-axial half of the forearm. The nerve was sutured with fine silk, and the wound was closed with silk sutures, without drainage. The limb was put up on a splint with the forearm flexed at the elbow, and the whole hand was left free for testing. The wound healed by first intention.

The following morning (April 26, 1903), the radial half of the back of the hand and dorsal surface of the thumb were found to be insensitive to stimulation with cotton wool, to pricking with a pin, and to all degrees of heat and cold. Around the base of the index and middle fingers was a small area insensitive to stimulation with cotton wool and von Frey's hairs, where a response was obtained to the prick of a pin. No sensation was evoked by any manipulation of the hairs within the affected parts on the back of the hand.

[1] To Mr. Dean our best thanks are due, not only for the exactitude with which he carried out our wishes, but also for his kindness in receiving Dr. Head into his house for the operation.

The area insensitive to cotton wool extended slightly further towards the ulnar aspect of the back of the hand than that of the cutaneous analgesia. Between the two lay a narrow zone, where a painful cutaneous stimulus produced a more unpleasant sensation than over the normal skin.

The most striking fact, however, was the maintenance of deep sensibility over the whole of the affected parts on the back of the hand. Pressure with the finger, with a pencil, or any blunt object was immediately appreciated. All those stimuli commonly used by the clinician

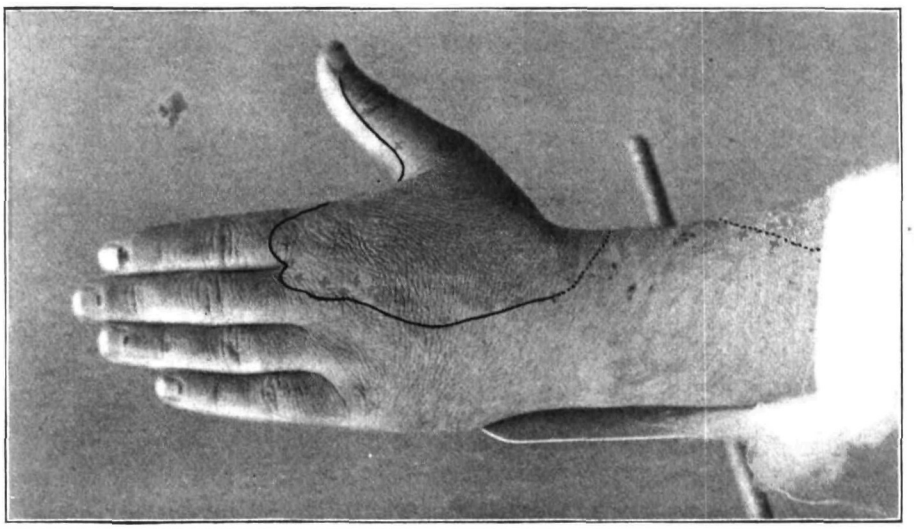


FIG. 1.

To show the extent of the loss of sensation produced by the operation.
The anæsthesia to cotton wool and to von Frey's hairs is bounded by the black line. The analgesia to prick and other cutaneous painful stimuli lay within the red crosses.
The darkness of the affected area is due to its deep red colour compared with the rest of the hand.

to test the presence of "touch" were appreciated and well localized. Mr. Dean, who was not familiar with our previous observations, said he should have thought that sensation of touch was intact, had he not known the nerves had been divided.

On May 4, nine days after the operation, the hand was exposed to a long series of experiments. The most striking features of this examination were :—

(*a*) That very moderate pressure on the abnormal area of the skin was appreciated and could be well localized, whilst touches with cotton

wool, or deformations of the skin, produced by drawing the hair outwards, caused absolutely no sensation.

(*b*) In spite of the existence of this sensibility, two compass-points could not be distinguished, even when separated by 8 cm.

(*c*) All sensation was lost to cutaneous painful stimuli, and to heat and cold. In fact, the condition might easily have been mistaken for one of analgesia and thermo-anæsthesia with intact sensibility to touch.

(*d*) Between the extent of the analgesic area and that insensitive to cotton wool, lay a border where the prick of a pin was abnormally painful.

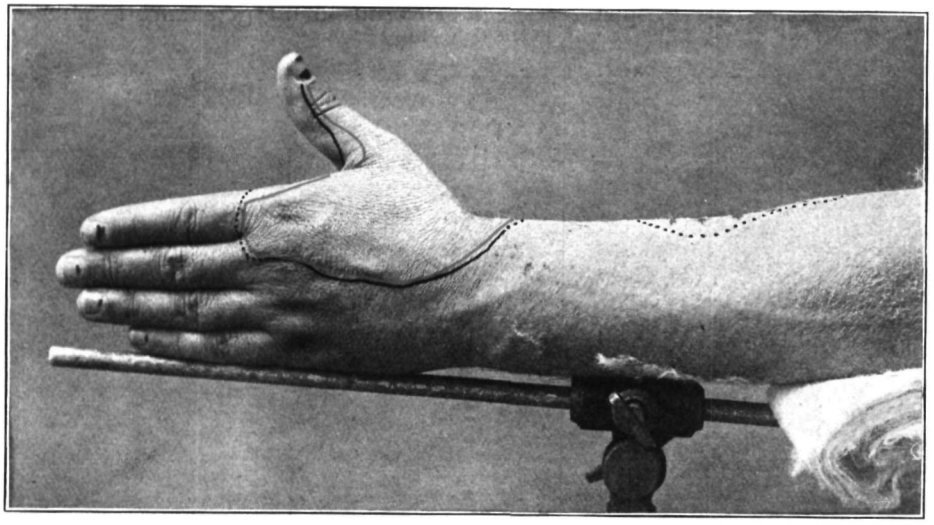


FIG. 2.

To show the extent of the loss of sensation twenty-one days after the operation (May 16, 1903). The black line encloses the loss to cutaneous tactile stimuli; the red line encloses the cutaneous analgesia. Wherever these lines are broken the border was an indefinite one.

(*e*) None of the cold-spots marked out before the operation reacted to the usual stimuli.

By May 4 the skin on the back of the hand had assumed a peculiar condition, which was described on the 7th by Dr. J. H. Sequeira in the following words:—

"The whole of the affected area is of a slightly deeper red than the rest of the skin of the hand. It is dry, and covered with minute hair-like scales. On palpation, the skin appears to be thickened and looks as if it were slightly œdematous; but it does not pit on pressure. A

striking feature is the absence of the normal elasticity, which is in remarkable contrast with the rest of the skin. The affected parts do not sweat, while the rest of the hand is permanently slightly moist."

From the time of the operation until the removal of the splint (May 23), the borders of the loss of sensation on the forearm underwent no material change. But H.'s skin has always been peculiarly susceptible to the action of chemical antiseptics, and the necessary cleansing at the time of the operation led to desquamation to within about 3 in. to 4 in. of the wrist. Fortunately, the hand had entirely escaped their action.

On the extensor aspect of the forearm, the loss of all forms of cutaneous sensation was bounded for the greater part by a definite line. Towards the radial aspect, the loss of sensation merged more gradually

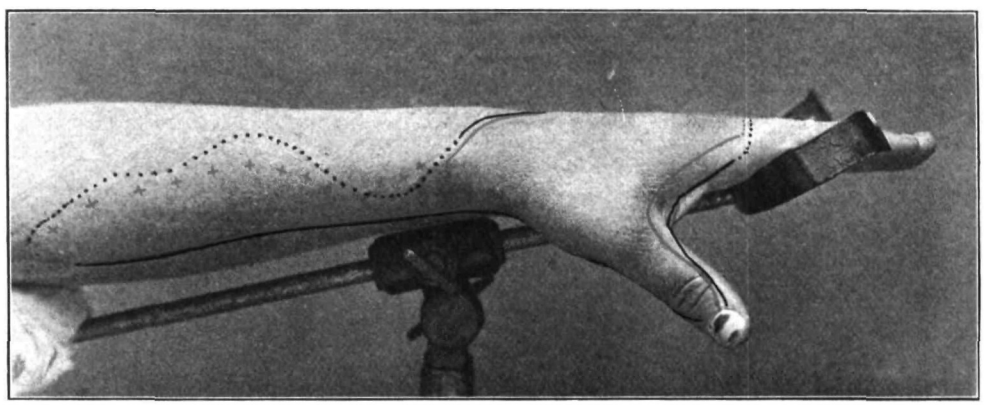


FIG. 3.
Lateral view on the same date (May 16, 1903).

into parts of normal sensibility. The borders formed a sinuous line, seen on figs. 3 and 4. Over the greater part of the forearm, the loss of sensation to prick was less extensive than that to cotton wool; but nearer to the wrist, the reverse condition seemed to exist.

The extent of the cutaneous analgesia on the hand was slightly less than that of the loss of sensation to cotton wool and von Frey's hairs, and to these stimuli all the boundaries were sharply defined, except at the base of the index and middle fingers.

The splint was removed on May 23, and it was then possible to wash the arm vigorously and to remove the loose scales of epithelium. We then discovered that the loss of sensation to prick was everywhere coterminous with, or slightly less extensive than, the loss to cotton wool,

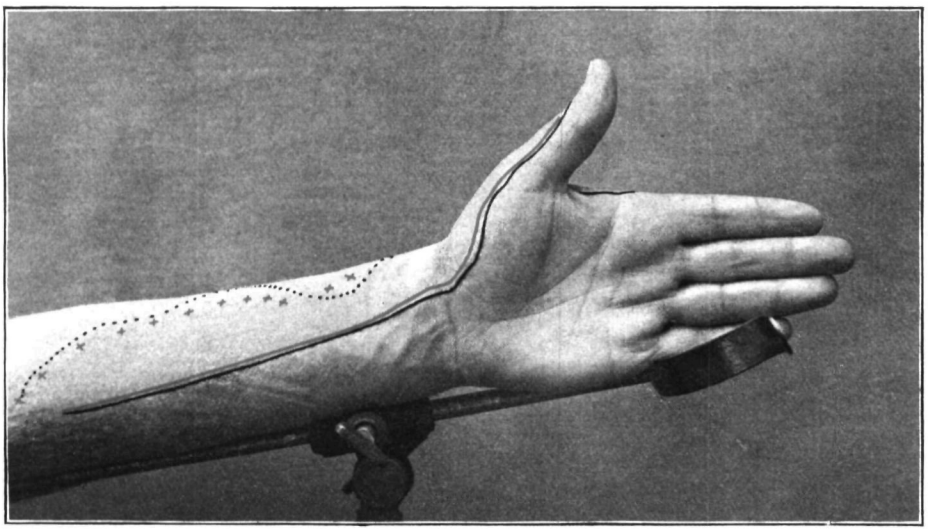


FIG. 4.
Flexor aspect of the forearm on the same date (May 16, 1903).

except near the wrist. Here there was a triangular area, shown on fig. 5, where cotton wool and No. 5 of von Frey's hairs were undoubtedly appreciated, although the skin was insensitive to prick.

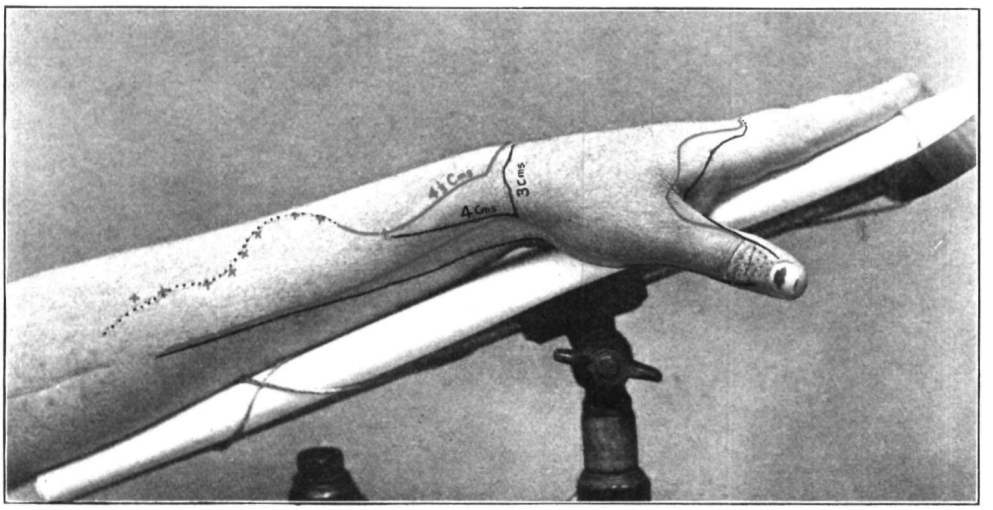


FIG. 5.
To show the loss of sensation on May 26, 1903 (thirty-one days after the operation). On the lateral aspect of the forearm near the wrist is shown the triangular area insensitive to prick and other cutaneous painful stimuli but sensitive to stimulation with cotton wool (*vide* p. 400).

On the back of the hand, sensibility remained exactly in the condition described immediately after the operation. Over the whole area of cutaneous anæsthesia, pressure-touches were appreciated and well localized. Pain could be produced as easily by pressure with the algometer over the back of the affected as over similar parts of the normal hand. Electrical stimuli produced no sensation except when the muscles contracted; then the smallest visible movement was appreciated. To recognize pure movement, produced electrically, without a concomitant cutaneous sensation is a remarkable experience.

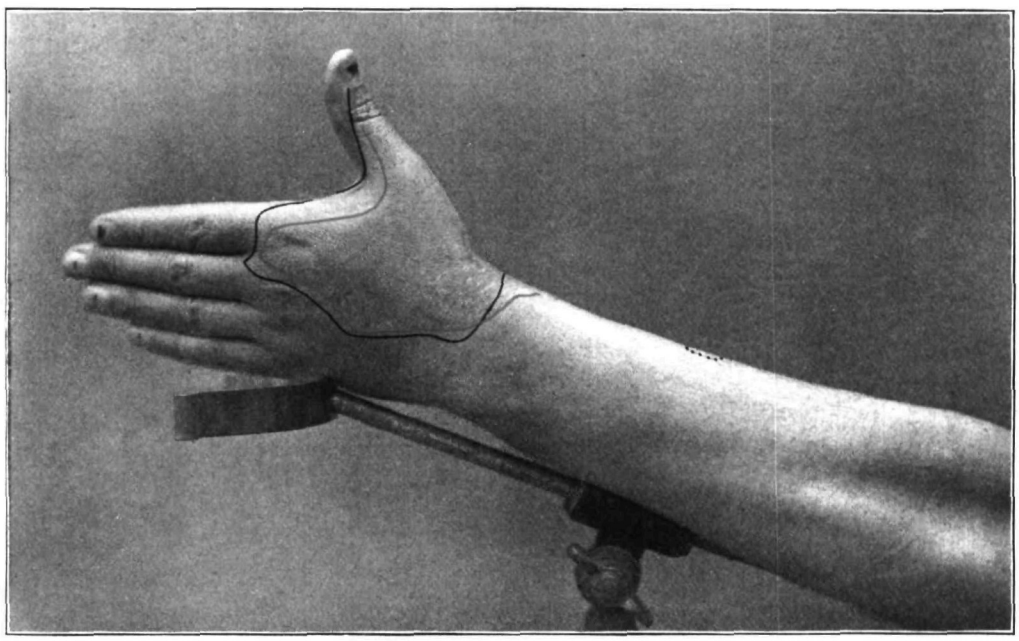


FIG. 6.
To show the loss of sensation on June 14, 1903 (fifty days after the operation).

Though sensitive to the tactile and painful elements of pressure, and to the passive movement of muscles, the back of the hand was anæsthetic to all thermal stimuli; the tissues could be frozen firmly with ethyl chloride without the production of even the slightest sensation.

The first noticeable change in the extent of the loss of sensation was discovered on June 7, forty-three days after the operation. The borders of the area insensitive to cotton wool remained unaltered, but the cutaneous analgesia was distinctly less extensive, and no longer coincided

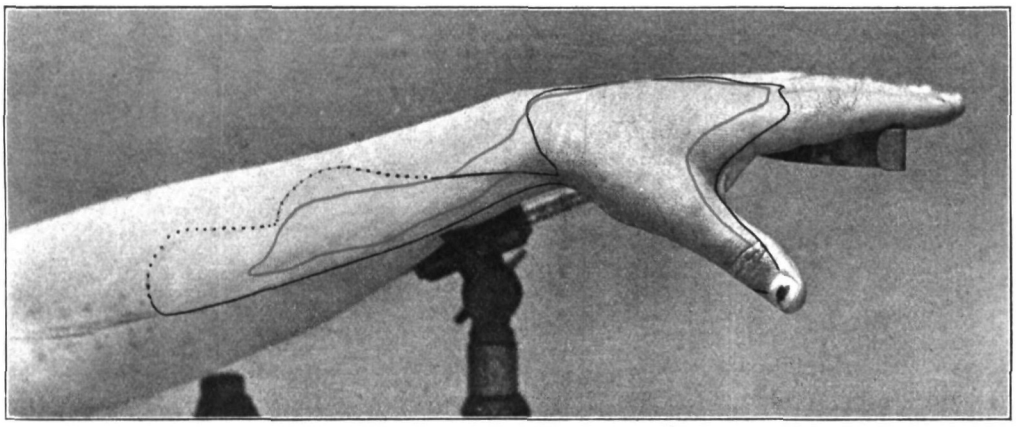


FIG. 7.
Lateral view of the forearm and hand on June 14, 1903.

with it on the flexor aspect of the forearm; the extent of the cutaneous analgesia had diminished for 3 in. (8 cm.), or more, peripheral to the scar. This was particularly noticeable, because the borders of the loss of sensation to cotton wool had remained unchanged.

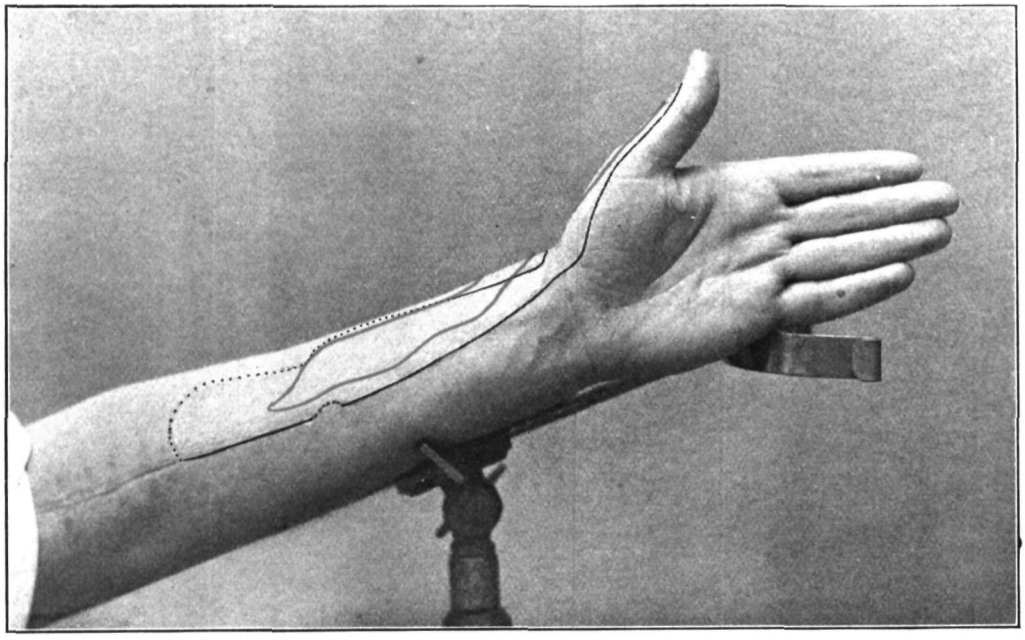


FIG. 8.
Flexor aspect of the forearm on June 14, 1903.

Moreover, the boundaries of the cutaneous analgesia were no longer definite, but were made up of islets, or points, of sensation. Passing from the area of complete loss to parts normally sensitive to a prick, the pin struck spots, where it produced a slowly developed, dull but painful sensation. If, however, this particular spot was not struck, it might be that sensibility was not encountered until another spot was reached, some millimetres nearer the unaffected parts of the limb.

On June 14, fifty days after the operation, the gradual shrinking in extent of the cutaneous analgesia on the arm was found to have continued (figs. 6, 7 and 8), although the borders of the loss of sensation to cotton wool remained entirely unaltered. The loss of sensation to cold corresponded in extent with that of the loss to prick; but, wherever the part was feebly sensitive to the latter stimulus, sensibility to cold seemed to be absent. To all degrees of heat the borders of the loss of sensation had remained unchanged, and the extent of the anæsthesia, even to temperatures between 50° C. and 60° C., uniformly exceeded that of the loss to prick.

By June 20 (fifty-six days after the operation), recovery of sensation had progressed still further. Not only had the extent of the absolute cutaneous analgesia shrunk considerably on the forearm, but the terminal phalanx and a portion of the basal phalanx of the thumb had become sensitive to prick. The extent of the area between the borders of the loss of sensation to cotton wool and to prick in the first interosseous space had increased to nearly 2 cm. (fig. 9). At this date, the markings of the previous week were still visible on the arm, and the boundary of the analgesia lay in many places 0·5 cm. within those determined six days before. And yet, in spite of this rapid improvement in sensibility to prick, the borders of the anæsthesia to cotton wool and von Frey's tactile hairs remained absolutely unchanged.

On the flexor surface of the forearm, there was nothing to show that cold could be appreciated within the border of cutaneous tactile anæsthesia. In the first interosseous space, cold was certainly appreciated well inside the limits of the loss of sensation to cotton wool; the border of the loss to cold lay about midway between that for cotton wool and that for prick.

By July 20 (eighty-six days after the operation), there was no part of the forearm where a prick could not be occasionally appreciated, although in many places this form of sensation was extremely defective. Moreover, considerable changes had occurred in the condition of the hand; the whole of the thumb and the skin over the radial half

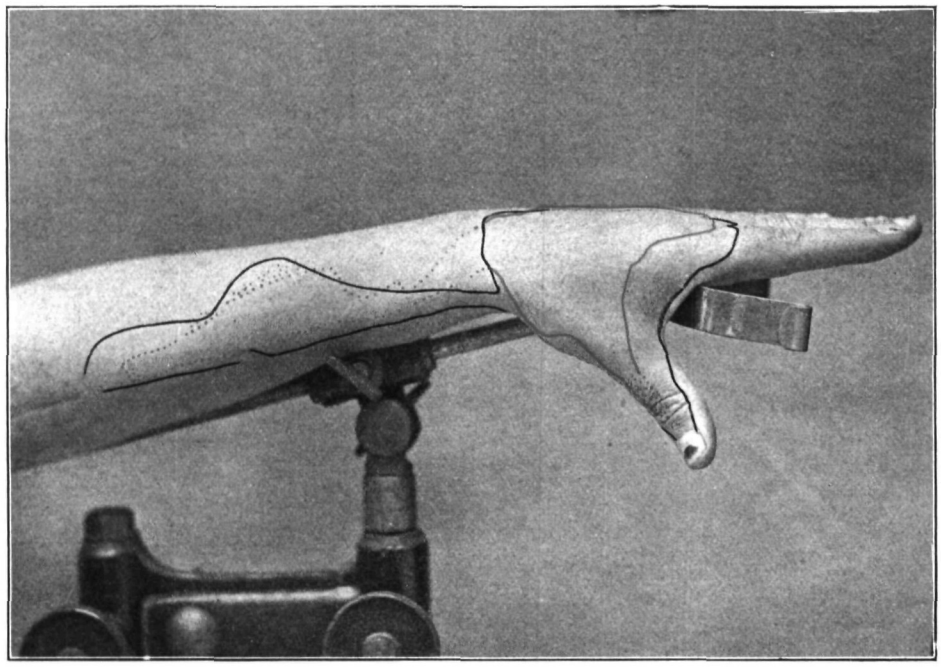


FIG. 9.

To show the loss of sensation on June 20 (fifty-six days after the operation). The cutaneous analgesia on the forearm could not now be defined accurately, but merged everywhere into parts sensitive to prick. It is therefore surrounded by a dotted broken border.

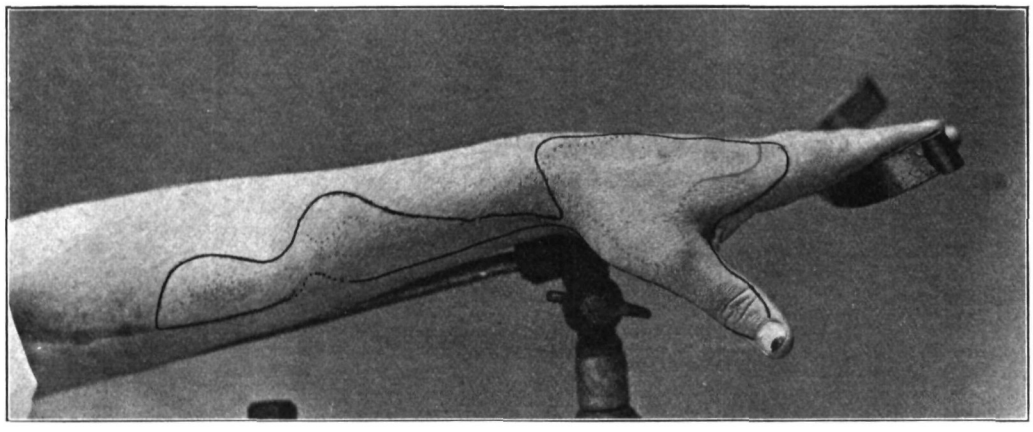


FIG 10

To show the condition on July 20, 1903 (eighty-six days after the operation). No part of the forearm was entirely insensitive to cutaneous painful stimuli.

of the first metacarpal had become sensitive to prick. The analgesic area on the back of the hand was diminishing from its radial aspect.

In spite of these changes, the borders for the loss of sensation to cotton wool remained exactly as before.

On the forearm, ice was not appreciated with certainty, until the original border of cutaneous analgesia was passed. Water above 50° C. produced pain within the parts now sensitive to a prick, but it was impossible to say whether the pain was accompanied by any thermal quality.

The terminal phalanx of the thumb was certainly sensitive to cold below 17° C. and more doubtfully to heat above 45° C. Within the area of dissociated sensibility in the first interosseous space, and over the ball of the thumb, it was difficult to be sure that any sensation of temperature was produced by ice-cold and hot water; but the border of the thermo-anæsthesia probably lay slightly within that for sensibility to cotton wool.

At this time, some of the hairs on the forearm within the affected area became sensitive to pulling. The sensation produced was slowly developed and excessively unpleasant. It died away, and recurred again, without further stimulation. These hairs lay entirely within the upper anæsthetic patch.

On August 10 (107 days after the operation), the sensibility to prick had further improved, although the extent of the anæsthesia to cotton wool remained entirely unaltered. On August 15, for the first time since the recovery of sensation began, it could be said that parts which were at first insensitive to heat and cold now responded definitely and constantly to these stimuli. Over the upper patch on the forearm, ice uniformly produced a sensation of cold. Temperatures above 50° C. caused a stinging sensation, usually called "burning," but it is doubtful to what extent this contained more than the painful element of heat.

The terminal phalanx of the thumb undoubtedly responded to temperatures above 45° C., and the sensation produced by temperatures above 50° C. contained a thermal element in addition to the stinging pain. Even the proximal phalanx of the thumb had become sensitive to ice, although still anæsthetic to heat.

On August 15 and 16, these observations on the upper patch of the forearm and the terminal phalanx were confirmed, and within these areas we were able to mark out definite cold-spots for the first time since the operation. Four of these lay in the upper patch, and four over the terminal phalanx of the thumb.

By September 9 (137 days after the operation), the whole forearm had become sensitive to cold, and cold-spots were discovered not only in the upper patch on the forearm and in the terminal phalanx of the thumb, but also over the more distal portions of the affected area. The forearm still remained insensitive to heat, except in as far as temperatures above 50° C. produced a peculiar form of painful sensation, usually called "burning."

In spite of the complete absence of any change in the behaviour of the affected parts to cotton wool, sensibility to prick continued to return steadily, and by September 24 (152 days after the operation)

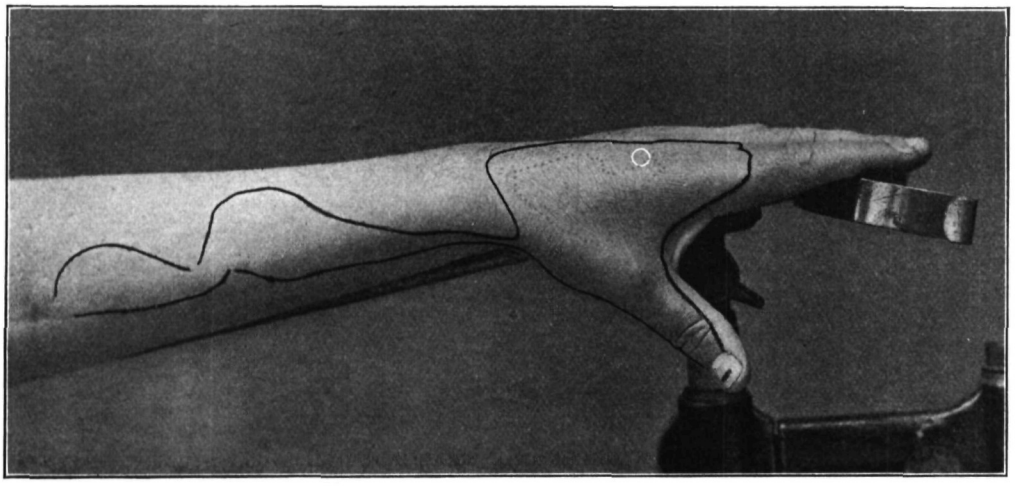


FIG. 11.

To show the condition on September 24, 1903 (152 days after the operation). Over the small irregular area on the back of the hand sensibility to cutaneous painful stimuli was greatly diminished and in places was absent.

The area occupied by the trophic sore is marked with a circle.

a small area only on the back of the hand remained insensitive to this stimulus (fig. 11).

Since July 10, when the back of the hand had been too energetically frozen with ethyl chloride, an indolent sore had existed in the centre of the affected area. It tended to heal if protected, but would break down again under the influence of the slight accidents of ordinary life. On September 23, attention was attracted to its condition by the presence of tingling, which had never been noticed before. This led to the discovery that painful sensation, of a dull and ill-defined character,

was present in the neighbourhood of the sore. From this time it healed with great rapidity, although no special care was taken to protect it. Once healed, it never broke down again after the return of sensibility to painful cutaneous stimuli.

About this time, part of the first interosseous space, which had become sensitive to prick, began to respond to ice; this return of sensation was found to be associated with a few definite cold-spots. But the affected area still remained insensitive to heat.

On October 3 (161 days after the operation), we noticed, for the first time, that cotton wool produced some sensation over the upper patch on the forearm. This change advanced with considerable rapidity, and on October 6 sensibility to cotton wool was present in a very defective form over both upper and lower forearm patches. The upper of these areas seemed to become sensitive by gradual encroachment from the edges, whilst the lower appeared to recover at the centre as quickly as at the periphery. Later we found that this response was due entirely to the return to the hairs of a peculiar form of sensibility (*vide* p. 385).

About this time (October 8), the upper patch on the forearm became undoubtedly sensitive to temperatures of and above 45° C. An excellent heat-spot was found in the centre of the patch, to which this return was certainly due.

By October 15 (173 days after the operation), no part of the hand was entirely insensitive to prick, although sensation was defective over the parts dotted on fig. 12.

The greater part of the back of the hand now reacted to the more extreme degrees of cold, and the cold-spots had multiplied greatly. By November 1 (190 days after the operation), cold could be appreciated everywhere over the back of the hand, and twenty-four cold-spots were discovered within the affected area. At the same time, one heat-spot was found near the base of the first phalanx of the thumb. This was the only part of the affected area on the hand sensitive to heat.

From this time, the cold-spots and heat-spots rapidly increased in number over the back of the hand, the increase proceeding step by step with the recovery of sensibility to cold and to heat.

With the gradual return of sensibility to pain, cold, and heat, we noticed that the sensation tended to be widely diffused, and was not infrequently localized in some part remote from the point of stimulation (September, 1903). If, for instance, ice was applied to the proximal portion of the forearm, a sensation of coldness was produced in the thumb. The site of this referred sensation remained the same, whatever

the nature of the stimulus, provided it was one to which the affected area had become sensitive.

By December 3 (222 days after the operation), the peculiar tingling sensation produced by cotton wool could be evoked by stimulating the thumb and the adjoining interosseous space. This sensibility rapidly increased in extent, until there was scarcely any part of the affected area from which it could not be produced (December 6). The sensation was one which could be expressed only as a general state of diffuse painless tingling. Moreover, it was found that parts which gave this reaction to cotton wool were insensitive to No. 5 of von Frey's hairs and to the

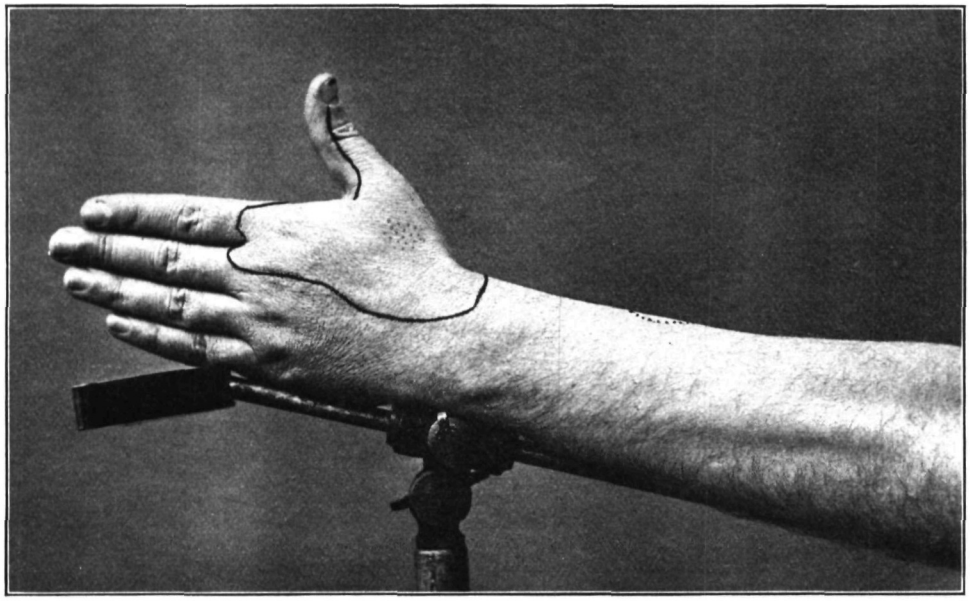


FIG. 12.

To show the condition of the back of the hand on October 15, 1903 (173 days after the operation). The healed sore can be seen as a scar in the neighbourhood of the red dots.

painless interrupted current, just as in the early days after the operation. Exactly the same borders could be marked out both on the forearm and hand by dragging a pin lightly from normal to abnormal parts; for as soon as the old border of cutaneous anæsthesia to touch was passed, the sensation became a widely diffused tingling pain.

Thus it would seem that the sensibility to cotton wool, which began to return to the forearm 161 days, and to the hand 224 days, after the

operation, was not the equivalent of the normal sensation of light touch over hairless parts, but was a peculiar form of hair-sensibility. For the areas endowed with it remained anæsthetic to the painless interrupted current and to No. 5 of von Frey's hairs; moreover, the sensation produced was widely diffused and was referred to remote parts, exactly like the sensation of prick and ice-cold over the same regions. This hypothesis was found at a later date to be correct. For on shaving the areas endowed with this form of sensibility, they became entirely insensitive to cotton wool.

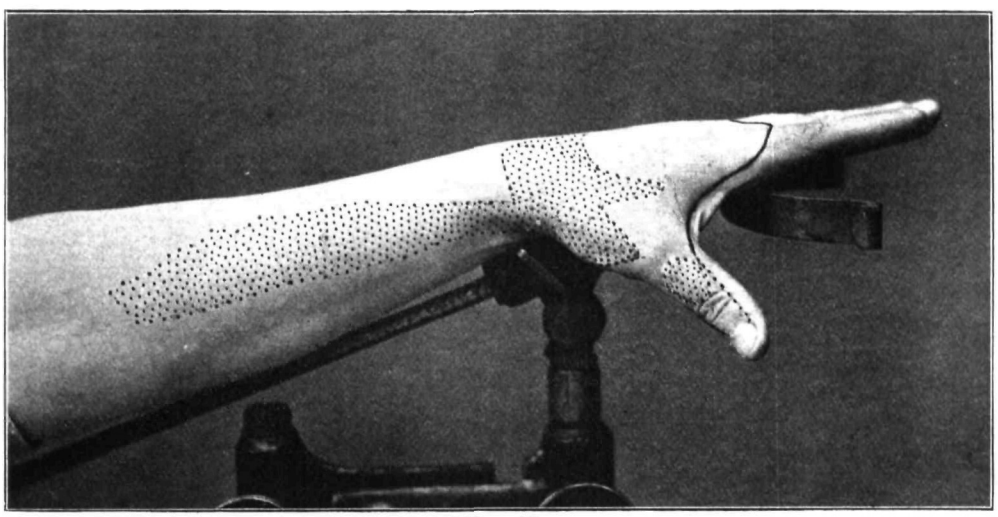


FIG. 13.

November 12, 1904 (567 days after the operation).
To show the manner in which sensibility returned to cutaneous tactile stimuli. The dotted area corresponds to the parts sensitive after shaving to cotton wool and to von Frey's tactile hairs (No. 5). These parts were also sensitive to temperatures of about 36° C.

We could not be certain that the forearm was sensitive to cotton wool when carefully shaved, until April 24, 1904, exactly a year after the operation.

On June 5, 1904 (407 days after the operation), the affected area on the forearm responded to temperatures of 37° C. This sensibility to warmth rapidly increased, and on June 26 was obtained, even with 34° C. Moreover, the sensation produced was one of warmth localized in the part touched. Except that it was not quite so acute, it exactly

resembled that produced on the normal skin under similar circumstances. It had none of the diffuse radiation and tendency to reference into remote parts, so characteristic of the sensation evoked by stimulating heat-spots.

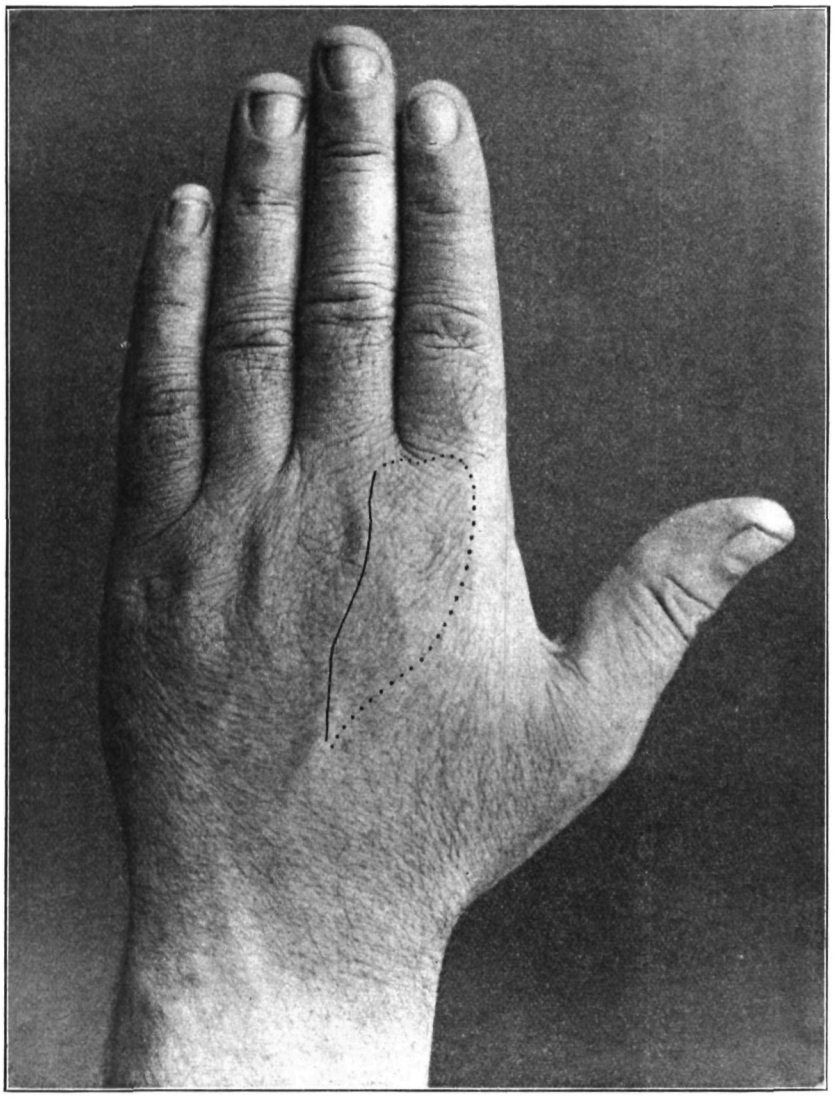


FIG. 14.

To show the extent of the affected area, which is still (1908) supplied with deep and protopathic sensibility only. Its radial border merges gradually into parts that have recovered more completely.

It was not until November 12, 1904 (567 days after the operation), that a portion of the back of the hand (fig. 13) began to be undoubtedly sensitive to warmth (35·5° C.) and to cotton wool after shaving. The diffusion and radiation so characteristic of the previous stage of recovery were at once greatly diminished; so profound was this change that we recognized it before we could be certain of the increased sensibility to thermal and tactile stimuli.

Up till the end of November, 1904, the improvement continued rapidly. But with the advent of winter cold the condition of the hand went back; the referred sensations reappeared, to become as definite as they had been six months before, and the hand became less sensitive to warmth and to cotton wool after shaving.

In March, 1905, it again began to improve. Part of the affected area on the back of the hand became sensitive to No. 5 of von Frey's hairs, and reference greatly diminished. By May 21, a large area on the back of the hand had become sensitive to cotton wool and to minor degrees of heat; stimulation with No. 5 was widely appreciated. A referred sensation could no longer be produced from any part in this condition.

Although this improvement continued throughout the summer of 1905, a small portion of the affected area, lying mainly in the neighbourhood of the knuckles of the index and middle finger, has remained insensitive to No. 5, or to cotton wool after shaving (fig. 14). Even at the present time, this part still is in a purely protopathic condition, sensitive to prick, to ice and to water above 37° C. All these stimuli cause sensations, referred to the dorsal aspect of the thumb and diffused widely around the point to which they are applied. It seems as if one of the branches of the external cutaneous had not reunited, leaving this part of the affected area to be supplied by its fellow and by the radial.

The history of the case may be summed up in the form of the following diary:—

On April 23, 1903, the radial (ramus superficialis nervi radialis) and both branches of the external cutaneus (N. cutaneus antibrachii lateralis) were divided in the neighbourhood of the elbow. Both nerves were reunited with silk sutures and the wound healed by first intention.

This operation did not interfere with sensibility to the tactile and painful aspects of pressure. But the whole of the affected area became insensitive to prick, to heat, and to cold; two points of the

compasses, applied simultaneously, could not be appreciated, but localization was preserved.

Forty-three days after the operation (June 7), the extent of the cutaneous analgesia had begun to diminish.

Fifty-six days after the operation (June 20), the analgesia on the forearm had greatly diminished, and the thumb had become sensitive to prick.

Eighty-six days after the operation (July 20), the whole forearm responded to prick, and the back of the hand was becoming rapidly sensitive to this form of stimulation. Cold was not appreciated except over the terminal phalanx of the thumb, and 50° C. gave rise to no sensation of heat.

One hundred and twelve days after the operation (August 15), the proximal part of the affected area over the forearm had become sensitive to cold.

One hundred and thirty-seven days after the operation (September 9), the whole forearm had become sensitive to cold.

One hundred and fifty-two days after the operation (September 24), the whole of the affected area, excepting a small spot on the back of the hand, had become sensitive to prick; the trophic sore healed.

One hundred and sixty-one days after the operation (October 3), cotton wool began to produce a diffuse tingling sensation over the forearm when the hairs were stimulated, but the whole of the affected area still remained insensitive to von Frey's tactile hairs. About the same time, the proximal patch on the forearm began to be sensitive to heat, and a definite heat-spot was discovered in this position.

One hundred and seventy-three days after the operation (October 15), the whole of the back of the hand had become sensitive to prick and, in a less degree, to cold.

One hundred and ninety days after the operation (November 1), the first heat-spot was discovered on the back of the hand.

Two hundred and twenty-five days after the operation (December 6), the hairs on the back of the hand responded with a diffused tingling to cotton wool, but the whole affected area of the forearm and hand still remained insensitive to von Frey's tactile hairs. This sensibility to cotton wool disappeared at once, if the arm was carefully shaved.

Three hundred and sixty-five days after the operation (April 24, 1904), the proximal patch on the forearm began to be sensitive to cotton wool after shaving.

Between *four hundred and seven* and *four hundred and twenty-eight*

days after the operation (June 5 to June 26, 1904), the affected area on the forearm became sensitive to temperatures between 37° C. and 34° C. The tendency to diffusion and reference greatly diminished.

Five hundred and sixty-seven days after the operation (November 12, 1904), the greater part of the affected area on the back of the hand had become sensitive to cutaneous tactile stimuli, and temperatures below 37° C. evoked sensations of warmth.

Chapter II.—Methods of Examination.

It was recognized by experiments before the operation that the ordinary distractions of a busy life were fatal to the detachment required by the sensory tests we wished to apply. We therefore determined that the work should be carried out in St. John's College, Cambridge.[1] The inner of a set of rooms on the top floor of the second court, belonging to Dr. Rivers, was devoted to these observations. Here, absolutely quiet and undisturbed, free from the petty worries of a busy life, H. gave himself over entirely to examination.

As a rule, he travelled to Cambridge on Saturday, after spending several hours in the out-patient department of the London Hospital. But, on Saturday evening, he was found to be in a condition of so great fatigue that no observations could be made until Sunday morning. If, therefore, it was necessary to carry out a long-continued series of tests, H. came to Cambridge on Friday night, returning to London on Monday morning. Occasionally longer periods could be devoted to these observations.

Between April 25, 1903, the date of the operation, and the last sitting with Dr. Rivers on December 13, 1907, 167 days were devoted to this investigation.

The greater part of the work was done in the morning. Then H. went for a walk or a ride, and in the summer occasionally spent the afternoon on the river. The time between 5 p.m. and 7 p.m. was commonly spent in control experiments on normal parts, or in amplifying the results obtained earlier in the day. During the evening, these were talked over whilst H. marked out the hand, and determined the position of the cold- and heat-spots in preparation for further tests next day.

The plan of investigation was debated beforehand, and was frequently

[1] Dr. Head wishes to take this opportunity of expressing his gratitude to the President and Fellows of St. John's College, Cambridge, for the generous hospitality extended to him during the five years he was their frequent guest.

committed to paper the night before the testing began. But R. always varied this order to such an extent, that H. remained ignorant of the results until the close of the sitting. This was especially the case with the compass-records; for instance, during many months, H. purposely refrained from inquiring into the nature of R.'s series of observations on the phenomenon of "double ones."

Throughout the examination, R. recorded exactly the procedure and H.'s answer at the time. At the close of a series, whilst still ignorant of the actual tests applied by R., H. dictated a note commenting on his experiences. Even then he was not told the nature of R.'s manipulations, unless some new fact had appeared which demanded immediate consideration.

Under no circumstances was H. allowed to know at the time whether his answers were right or wrong. For if he was told he had answered wrongly, he was roused to an intense determination to do better, producing thus a mental condition which was found to be unfavourable for the appreciation of sensory stimuli. Knowing his answers had not been correct, he would catch at every accessory circumstance in his attempt to interpret his sensations.

H. always sat with his eyes closed throughout the examination, as he found that this produced in him the condition most favourable for sensory testing. He always answered more correctly to all tests which required no close introspection when he did not attempt to think of what was going on. He would sit with closed eyes, his head resting on the right hand and his attention wandering widely over internal images. He soon learnt to adopt at will this state of passivity, provided he was undisturbed. But a knock at the door, or the entry of the servant, would rouse him into a state in which he again began to interpret his sensations.

H.'s mental processes are based upon visual images to a remarkable degree. Every thought is in some way bound up with internal vision, and even numbers, the days of the week and abstract ideas, such as virtue and cowardice, are associated with images of varying tones of white and black. He cannot recall musical sounds, except by seeing the notes or attaching the sounds to words which are clearly visualized. He has no power of reproducing directly scents or cutaneous sensations. He knows that the scent of violets is pleasing, and recognizes it with ease whenever it is present; but he is unable to recall a scent or a tactile impression in the same way that he can project the memory-picture of an object once seen.

In all these points, he corresponds to the common group of strong visualizers who learn to depend so exclusively on visual images that all other less dominant faculties of sensory reproduction fall into disuse. Throughout this paper we shall frequently allude to the part played in H.'s answers by these vivid mental images.

He was able to reproduce the image of a thing seen with such accuracy that it could be searched for details, at first unnoticed. But this was not the case with any other sensory impression. As soon as the stimulus was removed, he retained so much only as had been noticed at the time; for he was unable to reproduce any sensory images, except those of vision. This peculiarity common to most of those who visualize strongly leads to the following difficulty in testing sensation. Suppose that H. was returning correct answers to stimuli of different kinds applied to the affected area; the one was said to cause a sensation of touch, another appeared hot, and a third seemed to be cold. If, after withdrawing the cold object, R. inquired unexpectedly concerning the nature of the referred sensation, H. was frequently puzzled. Had the question referred to the qualities of a thing seen, H. would have recalled the visual image, examined it carefully and answered accordingly. But as he could not recall any tactile or thermal image of the cold object, he was unable to answer a question relating to some sensory quality to which his attention had not been directed at the time. A prick or other painful stimulus, however intense, evoked a sensation that could not be reproduced.

In the same way when tested with the compasses, H. might answer "two" rightly or wrongly; but if, after the points were withdrawn, he was asked unexpectedly whether they seemed close together or far apart, he was unable to give an opinion. This occurred when the test was applied over both normal and abnormal parts, provided the compasses were suitably adapted.

Again, some unexpected feature in the sensation might arouse H.'s attention, but inability to reproduce the sensory image greatly hindered its introspective study. It was often necessary to repeat the stimulus several times before H. could appreciate each separate aspect of the sensation.

Now, sense-organs, and particularly those of the skin, do not react in an exactly similar way to every repetition of the stimulus. As this is particularly the case with those of the protopathic system, H.'s inability to recapture the features of a somatic sensation in the form of a reproduced image considerably hindered his introspective analysis. For this

reason, every record dictated by H. was the direct result of introspection exercised during the period occupied by the stimulus. We have laid stress on this peculiarity, because the majority of persons in this country seem to belong to the group of those who depend on visual images, and approximate, at any rate as far as somatic sensations are concerned, to the condition of H.

Since H. was at the same time collaborator and patient, we took unusual precautions to avoid the possibility of suggestion. No questions were asked until the termination of a series of tests; for we found it was scarcely possible, in the long run, to ask even simple questions without giving a suggestion either for or against the right answer. Sounds and movements, that would have conveyed no information to an ordinary person, would disturb H.'s judgment in a case requiring fine discrimination. The clinking of ice against the glass, the removal of the kettle from the hob, tended to prejudice his answers and destroyed that negative attitude of attention essential for such experiments. R. was therefore particularly careful to make all his preparations beforehand; the iced tubes were filled and jugs of hot and cold water ranged within easy reach of his hand, so that water of the temperature required might be mixed silently.

Towards the end of a series of observations with finer tests over an area of defective sensibility, H. would frequently become uncertain in his answers, because he had forgotten his sensations with the coarser forms of the same stimuli. He might, for instance, speak of contact with the neutral tube as warmth. But occasional unexpected stimulation with a tube at 38° C. would at once correct this tendency, and throughout the further observations the neutral tube would be recognized with certainty. After a long series of "double ones," the application of the compasses widely separated so as to produce a definite sensation of two points frequently produced a similar steadying effect.

At first, we marked out both the affected area of the forearm and back of the hand into squares of approximately 1 cm. But we found the larger area on the forearm unmanageable, especially during the period when sensation changed rapidly. We therefore confined our attention, for the more minute investigations, mainly to a portion of the radial half of the back of the hand 5 cm. in every direction. This was marked out as follows: the hand was laid flat on the table and a line drawn along the axis of the third metacarpal bone. This corresponded almost exactly to the boundary between the normal and affected parts of the back of the hand. As base line, we used a fold of skin over the

wrist which was prolonged backwards to meet the longitudinal line at a right angle. From this point, the line along the metacarpal was divided into seven portions, each 1 cm. in length. From the seventh division a line was drawn in the direction of the thumb at right angles to the longitudinal border. This was divided into five portions of 1 cm. in length. By drawing longitudinal lines from each of these points parallel to the axis of the third metacarpal, and by crossing these by five transverse lines parallel to the distal base line, a series of 1 cm. squares, twenty-five in number, could be constructed. On most occasions, we used these squares only as shown on fig. 17, but at times the whole of the back of the hand was marked out into centimetre squares (fig. 21). This was a somewhat tiresome procedure and materially disturbed the sensibility of the affected area. Such marking should never be undertaken shortly before sensory tests are employed. Moreover, it is extremely difficult, even with the greatest care, to ensure the exact correspondence of the squares on different occasions. The skin on the back of the hand is extraordinarily flexible, and any change in the position of the fingers modifies the size and appearance of the squares to a remarkable degree. After the base lines had been settled, we therefore attempted to mark out the squares with the hand exactly in the position adopted in the photographs. Occasionally, these squares were not allowed to become erased for long periods (*e.g.*, from January 28 to March 12, 1906), so that, whatever its faults, we might be certain we were photographing the same field.[1]

On returning to London after each series of sittings, life-sized photographs were taken of the markings on the back of the hand and another set on a smaller scale, including the forearm. Our best thanks are due to Mr. Wilson, Photographer to the London Hospital, for the care and skill with which these records were taken.

Many of the methods used by us in this research have already been described in papers written in conjunction with Mr. Sherren [17] and with Dr. Thompson [18]. We shall therefore confine ourselves to those points, which specially concern the present paper.

Superficial tactile sensibility is usually tested by means of cotton wool stroked gently across the part. Unfortunately, however, such a method suffers from two disadvantages: it frequently fails to act as an effective stimulus over hairless parts, such as the palm of the hand, and

[1] We would suggest that if this experiment is repeated it would be wise to tattoo certain fixed points on the skin before the operation. This would ensure that each square always occupied exactly the same area.

any mechanical disturbance of the hairs excites both protopathic and epicritic sensibility. Gentle stroking with cotton wool is not a specific stimulus to hair-clad parts, as far as the peripheral nervous system is concerned. Since the whole of the area affected by our experiment was covered with long hairs, we have always used this test, both before and after shaving. It is no easy task to shave the forearm and back of the hand so cleanly that no stumps project above the surface of the skin. But throughout the protopathic stage, H. soon learnt to recognize by the widespread tingling character of the reaction, that one or more hairs had not been completely shaved. This was invariably confirmed by the use of a magnifying glass of low power, and these hairs were then removed by the direct reapplication of a sharp razor.

We never tested any part immediately after shaving, on account of the material diminution in sensibility it produced. Usually the part was cold-lathered, shaved and then carefully cleansed in hot water. After an interval of an hour or more, the tests with cotton wool were reapplied. The hand could never be shaved over-night, as by morning the hairs were found to have grown sufficiently to vitiate the experiment.

These precautions were wasteful of time, and the presence of the hairs was often necessary for the series of observations upon which we were engaged; we therefore learnt to depend upon von Frey's method of testing cutaneous tactile sensibility. Before the operation, Professor von Frey presented us with eight graduated hairs set in handles, which we have used constantly in this research. We cannot sufficiently express our gratitude for his liberality and for the kindly interest he has shown throughout this work.

Each of these graduated hairs for testing tactile sensibility will be spoken of by the number in the first column of the following table. As we have used the same hairs on every occasion, the actual pressure exerted by each is alone necessary for comparing our results. For completeness, however, we also give the measured radii of the elliptical section of each hair. Now it is obvious that from these measurements we can arrive at the pressure per unit area, if the force exerted in bending the hair is divided by its total area in mm.^{2}. The result is expressed in grm./mm.^{2}. But von Frey states ([11] pp. 223 to 229) that this is not a correct method of comparing hairs which are used as graduated tactile stimuli. For this purpose he divides the pressure in milligrammes by the radius of a circle of the same area as the elliptical section of the hair. The result expressed in grm./mm. will be found in the last column of the following table:—

Tactile Hairs.

Number by which the hair is known	Pressure in grammes	Measured radii in μ	Total area in mm.^{2}	Radius of a circle of the same area in μ	Pressure per unit area	Tension
1	0·04	30 × 54	0·005	40	8 grm./mm.^{2}	1 grm./mm.
2	0·1	47·5 × 57·5	0·0085	52	12 grm./mm.^{2}	2 grm./mm.
3	0·21	55 × 90	0·015	70	14 grm./mm.^{2}	3 grm./mm.
4	0·23	40 × 80	0·011	58	21 grm./mm.^{2}	4 grm./mm.
5	0·36	60 × 90	0·017	73·5	21 grm./mm.^{2}	5 grm./mm.
8	0·88	100 × 120	0·0377	110	23 grm./mm.^{2}	8 grm./mm.

Towards the end of our research, we received a second set of hairs from Professor von Frey which were useful in measuring the punctate pressure capable of producing cutaneous pain. These so-called "pain-hairs" exercise considerably greater pressure than those used for testing cutaneous tactile sensibility, and are graduated by calculating the pressure per unit area. Thus, we shall speak of the tactile hairs as No. 5, No. 8, &c., whilst the so-called "pain-hairs" will be known by the pressure they exert per unit area.

So-called "Pain-Hairs."

Number by which the hair is known	Pressure in grammes	Measured radii in μ	Total area in mm.^{2}	Radius of a circle of the same area in μ	Pressure per unit area	Tension
35	1·4	100 × 130	0·041	114	35 grm./mm.^{2}	12 grm./mm.
40	1·8	115 × 125	0·045	120	40 grm./mm.^{2}	15 grm./mm.
70	3	115 × 115	0·042	115	70 grm./mm.^{2}	26 grm./mm.
90	3·6	100 × 130	0·041	114	90 grm./mm.^{2}	32 grm./mm.
100	3·5	80 × 140	0·035	110	100 grm./mm.^{2}	32 grm./mm.
110	4·8	105 × 130	0·044	120	110 grm./mm.^{2}	40 grm./mm.
120	4·3	95 × 125	0·037	110	120 grm./mm.^{2}	39 grm./mm.
150	11	125 × 185	0·073	150	150 grm./mm.^{2}	73 grm./mm.
222	10	115 × 125	0·045	120	222 grm./mm.^{2}	83 grm./mm.
266	12	115 × 125	0·045	120	266 grm./mm.^{2}	100 grm./mm.

Throughout the greater part of this research, we have attempted to measure roughly the force applied in pricking the skin by means of an instrument we have called the "algesimeter." It consists essentially of a sharp needle attached by a flexible joint to a rigid rod. This is weighted and slides freely through two supports placed 10 cm. apart projecting horizontally from a vertical brass bar. When the needle is brought into contact with the skin, the full pressure of the weight on the rod would be

exerted on its point, were it not for a fine counteracting spring. This spring attached to the rod and to the upper brass support exactly balances the weight, and the needle exerts no pressure. But, if the instrument is pressed on the skin, this spring is no longer completely extended and the weight exerts a pressure in proportion to the amount, to which it is no longer counterbalanced by the coiled spring. This is read off on a scale attached to the bar, that unites the two guiding arms of the instrument.

Six divisions of this scale correspond to the pressure of 1 grm.; but readings below 15 are of little value as the weight hardly comes into action owing to the friction of the rod. Thus the corrected readings are as follows:—

25	scale	divisions	...	...	=	5 grm.
31	,,	,,	...	...	=	6 ,,
37	,,	,,	...	...	=	7 ,,
43	,,	,,	...	...	=	8 ,,
49	,,	,,	...	...	=	9 ,,

No such apparatus can give anything but approximate readings. For the moment at which pain is produced by the needle depends on the rapidity with which it is applied. If it is placed on the normal skin with the slightest jar, pain is produced at once, before the spring has begun to be affected. Moreover, the sensation of a point merges gradually into the pain of a prick over normal parts. Throughout the stage of recovering sensibility to prick, no pain was produced until considerable pressure was applied, when the characteristic pain made its appearance. Thus, the readings of the algesimeter formed a useful record of the progress of returning protopathic sensibility within the affected area; but we do not recommend it for general use on the normal skin.

All our earlier observations on the pressure necessary to produce deep pain were made by means of Cattell's pressure algometer. More recently we have used the modified form described in the paper by Head and Thompson ([18] p. 546).

The conditions of our experiment enabled us to investigate thermal sensibility with unusual completeness. Not only was the part explored with tubes containing hot and cold water, but we carefully studied the distribution of the heat- and cold-spots, especially on the back of the hand.

In our preliminary investigations before the operation, we found that different parts of the back of the normal hand were not equally sensitive to thermal stimuli. The skin over the knuckles responded badly, and

over the long tendons sensibility seems to be less than over the parts between. After the operation, we avoided these situations as much as possible, especially when employing the finer thermal tests.

Many difficulties surround the testing of sensibility to heat and cold, particularly when dealing with intermediate degrees. A glass tube cannot be employed for finer observations, owing to the great difference between the temperature of its external and internal surfaces. We have, therefore, throughout used flat-bottomed silver tubes with a diameter of 1·25 cm. These tubes were filled with broken ice, or with water at the temperature desired, and contained a thermometer. They were never warmed or cooled from without. When used for testing sensibility to heat, several tubes ranged in a wooden stand were filled with water at temperatures considerably higher than those we wished to use for testing; from these, a tube was selected as soon as it had sunk to the temperature required. These silver tubes lose their heat so rapidly that it is possible to use the same one for a short series of tests only.

With such precautions, few difficulties attend the testing of sensibility to the more extreme degrees of heat and cold. But occasionally, when the part is sensitive to painful stimuli but insensitive to heat, a tube at 50° C. and above may be said to be hot, solely on account of the peculiar pain produced. H. soon learnt to differentiate this pain, due to a hot object, from a true sensation of heat; he frequently said, "Any ordinary patient would have called such stimuli hot, because the pain produced is of a kind associated in daily life with the action of hot bodies only. Further, a patient is told to say if he feels heat, cold, or a touch. Given, then, that he knows his thermal sensibility is being tested, he would certainly call the sensation I experience 'hot.'"

Occasionally, contact with a neutral tube would cause an indeterminate and somewhat tingling sensation over the affected area; this was frequently said to be warm, and was one of the greatest difficulties against which we had to contend (*vide* p. 402).

Fewer difficulties surround the testing of sensibility to cold; but it must be remembered that a silver tube always seems colder than one of glass containing water at the same temperature, on account of the greater rapidity with which it abstracts heat. Cold stimuli, more particularly those used for testing cold-spots, are liable to cause a vaso-constriction, shown by a blanching of the skin. This condition is peculiarly unfavourable for all sensory tests.

The cold-spots were sought for with fine copper rods of about 1 mm.

in diameter. These were placed in a glass containing broken ice; on removal, each rod was carefully wiped and, after its flat base had been applied to the skin, was returned again to the ice. We found it best for H. to mark out the cold-spots over night, independently of any previous diagram or photograph. Next morning, they were tested by R., who confirmed or rejected these observations. After the spots had been charted, the result was compared with previous photographs, and if any spots of the first order did not appear, a further examination was made. At the end of the series of sittings, a photograph was taken of the final results (figs. 17 and 18). Occasionally, the back of the hand was protected by a glove, and the marks preserved for several weeks or even months.

For the discovery of heat-spots, we used a simple method which, as far as we can discover, has not been described before. We chose a "soldering iron" consisting of a large copper block fixed to an iron rod let into a wooden handle. This block, about 3 in. (7·5 cm.) in length and 1 in. (2·5 cm.) across every face, we cut down to a pyramidal point. The apex of the pyramid was flat and 1 mm. square. Into the copper block we bored a circular shaft, passing obliquely downwards in the direction of the point. This was of sufficient size to contain the bulb of a thermometer, just under 1 cm. in diameter.

Two of these irons were placed in a jug containing hot water. When sufficiently heated, one of them was removed and dried; the thermometer was placed in the cavity and the instrument laid on a cloth, until the required temperature was recorded. It was then held firmly in the hand like a large pen, and lightly applied, vertically, to the surface of the skin. So large a block of copper retains its heat for a considerable time, and the thermometer gives a sufficient indication of its temperature. This should lie between 50° C. and 40° C., preferably at about 45° C. Higher temperatures cause distinct pain, which complicates the observations; a temperature below 40° C. fails to stimulate most of the heat-spots.

A low external temperature greatly increased the difficulty in discovering both heat- and cold-spots; and in the winter, when the affected hand seemed numb and cold, previous immersion in warm water greatly facilitated their determination.

To test the power of discriminating two points we used a pair of carpenter's compasses, the points of which had been ground down until they gave no sensation of sharpness.[1] For recording our observations,

[1] Most of the instruments, called æsthesiometers, used for this purpose are provided with points so sharp that they are wholly useless. The sharp ivory points of Spearman's instrument should be replaced by blunt ones.

we used the method suggested by McDougall [22]. The compass-points were set at a certain distance from one another; they were then applied to the part to be tested in such a way that sometimes two points, sometimes one point only, touched the skin. The stimuli followed one another in an entirely irregular order, but so that, ultimately, H. had been touched ten times with one point, ten times with two points. Each correct answer was marked with a stroke, whereas a mistake was recorded by a cross. Thus if he answered "one," when touched with two points, a cross was placed below the line; if one point had been called "two," the cross was marked above. By this method it was at once obvious in how many instances he had answered correctly among the ten single and ten double stimuli. The answers whether right or wrong were ranged in strict sequence above and below the horizontal line.

Perfect appreciation of the compass-points at a distance of 4 cm. would be represented thus—

$$4 \text{ cm. } \frac{1 \mid \text{III.} \quad \text{II.} \quad \text{IIII.} \quad \text{I.}}{2 \mid \text{IIII.} \quad \text{III.} \quad \text{III.}}$$

If, however, H. was unable to differentiate the two points, answering "one" to every stimulation, the record would stand—

$$4 \text{ cm. } \frac{1 \mid \text{IIII.} \quad \text{II.} \quad \text{IIII.}}{2 \mid \text{XX.} \quad \text{XXX.} \quad \text{X.} \quad \text{XXXX.}}$$

Less complete failure would be represented by some such formula as—

$$4 \text{ cm. } \frac{1 \mid \text{IIXX.} \quad \text{XI.} \quad \text{IXXI.}}{2 \mid \text{XIX.} \quad \text{IIXX.} \quad \text{XXI.}}$$

In the following chapters these records are translated into the number of answers which were right (R.) or wrong (W.) for the sake of simplicity.

Observations made before the operation showed that the threshold for the flexor aspect of the left forearm lay at about 3·5 cm., when the compass-points were applied in the longitudinal axis of the limb.[1] Over the radial half of the back of the hand, under similar conditions, it lay between 1·5 cm. and 2 cm.

Of all sensory tests, the results obtained with the compasses are most influenced by accessory conditions. A stranger entering the room, or anything that disturbed the quiet state of internal absorption, would at

[1] Throughout this research all compass-tests have been applied in the longitudinal axis of the limb.

once diminish the accuracy of H.'s answers. On one occasion, R.'s servant entered our workroom in the middle of an almost perfect series of answers: they at once became less accurate—

$$6 \text{ cm. } \frac{1 \mid 2 \text{ R. } 3 \text{ W.}}{2 \mid 5 \text{ W.}}$$

After his withdrawal H. again began to answer as before—

$$6 \text{ cm. } \frac{1 \mid 9 \text{ R. } 1 \text{ W.}}{2 \mid 9 \text{ R. } 1 \text{ W.}}$$

Any profound cooling of the skin, or even the occurrence of a pilomotor reflex, greatly diminishes the accuracy of the answers to compass stimulation. When the coat is removed, and the sleeve is rolled up, "goose-skin" is frequently produced; testing should not be begun until this has entirely passed away.

We always began a series of tests with the compass-points widely separated from one another (9 cm.). Not uncommonly the records considerably improved as the distance was gradually diminished, and were frequently better at 7 cm. than at 9 cm.

This well-known phenomenon seemed, in H.'s case, to be associated with the increasing detachment of his attention from the procedure of testing. The following series of records obtained from the abnormal area on the left forearm are a good instance of such improvement.

$$6 \text{ cm. } \frac{1 \mid 5 \text{ R. } 5 \text{ W.}}{2 \mid 10 \text{ R.}} \qquad 5 \text{ cm. } \frac{1 \mid 5 \text{ R. } 5 \text{ W.}}{2 \mid 6 \text{ R. } 4 \text{ W.}} \qquad 4 \text{ cm. } \frac{1 \mid 9 \text{ R. } 1 \text{ W.}}{2 \mid 9 \text{ R. } 1 \text{ W.}}$$

The improvement at 4 cm. was associated with complete wandering of attention from the manipulations. When at the close R. asked whether there was anything to say about these observations, H. could have quite believed that nothing had been done. He was thinking about a book he had been reading and was completely absorbed, until recalled by R.'s question.

Occasionally, especially after exercise in the open air, this condition of detachment would pass into sleep. We noticed that the answers seemed to improve up to the point at which H. ceased to reply and therefore made several observations on the effect of somnolence on the compass-records. On October 26, 1907, H. fell asleep at the close of the following record—

$$4 \text{ cm. } \frac{1 \mid 7 \text{ R. } 3 \text{ W.}}{2 \mid 7 \text{ R. } 3 \text{ W.}}$$

an unusually good formula for the affected forearm. He was wakened and after a short interval it was found that the same distance of 4 cm.

was completely below the threshold; every double stimulation was said to be "one." He was allowed again to settle himself in the armchair and R. continued to test him with the points of the compasses at the same distance. With the return of the somnolent state the records improved; the total sixty stimulations gave the formula—

$$4 \text{ cm. } \frac{1 \mid 21 \text{ R. } 9 \text{ W.}}{2 \mid 26 \text{ R. } 4 \text{ W.}}$$

but of these the first and second twenty obtained when H. was more nearly asleep were better than the last series.

	First series	Second series
4 cm.	1 | 6 R. 4 W. / 2 | 9 R. 1 W.	1 | 7 R. 3 W. / 2 | 10 R.

This sleepy condition which is so favourable for results with compasses is one that requires absolute freedom from all external appeal to responsible action. It is a condition which H. has never succeeded in producing surrounded by the multifarious interruptions of home.

Conversely, concentration on the details of the compass-test greatly diminished the accuracy of H.'s answers. During a large number of examinations, directed towards elucidation of the phenomenon of "double ones," H. was asked to state whether the two sensations seemed to be far apart and, if possible, to indicate the position of the two spots. This required much concentration of attention on the details of testing and considerably raised the threshold.

To measure the power of appreciating roughness, we used Graham Brown's æsthesiometer. This instrument consists of a smooth metal surface from which small cylinders can be made to project for a measurable distance. In the pattern we used, a complete turn of the screw caused each of the six small cylinders to project 0·5 mm. As each complete turn was divided into ten equal parts, each of these divisions represented a projection of 0·05 mm.

The smooth surface was passed across the skin, and then the cylinders were made to project until a sense of roughness or "raking" was produced. In every case, the most careful comparative observations were made over similar parts of the sound limb.

For some of our observations on localization, we used the method of Victor Henri [19]. H. was given a life-sized photograph of the back of his hand and was told to mark on it the spot stimulated. But for the majority of our observations, we depended on verbal description of its position or on pointing with the index of the right hand. H.'s strong powers of visualization rapidly led to the development of what

may be called a visual map of the affected area. He had but to close his eyes to see a picture of his hand with the affected area marked upon it as clearly as in a photograph. As soon as a spot was stimulated, he saw its position on this map and at once described the neighbouring landmarks. He could even give approximate measurements; for instance, he would say that the point stimulated lay in "the interosseous space about 1 in. from the head of the first metacarpal." Occasionally, he was allowed to point with the index finger of the right hand; but, since this in itself acts as a stimulus, it should be rarely permitted and should be reserved for special occasions.

Unfortunately, the affected area on the back of the hand was too small for the satisfactory determination of the relative shape of different objects applied to the skin. Squares, triangles, and circles of wax or of india-rubber which lay well within its borders could not be distinguished with certainty over similar parts of the normal hand.

Deep sensibility was not disturbed by the operation. The vibrations of a tuning-fork were appreciated from the beginning, and this test played no further part in our investigations.

Chapter III.—The Phenomena of Deep Sensibility.

That the muscles were endowed with sensory nerves was a necessary corollary to the universal acceptance of a "muscle sense." But Sherrington [25] was the first to demonstrate afferent fibres in the nerves of skeletal muscles. By degenerative methods he traced their course to the muscles, and, in the opposite direction, showed that they entered the spinal cord by the posterior roots of those segments which gave rise to the motor fibres of the same muscles. This discovery did not receive the attention which was due to it, because it seemed to be little more than the last stone necessary to support the universally accepted hypothesis of "muscular sense."

But we long ago suspected that the existence of so many afferent fibres in the muscular nerves was not connected with the power of estimating movement only.

At the beginning of their investigation, Head and Sherren were brought face to face with the problem of "deep sensibility." They found, when all the cutaneous sensory nerves to a part were divided, that it was not of necessity totally anæsthetic. But, although they saw that the only structures which could account for the existence of this sensibility were the afferent fibres in the nerves of the muscles and tendons, accidental lesions of nerve trunks gave little opportunity for bringing this

question to a direct issue. Accidental lesions usually divide mixed nerves containing both the fibres to the skin and to the muscles. By chance it may happen that one group has regenerated whilst the other group remains divided (as in Case 28, p. 321, Head and Sherren [17]). But it is impossible to say how far the characters manifested under these conditions by deep sensibility are normal, and how far they are due to incomplete regeneration.

We therefore determined in our experiment on nerve division to bring this question to a direct issue. A large area of skin was to be robbed of its sensory functions entirely, but the sensibility of the deep parts was to remain undisturbed. By this means, we hoped to have the opportunity of discovering the nature of the sensibility subserved by the afferent fibres of the nerves to the muscles and other deep structures. The result far exceeded our expectation. We found that deep sensibility is an important factor in the sum of afferent impulses which pass into the central nervous system. For the impulses conducted by the afferent fibres of these deep nerves underlie our sensations of tactile and painful presure, of the locality of deep touch, and of the position of the parts in space.

All these sensory qualities are associated with some aspect of pressure, and all are undisturbed by the denervation of the skin. They can therefore be united into one group under the name of "deep sensibility," which will form the subject of the present chapter.

The observations upon which the statements in this chapter are based were made between April 26 and July 20, 1903, when cutaneous sensation began to return to the back of the hand. During this period the sittings occupied twenty-two separate days; so that we had ample opportunity for studying the peculiar behaviour of a part where the skin had been rendered totally insensitive.

(1) *Tactile Pressure.*

As soon as H. regained consciousness after the operation, he was delighted to find that no part of the back of the hand was insensitive to a touch with the finger or similar hard object. The next day he was carefully tested by Mr. Sherren, who found that over the area of cutaneous insensibility on the back of the hand a pressure-touch with the rounded end of a pencil was not only appreciated every time, but was localized to within $\frac{1}{2}$ in. (1·25 cm.) of the spot touched.

Nine days after the operation, Dr. Rivers summed up the results of an extended series of observations in the following words:—

"The most striking features of the examination of May 4 were that slight pressure on the abnormal area of the skin was appreciated and could be localized, whilst touches with cotton wool or deformations of the skin, caused by drawing a hair outwards, produced absolutely no sensation."

Whether a sensation was or was not elicited, when a thick camel's hair brush was applied to the dorsum of the hand, depended largely on the way in which the brush was used. If applied suddenly and vertically to the skin so as to cause a jar, a slight sensation of touch was produced; but when the pressure was made more gradually, no sensation was appreciated until distinct deformation of the brush occurred. Even in this case slight pressure only was necessary to evoke a sensation.

In the same way, stroking the part gently with a wisp of cotton wool was entirely unperceived, in spite of the thick growth of hair on the back of H.'s hand. But cotton wool, balled together into a "swab," such as is used for sponging a wound, caused a sensation if pressed upon the affected area. Slight pressure with such a ball of cotton wool might be perceived when it was put on or taken off only, and it was possible to place it on the skin with so slight a pressure that it was not appreciated at all.

The more gradually contact was established between the stimulating object and the affected part, and the smaller the pressure applied, the less likely was it that a sensation would result. All our observations showed that parts endowed with deep sensibility only are especially sensitive to jarring impact.

Not even stimulation with No. 8 of von Frey's hairs could be recognized, when applied to the affected area on the back of the hand.

When the skin was gently raised between the finger and the thumb so as to form a loose fold, it was found to be entirely insensitive, even to grave pressure.

Similarly, no sensation was experienced when considerable traction was exerted on a hair; the skin could be elevated to the maximum extent until the hair was pulled out, and no sensation was evoked. But a scarcely visible deformation of the skin by pressure was at once appreciated.

On several occasions, when the back of the hand was deeply frozen with ethyl chloride, touches were distinctly appreciated on the frozen area. On one occasion, H. stated that he could recognize no difference between the touches on the frozen portion and those on the surrounding parts. In this observation, not only was any possible sensibility of the

skin excluded, but also that of the more superficial layers of the subcutaneous tissues, and it shows that they are endowed with sensibility at a considerable depth.

Several introspective observations were made on the character of the sensations of deep touch. On one occasion, H. recorded that without careful attention, no difference in quality would have been noticed between touches produced by pressure on the anæsthetic and normal areas. Pressure with the head of a pin on the normal skin produced a tactile sensation, together with sensations of slight cold and of hair-stimulation. On the affected area, the latter elements were no longer present, but the fundamental quality of the sensation seemed to remain the same, so that when the head of the pin was passed across the border separating the normal and affected areas, a considerable effort of attention was necessary to detect when the change occurred. The differences in quality were of such a kind that it is very improbable they would be noticed by any but a trained observer. On a later occasion, observations were made by stimulating the normal right hand covered with a thin rubber glove, when H. noted that the quality of the touches resembled that experienced from the abnormal area.

The most extended observations were made on the back of the affected hand, because of the rapidity with which sensation began to return to the skin of the forearm. But during the short time at our disposal, the anæsthetic parts of the forearm were found to behave exactly in the same way as the insensitive area on the dorsum of the hand.

In conclusion, there is no doubt that the back of the hand was so sensitive to contact, that most observers would have said the sensation of touch was unaffected.

(2) *Roughness.*

One of the most striking features of a part endowed with deep sensibility is the ease with which roughness can be appreciated.

The utility of Graham Brown's æsthesiometer depends on our power of appreciating roughness, when small cylinders are made to project for a measurable distance from a smooth metal surface. When these projections can be perceived, the sensation is one as if the part was "raked." It was found that, in this respect, the affected parts of the left hand were in no way inferior to similar parts of the right hand.

Thus on June 7 the following readings were obtained :—

R. (sound).		L. (affected).
0·025 mm.	Not appreciated	Not appreciated.
0·033 mm.	Slightly rough	More definitely rough.
0·041 mm.	Definitely rough	Definitely rough

There was no gross difference between the two sides, but, if anything, the superiority was on the side of the affected hand. On this occasion, H. dictated the following note: "When the instrument was moved across the first interosseous space, I was more certain on the left hand than on the right that it was smooth or rough. On the sound hand I was more frequently confused by the sensations which arose from the necessary contact with hairs; no such confusing accessory sensations arose on the abnormal hand. The sensation of raking was much purer on the affected side."

If the anæsthetic skin was gently lifted into a large fold, this roughness ceased to be appreciated until the projections were extended to 0·65 mm. or 0·75 mm. Even then, the "raking" was rarely appreciated, and it was doubtful whether this sensation was not due to traction communicated to deeper structures.

Thus, the power of appreciating roughness is evidently a function of deep sensibility. Complete anæsthesia of the skin, far from diminishing this sensation, seems to make its recognition slightly more easy by removing the possibility of other disturbing sensations.

(3) *Painful Pressure.*

Although the skin of the affected area was totally analgesic to prick and to the painful interrupted current, excessive pressure produced a characteristic aching pain over the back of the hand from the beginning of the experiment.

The first measurements with the pressure algometer were made on June 7, and resulted as follows:—

	R.	L.
First series	4	1·5
	4·5	2·0
	4	2·0
Second series	3·5	3·5
	3·5	2·0
	4·0	2·5

Another series gave the following results, when pressure was applied in the first interosseous space:—

R.			L.
3·25	...	...	2·0
2·5	...	...	2·5
3·25	...	...	1·75
3·25	...	...	2·0

These observations showed so consistent a tendency for lower readings to appear on the affected than on the sound hand that pressure was increased, until H. said the pain was severe. This point was reached on the left (affected) side at 3·5, at 5 on the right (sound) hand.

There were local differences on both sides in the amount of pressure necessary to cause pain, but in every case the readings were less over the affected area than over similar parts of the sound hand.

Comparative readings were taken over the second metacarpal bone and over the interosseous space, with the following result :—

				R.			L.	
Over the metacarpal bone	...	...	...	4	3	...	2	2
Over the muscle of the interosseous space			...	3	4·25	...	3·5	3·25

H. thought that the difference between the two hands lay not so much in the quality of the sensation as in the way it developed. On the affected side, pain emerged rather quickly as a definite aching from a dull sensation of deep pressure. On the sound side, the development was more gradual out of a mixed general sensibility. Desire to withdraw the hand was more urgent on the affected side. Moreover, H. said, "I feel more frightened at the application of pressure on the affected side."

When the algometer was pressed on a raised fold of skin against counter pressure of R.'s fingers, no pain was produced with pressures of 8·5. On the normal side, pain was produced with a pressure of 2·25.

Thus, in conclusion we can say that it is one of the properties of deep sensibility to answer to the stimulus of excessive pressure by the production of pain. This pressure-pain is apparently wholly due to the activity of those nervous structures which are not interfered with by complete denervation of the skin.

(4) *Localization.*

The most surprising quality of this deep sensibility is the ease with which tactile pressure is localized. Three methods were employed for testing the power of localization. First, H. kept his eyes closed, but tried to point to the spot touched with his right hand; or he was allowed to open his eyes and point, without contact with the skin, to

the place he supposed had been touched. Lastly, R. touched the affected area at a spot he had marked on a life-sized photograph of the left hand, whilst H. attempted to mark the spot on a similar photograph. This is the method of Victor Henri [19], and in this case it gave surprisingly good results.

A fortnight after the operation, on May 9, it was found that of twenty-nine touches within the affected area, seventeen were quickly appreciated and accurately localized, six were not localized correctly, and six were not appreciated at all. It must be remembered, that at this stage the skin over the affected area was swollen, which somewhat hindered these experiments. The passing away of the swelling rendered the later experiments even more striking.

On May 17 a series of twenty-four observations was recorded by Henri's method on life-sized photographs. The results were remarkable, and it could not be said that there was any difference between the two hands in the quickness and accuracy with which pressure, touches were localized.

R. chose nine spots in various parts of the affected area unknown to H.; these are marked in black on the annexed figures (figs. 15 and 16). The following table gives the places stimulated in order and the position of the spots marked by H. on his photograph :—

(2) Localized exactly.

(3) Localized 1·3 cm. from the spot touched.

(4) Localized exactly.

(8) Lay over the interphalangeal joint of the thumb, and was localized near the metacarpo-phalangeal joint at a distance of 2·5 cm.

(1) Localized exactly.

(9) Over metacarpal of thumb—localized at a spot 2·5 cm. distant in interosseous space.

(6) Localized 0·5 cm. from spot touched.

(5) Localized 0·75 cm. from the spot touched.

(7) Localized 1·0 cm. on the proximal side of the point touched.

(2) Localized exactly.

(4) Localized exactly, so much so that the mark of the previous record was identical with that of this stimulation.

(7) Localized 1·0 cm. from point touched over the same spot as before.

(6) Localized exactly.

(8) Localized exactly.

(9) Localized 3 cm. distal to the spot stimulated.

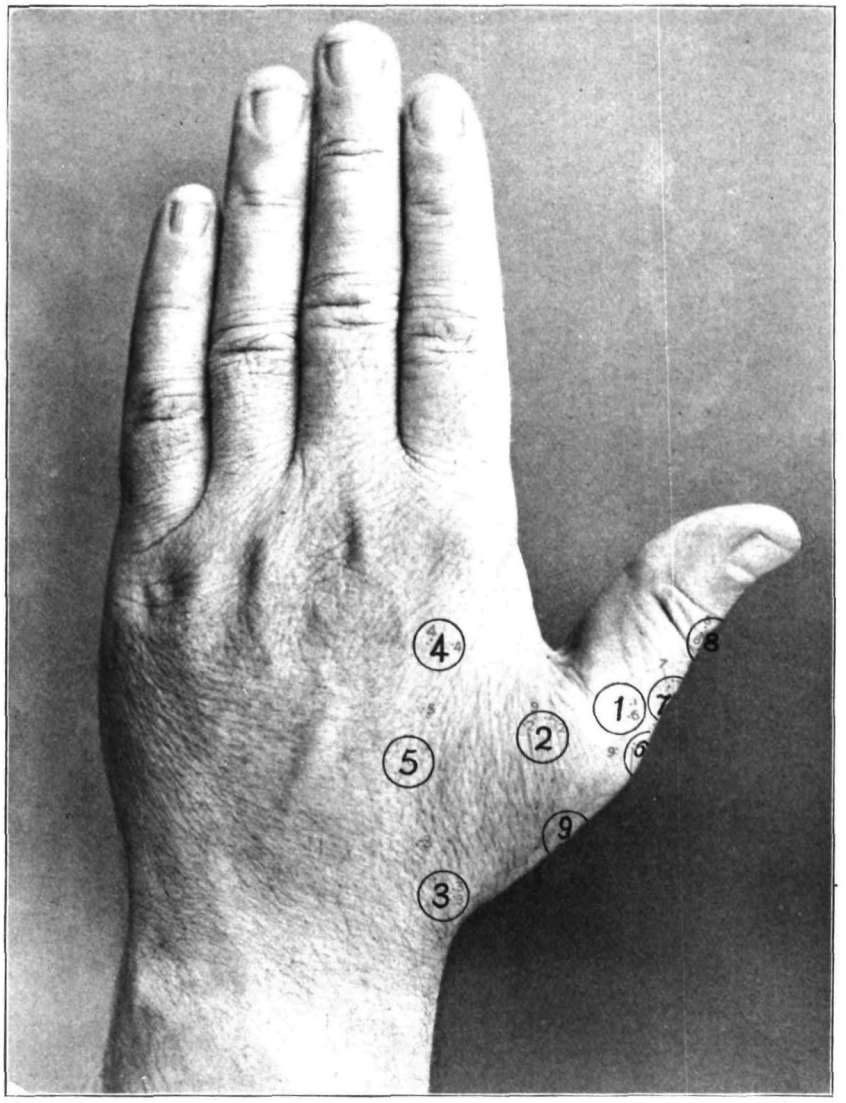


FIG. 15

Reduced to two-thirds the natural size (May 17, 1903).

Certain spots were marked on a life-sized photograph of H.'s hand. These are shown by black numbers within a circle of 1 cm. in diameter.

H. was given a similar photograph and marked upon it in each case the spot he thought R. had touched.

The photograph showing the spots stimulated and that showing H.'s localization have been combined; the marks made by H. are printed in red. Thus, for instance, a red 3 shows the spot marked by H. as the locality of a stimulus applied by R. to the area marked with a black 3.

The order of stimulation is given in the text.

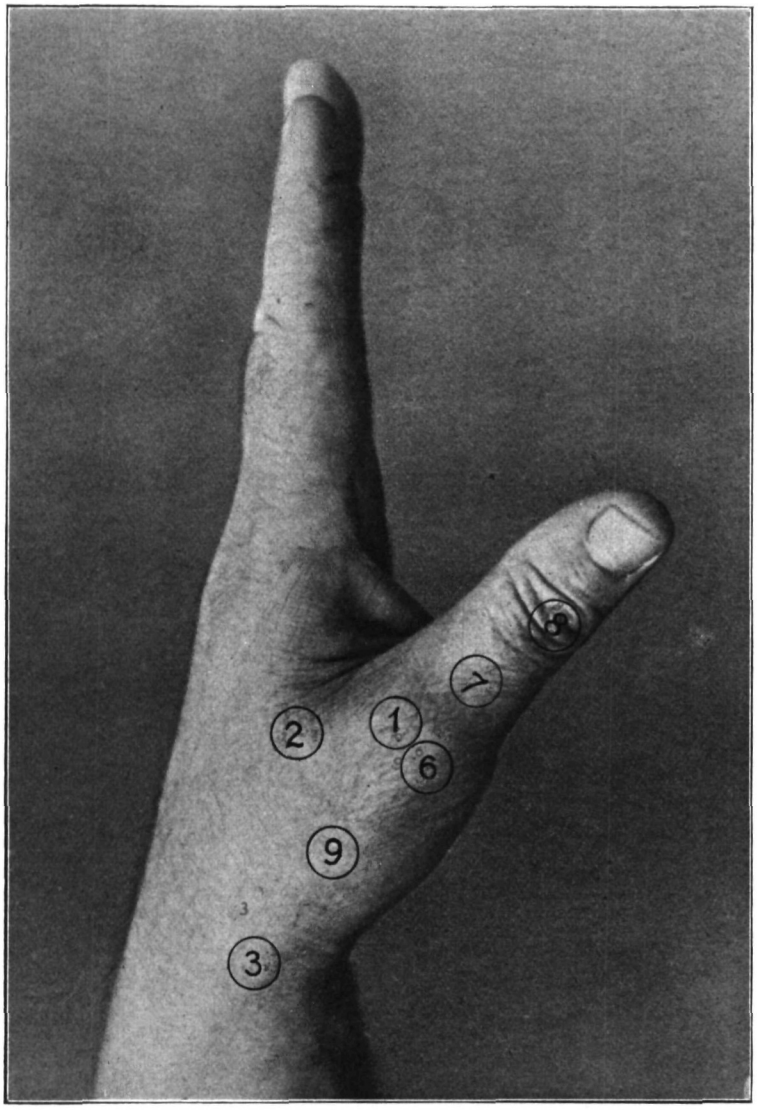


FIG. 16.

In order to test the localization over the spots 8, 7, 6, 9 and 3 two photographs of the lateral aspect of the hand were used exactly as described under fig. 15. These have been combined in the same way and the marks made by H. have been printed in red.

(7) Localized exactly.
(3) Localized exactly.
(6) Localized exactly.
(7) Localized exactly.
(9) Localized 2 cm. distal to the point stimulated.
(3) Localized exactly.
(8) Localized exactly.
(2) Localized exactly.
(6) Localized exactly.

Point 2 was touched three times and in every case was localized exactly.

Point 3 was localized twice exactly and once 1·3 cm. from the spot touched.

Point 4 was localized twice exactly.

Point 6 was twice localized exactly and twice within 0·75 cm. of the spot touched.

Point 7 was twice localized exactly and twice 1·0 cm. from spot touched. The two erroneous localizations fell over the same point.

Point 8 was twice localized exactly. Once it was localized over the proximal joint at a distance of 2·5 cm.

Point 9 showed the worst localization of any of the spots chosen, and was always localized distal to the point of stimulation; twice 3 cm., and once 2 cm.

Thus, all our experiments showed that the localization of a touch sufficiently heavy to cause a sensation was remarkably accurate. This power of localization remained after freezing with ethyl chloride, though, owing to the haste with which such observations had to be made, it was somewhat less accurate than at other times.

(5) *Spacial Discrimination* (*Compasses*).

In spite of the remarkable power of localization, H. was entirely unable to discriminate one from two points of the compasses, even when separated for the widest distance permitted by the size of the affected area on the hand, 6 cm. in a direction longitudinal to the axis of the limb. And yet, over a similar part of the normal hand, a perfect record was obtained at 2 cm.[1]

[1] Occasionally, when the compasses were applied over the anæsthetic skin of the forearm with the points at distances exceeding 10 cm., H. recognized them as two. But he was clear that this depended on the localization of one point at one place and the other in a widely distant part of the limb. He had no sense of inevitable "twoness," as when the two points were separated to a distance above the threshold on the normal skin. The process was one of judgment, in that he knew he was being touched near the wrist and also somewhere up the forearm.

But, as soon as the second point was placed upon the skin a fraction of a second later than the first, H. at once recognized that he was being touched in two places.

When the compasses were 3 cm. apart, he called every simultaneous contact "one," whilst four out of five stimulations with two points successively were recognized and the fifth was said to be doubtful :—

3 cm.														
	One point				1	1		1	1		1			
	Two points simultaneously	1	1				1	1		1				
	Two points successively	2			2	2			D		2			

Even at a distance of 1·5 cm. H. was surprisingly often right in his answers provided stimulation was successive :—

1·5 cm.														
	One point			1	1					1				
	Two points simultaneously					1	1			1		1	1	
	Two points successively	1	2	2	2	2	2		D		2	D		

On the sound side the formula was as follows :—

1·5 cm.														
	One point				1			1	1	1				
	Two points simultaneously	1	2	2	2				2					
	Two points successively		2			2	2	2			2			

And in every case where a right answer was given, H. recognized whether the two points were applied simultaneously or successively.

Thus it is evident that the presence of deep sensibility alone does not make it possible to discriminate two points applied simultaneously.

(6) *Appreciation of Size and Shape.*

All appreciation of size was lost over the affected area endowed with deep sensibility only. Even the flat and the edge of a knife could not be distinguished from one another. H. seemed to have no power of telling the relative size of a series of wax figures, although he at once recognized the relative pressure with which they were applied.

A small square of 1 cm. was placed on the skin with considerable pressure and compared with another figure 4 cm. in diameter applied with little pressure. H. made no statement with regard to the relative size of the objects, but said the first gave a sense of greater pressure. This was repeated many times on different occasions with the same result.

All power of telling the head from the point of a pin was entirely absent over the affected parts.

Unfortunately, the size of the area on the hand did not permit of the complete application of tests for shape. It was found that even a circle, a square or a triangle, cut out of wax so that all lay entirely within a 4 cm. square, could not be distinguished with certainty on the dorsal surface of the sound hand. But, although the answers were wrong as regards the shape, H. had a definite sensation of pressure on a circumscribed surface, a surface with borders and angles. On the affected hand, the sensation was one of pure pressure accompanied by no idea that the object by which the pressure was produced had any shape. Thus, on June 22, it was noted that on the back of the left hand there was a complete absence of any element of shape in the sensations. Pressure was experienced, and this was well localized, but there was nothing to indicate that the body producing the pressure had any shape. But on the sound side there was a distinct impression of form, chiefly of angles here and there, though the total shape could not be perceived correctly.

When a very large surface was applied, H. thought it seemed to him large, because he had a visual picture of his hand on which he had certain points of reference, such as the first and second metacarpal bones with their tendons. He imagined the object was large, because he perceived a sensation from both these widely separated places. But this failed entirely if both spots could be touched strictly simultaneously when the large object was applied to the skin.

(7) *Perception of Movement on the Skin.*

In some of the observations in which the skin was stimulated successively with compass-points, the sensation produced was not so much one of "twoness" as of rocking or pushing on the skin. This led us to test whether the affected area was especially sensitive both to progressive movement over the skin and to rotatory movement of a round object in which the stimulated area of the skin remained the same.

Slight movements were readily appreciated on the affected side, but we could not detect any definite difference in sensitiveness between the two hands.

(8) *Recognition of Muscular Movement.*

Head and Sherren ([17] p. 214) were able to show that perfect recognition of passive movement of the joints was possible when the

nerves to deep parts alone were intact. In the case of H. we had no means of attacking the problem, for no part of any finger was totally insensitive to cutaneous stimulation.

But we were able to show that the interrupted current could produce sensation by contracting the muscles only. Even the slightest contraction of the abductor indicis or the adductor pollicis produced a distinct sensation of movement, localized in the muscle. No pain was evoked, unless the muscle was thrown into cramp.

(9) *Temperature.*

The existence of deep sensibility conveys no capacity for appreciating stimulation with any degree of temperature. Ice and water at 60° C. were equally incapable of evoking a response over the affected area of the hand. The parts could be frozen stiffly with ethyl chloride, and H. remained unconscious of any stimulation, provided the normal skin was carefully protected with a thick layer of impervious material.

This freezing produced a numb aching, in no way allied to a thermal sensation, but resembling the "numbness" produced by extended exposure of the hands to severe external cold.

In conclusion, we have shown that the peculiar aptitude possessed by a part innervated solely by the afferent fibres of a muscular nerve is the appreciation of all stimuli which produce deformation of structure. Pressure or jarring contact are quickly appreciated and localized with remarkable accuracy. "Roughness" is as well recognized on the affected as on the sound hand.

Two points can be discriminated if applied successively, but not when contact is made strictly simultaneously.

Although pressure is well localized, all sense of relative size is lost over the affected parts.

Excess of pressure produces an aching pain; and the cramp, caused by repeated electrical stimulation of the muscles, is at once appreciated.

Pressure, which ordinarily causes a sensation of touch or of pain, produces no effect upon consciousness when applied to a fold of skin elevated into a ridge, thus proving that the sensations which are present are not due to any end-organs remaining in the skin.

The presence of deep sensibility conveys no power of appreciating any temperature stimulus.

Chapter IV.—Protopathic Sensibility.

Section 1.—*Borders of Dissociated Sensibility.*

The nature of our experiment laid bare the peculiar qualities of deep sensibility in an unequivocal manner; for all sensory impulses were destroyed, except those passing by way of the afferent fibres of nerves of muscles and tendons. Deep sensibility, as we have described it, is the expression of one set of afferent impulses, uncomplicated by the simultaneous activity of those arising in the skin. It cannot be the result of any abnormal reaction on the part of the central nervous system, nor can it bear any relation to the processes of regeneration.

But when we attempt to analyse the complex of afferent impulses, which travel by way of the cutaneous nerves, we are hampered by the following difficulty: It is not possible to arrange the experiment in such a manner that a large area of skin shall be rendered insensitive to certain stimuli, without at the same time gravely impairing its sensibility to those we desire to study. It is impossible to produce a condition analogous to that of total cutaneous anæsthesia with complete integrity of deep sensibility. We can, it is true, find parts that are sensitive to one group of cutaneous stimuli and insensitive to another; but even these are areas of lowered sensibility.

In our case, we had even less opportunity than usual for studying the primary dissociation of cutaneous sensibility. For, on the anterior surface of the forearm, the loss of sensation to prick and to cotton wool corresponded exactly. Towards the radial aspect its boundaries were ill-defined to both stimuli, merging gradually into parts of normal sensibility. But over the back of the hand lay a narrow border, 2 mm. in breadth, insensitive to cotton wool but sensitive to prick. Within this area, so vivid was the response that the skin might have been considered over-sensitive to painful stimuli. Within ten days of the operation, R. noted that the border on the back of the hand was "hyperalgesic." H., describing his sensations, said that within this area the prick of a pin was intensely disagreeable, far in excess of anything experienced on normal parts; he could not refrain from crying out and withdrawing his hand. When the hairs were pulled, no response was obtained from any part of the analgesic area. But, as soon as that portion was reached where the skin was sensitive to prick but not to light touch, H. at once exclaimed that the sensation was "stinging"; he was unaware of the nature of the stimulus, but experienced a diffuse

unusually disagreeable sensation only. If the induction coil was so arranged that it produced a current, scarcely, if at all, painful over the normal skin, it caused a more disagreeable sensation over the area of dissociated sensibility.

When the normal skin was pricked, H. at once said, "That was a prick," but did not cry out or withdraw his hand. But a prick or any other painful stimulus applied within the area of dissociated sensibility produced an immediate withdrawal of the hand and an exclamation of pain. Yet, in spite of this vigorous expression of discomfort, he was able to recognize that the dissociated border was less sensitive even to cutaneous painful stimuli than the normal skin. A stronger stimulus was required to produce pain, but when once evoked the sensation was more disagreeable than over normal parts.

Within three weeks of the operation, another small dissociated zone appeared in the first interosseous space around the distal border of the affected area. Here sensibility to painful cutaneous stimuli was so low that they were followed by no increased reaction. A prick produced a slowly developed, dull aching, different from the exaggerated discomfort evoked on stimulating the border on the back of the hand. Moreover, this small area in the interosseous space was insensitive to all thermal stimuli, and neither cold- nor heat-spots could be discovered within it. It was evidently so little sensitive to protopathic stimuli that the skin could respond to painful stimulation only, and even this response was extremely feeble.

Section 2.—Pain.

The back of the hand became sensitive to painful cutaneous stimuli within eighty-six days of the operation. With the steady increase of this form of sensibility, the response to the prick of a pin began to assume the characters of diffuseness and increased unpleasantness, with which the sensations from the dissociated border on the back of the hand had already familiarized us.

At first the sensibility was low and the innervation evidently defective. But in time the whole of the back of the hand responded vividly to cutaneous painful stimuli, though still anæsthetic to von Frey's hairs and other forms of light touch. Within this area the prick of a pin produced an intensely unpleasant sensation of pain. When the point was dragged across the hand from normal to abnormal parts, the sensation became more unpleasant immediately the boundary of the

affected area was passed. The change was so sudden and the new sensation so disagreeable that the border could be marked out to within 2 mm.

But although the response was greater, H. early recognized that sensibility to prick was still defective. Tested with the algesimeter, it was found that pain was not produced until the instrument registered from 30 to 40, whilst on similar parts of the normal hand the point was painful at about 25. Thus, although the sensation produced over this protopathic area was much more unpleasant than over normal parts, the sensibility, as measured by the pressure exerted on the point, was distinctly diminished.

Most clinical observations on parts in a protopathic condition must of necessity be made before this form of sensibility has been completely restored. For in most cases epicritic sensibility begins to return whilst the measured pain-threshold is considerably higher than that over similar parts of the normal limb.

Fortunately, a portion of the affected area on the back of the hand still remains insensitive to all epicritic stimuli at the end of five years. Here protopathic sensibility has reached a high grade, and pain is produced as readily by the algesimeter as over normal parts. But, although the stimuli are identical, the sensation over the protopathic area is much more unpleasant. It would be certainly described as "more painful" by any ordinary patient.

The threshold for painful sensation measured by means of the "pain-hairs" is the same over this protopathic area as over an analogous part of the sound hand. No. 120 was painless, but No. 150 caused distinct pain over many places on both hands; with No. 200, the points from which the characteristic stinging pain could be evoked were very numerous. But, although the threshold was the same in the two cases, the sensation produced was much more unpleasant over the protopathic area. It radiated widely and was localized in remote parts; everything conduced to the impression that the pain was greater.

Thus, we may conclude that painful cutaneous stimuli produce a more unpleasant and more diffused sensation within highly protopathic areas than over normal parts. Moreover, this is the case even when such tests as the algesimeter and the pain-hairs show that the threshold of painful sensation still remains higher than normal.

Existence in the normal skin of what may be called "the sense of a point" renders difficult all comparison of the threshold for pain over normal and protopathic areas. As soon as a sharp point is brought into

contact with the normal skin of the hand, a person recognizes that he is touched with a pointed object; even with the indicator of the algesimeter at zero, H. always knew that he was about to be pricked on the normal skin, although no actual pain was produced until it registered from 20 to 30 on the scale. Over protopathic parts this sense of a point was absent. Contact with the instrument produced no response, if jarring was avoided. With gradually increasing pressure, a diffuse sensation of pain slowly developed, preceded by no indication that the stimulus was a pointed object. This would certainly mislead an ordinary patient; but H. found with practice that he could recognize, over normal parts, when this sensation of a point changed to pain.

We have spoken of the wide diffusion of the painful sensation and of its tendency to be localized in parts widely remote from the point stimulated. This reference is not fortuitous, but stimulation of the same spot usually produced a sensation in the same remote area. Thus, the skin between the knuckles of the index and middle fingers was linked up in a remarkable manner with the dorsal aspect of the thumb, and an area in the neighbourhood of the wrist was peculiarly associated with sensations in the proximal part of the forearm. A full description of these referred sensations will be given in chapter VIII.

During the period of returning sensibility to prick, it was evident that some points within the affected area responded, whilst others remained insensitive. Recovery was not uniform, but the skin became dotted with spots sensitive to painful stimuli.

Von Frey has shown that within any chosen area of the normal skin certain points respond more readily to painful stimulation. A stiff hair of known bending strain will cause pain at some spots but not at others. By this means it is possible to measure the force necessary to cause pain in any part of the body. These small areas have been called pain-spots on the analogy of the well-known heat- and cold-spots. But they are in reality points of maximum sensibility to pain, and when von Frey states that a certain hair evokes sensation from the pain-spots of a particular area, he in no way denies that hairs of greater bending strain may cause pain at other points within it.

When we attempted to map out these maximum spots within an area of recovering sensibility, we met with many difficulties. Spots could be marked out which were sensitive to painful cutaneous stimuli; but on again testing the area, many of these spots would not react, and new sensitive points were found between them. Moreover, even those which seemed to be constant from day to day were easily fatigued, and

consecutive stimulations rarely produced the same results. Thus, we prefer to say that sensibility to prick returned by means of small sensitive spots within the analgesic area; these increased in number as the innervation of the part improved.

Long after the back of the hand had become sensitive to prick, the high threshold for pain showed that its innervation was still defective. But nearly five years after the operation the threshold over the permanently protopathic area had fallen to normal. It might have been thought that this would have formed a perfect field for the investigation of pain-spots. Here 200 grm./mm.^{2} everywhere produced a painful sensation, resembling the sting of an insect. At some points, this was more intense than at others; but we were unable to mark out definite pain-spots with this stimulus. When we used 150 grm./mm.^{2}, pain was produced at some points but not at others, exactly as on the normal skin. Yet when these spots were tested from day to day, they were not constant. Sometimes they reacted to 150 grm./mm.^{2}, and sometimes they failed to respond. Here and there, we found a particularly active spot which sometimes reacted to 70 grm./mm.^{2}. By using hairs between 70 and 150 grm./mm.^{2}, this spot could generally be rediscovered, but not always with the same stimulus.

Thus it would seem, that, when a portion of the skin has long been sensitive to pain, but does not respond to tactile stimuli, spots of maximum sensibility may be found equivalent to those described by von Frey. But at no point is it certain that pain can not be produced by increasing the strength of the cutaneous stimulus.

In conclusion, we find that, during the greater part of the protopathic period of recovery, the threshold for cutaneous painful stimuli is higher than normal. But a small area on the back of H.'s hand has remained in this condition up to the present time (1908); here the threshold, measured with hairs of known bending strain, has sunk to normal. But in both cases, even when the protopathic sensibility of the affected area was demonstrably defective, the sensation of pain evoked radiated widely and was referred into remote parts. It was more unpleasant and was usually said to be "more painful" than the pain which followed application of the same stimulus to the normal skin. We believe that the sensation of pain evoked by punctate cutaneous stimuli is due to small sensitive areas in the skin analogous to the heat- and cold-spots. These vary greatly in activity and threshold, and the "Schmerzpunkte" of von Frey are the pain-spots of the lowest threshold in any particular part of the skin.

Section 3.—Heat and Cold.

No return of sensation to any form of thermal stimulus could be discovered on the forearm until August 15 (112 days after the operation). We then found that the proximal portion of the affected area was sensitive to ice-cold. The next day cold-spots had reappeared over these parts, but nowhere else within the affected area. Of these spots, four lay within the upper (proximal) forearm patch[1] and five over the dorsal aspect of the thumb; five responded uniformly, even to a drop of cold fluid, whilst four were what we have called spots of the second grade. It is therefore certain that the earliest return of sensibility to cold coincided with the reappearance of cold-spots.

A similar return of sensation (September 9) within the lower (distal) forearm patch[1] was associated with the reappearance of six cold-spots. When this area was stimulated with a cold test-tube, a sensation was experienced in the region of the metacarpal of the thumb. This is the phenomenon of "reference," which will be considered fully later. We found that this peculiar sensation at a distance could be evoked by stimulating a single cold-spot. The character of the reaction to widespread stimulation was the same as that of an isolated spot, additional evidence that the sensibility to cold depended on the reappearance of the cold-spots.

In the same way, the return of sensibility to cold in the neighbourhood of the base of the first phalanx of the thumb was associated with the appearance of a single cold-spot. On September 20, we found that whenever the silver test-tube fell within a certain area of about 1 cm. in diameter, it caused a brisk sensation of cold. On testing this part with the ice-cold rods, a single spot was discovered, to which the sensibility of the whole area was evidently due.

Over the lower part of the forearm, in the neighbourhood of the wrist, lay a triangular area, sensitive to cotton wool, but entirely insensitive to prick and to cold. On October 15, for the first time, a test-tube containing ice evoked a sensation of cold; this was due to the reappearance of a single cold-spot in the centre of the triangle.

Parts on the back of the hand, such as the interosseous space, first responded to cold on October 10. Here also the return of sensibility

[1] The area of disturbed sensation on the forearm could be divided roughly into three portions (fig. 7). The upper patch extended for about 2 in. (5 cm.) distal to the scar; this was followed by a more elongated patch, passing by means of a narrow neck into the anæsthetic area on the back of the hand. These will frequently be spoken of as the "upper" and "lower" forearm patches and the "neck."

was coincident with the reappearance of cold-spots. Moreover, in consequence of the wide distances between them in this early stage of recovery, we were able to show that sensibility to cold was confined to the neighbourhood of the cold-spots; parts which lay between them were insensitive to all cold stimuli.

The return of sensibility to heat was considerably delayed in comparison with that to cold; but its relation to the reappearance of heat-spots was strikingly evident. The sparsity of these organs, and the large area of skin between any two groups of heat-spots, make it peculiarly easy to prove that they are responsible for all the sensations of heat experienced during the protopathic period of returning sensibility.

Until October 8, heat produced no sensation anywhere within the affected area of the forearm or hand. But on this date, 166 days after the operation, tubes at 45° C. were occasionally said to be hot when applied to the upper patch on the forearm. Here a definite heat-spot was found to have made its appearance.

On November 1, the back of the hand reacted for the first time to temperatures above 45° C., in the neighbourhood of the head of the first metacarpal bone. Here a distinct spot was found which subsequently proved to be one of the most constant and active of all the heat-spots on H.'s hand. By November 9, a second spot had made its appearance, which reacted constantly and vividly, producing a sensation of warmth which radiated over the greater part of the first interosseous space.

From this time the total number of heat-spots increased greatly; but by January 25, 1904, the total number within the affected area on the back of the hand did not exceed fifteen. In the space between these spots it was easily shown that the skin was entirely insensitive to all degrees of heat (figs. 17 and 18).

It was evident that the return of thermal sensibility at this stage was entirely dependent on the existence of cold- and heat-spots. Owing to the complete absence of sensibility to such stimuli everywhere except in the neighbourhood of these spots, investigation of their reactions was particularly easy, and an enumeration of the characters of thermal sensibility in the protopathic stage becomes an account of their peculiar properties.

One of the difficulties associated with the investigation of punctate sensibility is the difference in the certainty and vividness with which the various spots react. Provided the conditions are favourable, some spots respond to every suitable stimulation, and H. learnt to recognize these

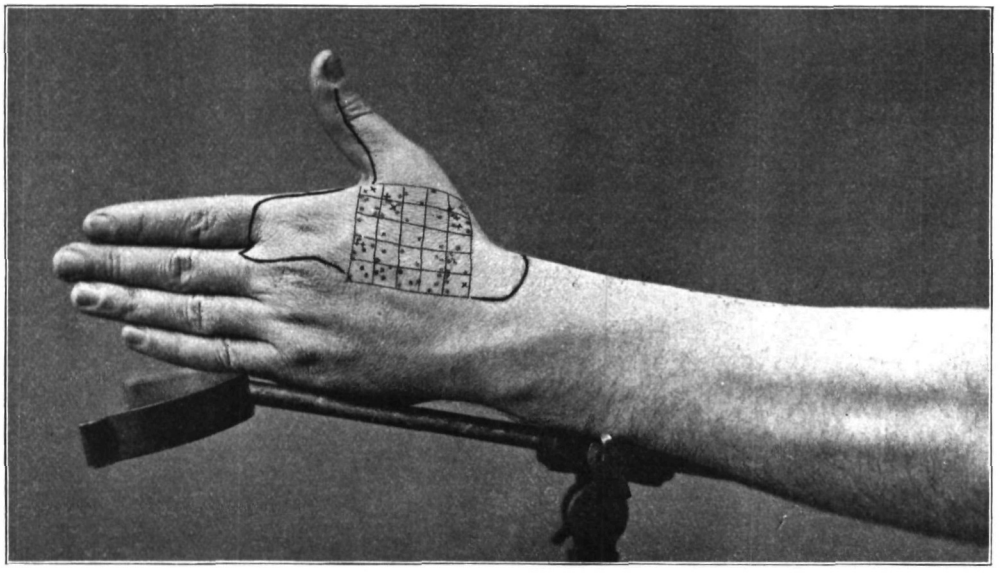


FIG. 17.

To show the photographic record taken on October 3, 1904, when the affected area of the hand was in a purely protopathic condition. Within the twenty-five squares each of 1 cm. the dots represent cold-spots, the crosses heat-spots. This photograph records the results of investigations which lasted six days.

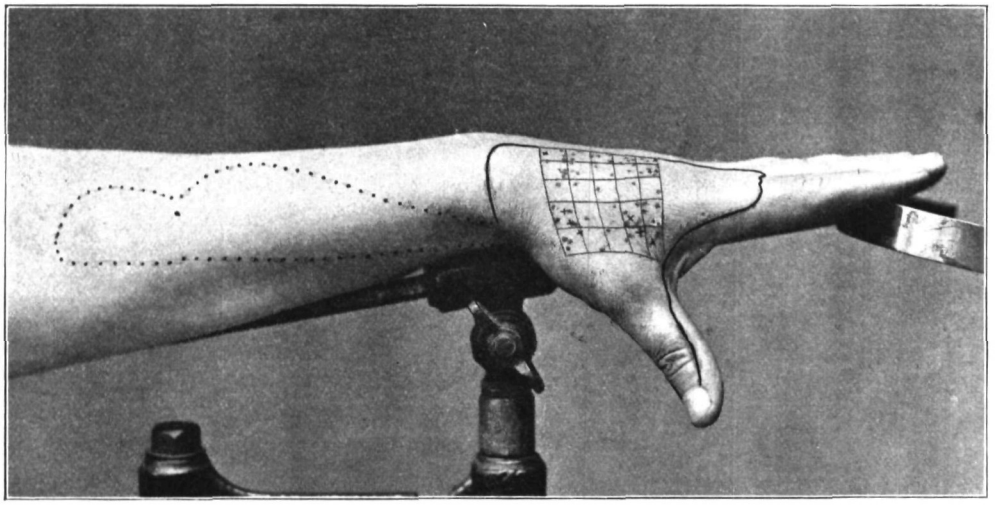


FIG. 18.

Lateral view of the hand taken on October 3, 1904

The dotted line encloses the area of diminished sensibility. The unbroken line on both figs. 17 and 18 encloses the parts in a condition of protopathic sensibility only.

first-grade spots, calling them by different names. They could be marked out with ease, whatever H.'s condition might be. But a considerable number of cold-spots responded with certainty only after a night's rest, when first stimulated, or when the rod had been recently removed from the ice. Such second-grade spots can be found over normal parts, but their discovery within a protopathic area is made easy by the total absence of any but punctate thermal sensibility.

Some of these second-grade spots will be found recorded on one photograph, some on another, and it is their existence which makes the marked area appear so different on various occasions. For instance, on a certain Saturday evening (July 9, 1904) all the cold-spots that could be discovered were those with which we had been familiar for many previous months. Next morning, we not only confirmed those marked out the night before, but obtained a response from a considerable number of other spots. On the third day, many but not all of these additional spots could be confirmed: but every one of those marked out on Saturday night, when H. was fatigued, responded readily throughout the whole sitting. Thus, it can never be said at any moment that all the cold-spots in existence have been marked. However carefully the squares may have been examined, it will always be found at another sitting under different conditions that some spots have escaped discovery and that some previously recorded no longer react. But, by extending the sittings over several days, and by preventing for long periods the disappearance of the marks on the back of the hand, we were able to show that at this stage of recovery, wide spaces existed where the skin never reacted to punctate thermal stimuli.

Von Frey long ago used a fine drop of ether, or even cold water, for discovering cold-spots, and we found that those of the first grade responded even to the drop of ink used to record their position. A spot was discovered by means of the ice-cold rod and then marked with coloured fluid at the temperature of the room. This produced a sensation of cold if the spot was an active one; the antecedent stimulation with the ice-cold rod did not exhaust a first-grade spot sufficiently to prevent an active response, even to so feeble a punctate stimulus as a drop of fluid at a temperature of about 13° C. to 18° C. This "reaction to marking" became, therefore, a useful criterion of the activity of any particular cold-spot.

Among the heat-spots we found fewer differences in activity. Most of them reacted constantly to suitable stimuli, and could be roused to activity time after time at short intervals. For instance, we never

failed to discover those within the affected area in the adjacent angles of 26 E and 25 D. On the normal part of the back of H.'s left hand, a spot in the fourth interosseous space and the spot in the extreme upper corner of square 26 A responded on every occasion. So constant was this last spot that we were able to use it as a test for the accuracy with which we had marked the vertical base line of the system of squares (fig. 17, p. 375).

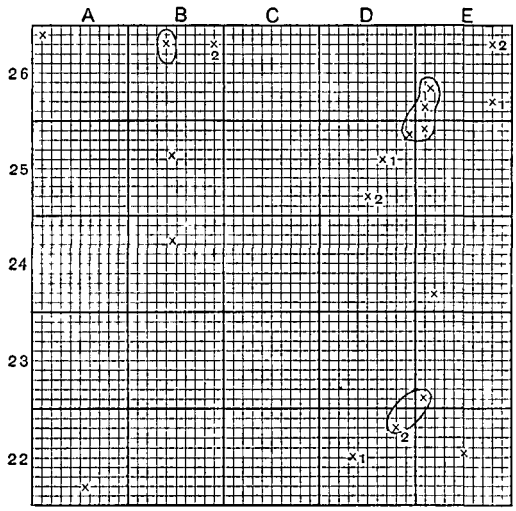


FIG. 19.

To show the position of the heat-spots within the twenty-five squares obtained by collating the eighteen photographic records.

Where a group of spots are enclosed they lie so thickly that sometimes one and sometimes another appeared on the photographs.

The numbers from 22 to 26 follow the longitudinal axis of the third metacarpal. The letters A to E lie directly at right angles across the back of the hand (*cf.* figs. 17 and 18).

The heat-spots are not only less numerous than the cold-spots, but they respond more constantly to suitable stimuli. Most of them are so isolated that their position can be rediscovered without difficulty and recorded with certainty. Some confusion arose at first in our records, because we did not recognize that some of the heat-spots lay in groups. Thus, in the adjacent angles of the squares 26 D and E, 25 D and E, lay a number of spots so close together that they were difficult to separate: sometimes one, sometimes another member of this constellation appeared in our photographs. In the same way, at the angle between 23 E and

22 D, lay spots which were sometimes recorded as lying in the extreme lower corner of the one or the extreme upper corner of the other square. But many like 26 A and 25 B lay completely isolated. Such spots were rediscovered or not according to the activity of their reaction; there was no doubt as to their position when once they responded to the warm point.

The most striking fact revealed by our photographic records, extending over nearly four years, is the large number of squares on the back of the hand from which heat-spots were uniformly absent. These squares remained totally insensitive to all degrees of heat, until after the return of sensibility to light touch. Out of the twenty-five squares, thirteen were completely devoid of heat-spots.

Fig. 19 shows the position of the heat-spots within the twenty-five squares on the back of the hand from photographs taken between the years 1904 and 1907. Many of them were recognized during the period of returning protopathic sensibility; but by April, 1904, twelve months after the operation, every heat-spot, with one exception, had been discovered. From this time we were unable to obtain any reaction to punctate heat stimuli from any part of this area in which a spot had not already been marked, and most of these heat-spots are easily demonstrable at the present time.

When we consider that these observations extended over four years, and were made under varying conditions of external temperature and bodily health, it is remarkable with what constancy many of these spots reacted.

By collating the photographs taken on eighteen occasions at the close of the observations, which were extended in some cases over weeks or even months, we obtained the following results:—

Of the sixteen positions shown on fig. 19, thirteen were marked out on ten or more of the photographic records as the site of an active heat-spot. Most of these are still easily discoverable, in spite of the return of sensibility to minor degrees of heat over the greater part of this area on the back of the hand.

	Present	Absent
Group at the angle of 26 E, 25 E and 25 D	18	0
26 A	18	0
25 B	17	1
26 E[1]	16	2
26 B[1]	15	3

	Present	Absent
25 D^1	15	3
22 E	14	4 (after Jan. 29, 1906)
24 E	13 consecutive times after discovery (Dec. 5, 1904)	
Group at the angle of 23 E and 22 D	13	5
Of this group 22 D^2 was ...	12	6
26 E^2	13 (1 doubtful)	5
26 B^2	11	7
25 D^2	10	8
24 B	8	10
22 D^1	5	13
22 A	5	13

It is difficult to make an analogous study of the distribution of the cold-spots on account of their greater number and the proportional increase of those of the second grade. This leads to a confusing diversity in the records. For when many cold-spots lie within each centimetre square, it is less possible to be certain of their identity than when it contains a single constellation. If two or three heat-spots are massed in the corner of a square, it matters little whether one or other of the group reacted on a particular occasion; they form an isolated unit in a wide area insensitive to heat. But it matters greatly if one member of a group of cold-spots was marked at one time, whilst a second one appeared on another record. A comparatively small diversity in response will materially change the relative position of the marked spot to the remaining groups within the same square and may make subsequent identification impossible.

On three occasions (October, 1904; March, 1906; and August, 1907), we not only made the usual photographic records of the spots which reacted at the time, but we also recorded on key-maps the site and characters of the various first-grade spots deduced from continuous observations extending over several weeks (fig. 20).

On collating these records, sixty-eight points in all were found to be marked as the site of cold-spots; of these, thirteen were present in all three sets of maps and photographs. But the uniformity with which these spots were recognized depends not only on the readiness with which they responded, but to some extent on their position. Two lying in close proximity to heat-spots of the first grade (26 A, 25 D) could

never be missed. Others lay in some peculiar situation which made their recognition unusually easy. Thus, the square 24 E contained one spot only. But in a square such as 26 B it is obvious that several groups of cold-spots are present, some of which were marked at one time, some at another. Of these No. 3 alone could be recognized with certainty in all the records.

The average number of cold-spots within the twenty-five squares, obtained by collating the whole series of photographic records, is fifty-one. On the photograph taken in March, 1906, at the conclusion of a

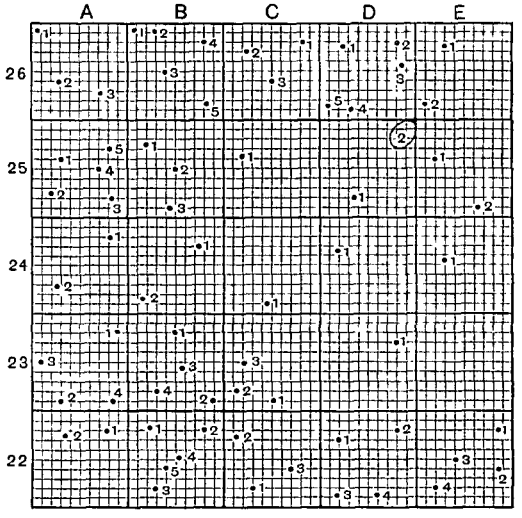


FIG. 20.

To show the position of the cold-spots within the twenty-five squares compiled from the records of October, 1904; March, 1906; and August, 1907.

series of observations lasting over many weeks, the cold-spots numbered in all fifty-eight, of which twenty-eight were said to belong to the first grade. But these spots are so unevenly distributed that in most of the photographs seven squares contain none at all.

General fatigue plays a considerable part in the ease with which a sensation can be evoked from temperature-spots even over normal parts. After a tiring day, H. was able to mark out those of the first-grade only, and could obtain no reaction from the many second-grade spots which were easily discovered after a night's rest.

If first-grade spots are selected for examination, it is not difficult to show most of the phenomena of spot-sensibility on the normal skin. But in our case the demonstration was greatly facilitated by the entire absence of any temperature sensibility apart from spots.

The range to which heat- and cold-spots react varies considerably according to the temperature of the hand and to other conditions, of which fatigue is the most important. But at no time could we find a heat-spot from which any sensation could be evoked by any temperature below 37° C.

At first, few heat-spots responded to temperatures below 45° C.; but as recovery progressed, the first-grade spots began to react to 40° C. Two spots only were sensitive to 37° C. under favourable conditions. Even now that part of the back of the hand which remains in a condition of protopathic sensibility is still insensitive to temperatures below 37° C.; the temperature most favourable for evoking a sensation of uncomplicated heat still lies between about 44° C. and 48° C. At 50° C., a stinging is produced which complicates the purity of the sensation of heat by the introduction of a new element.

We wish to warn observers against the difficulties caused by using too high temperatures. Over a first-grade spot, 55° C. produces first a sensation of heat; this is accompanied by a peculiar tingling, foreign to spot-sensation in its pure form. It resembles more clearly the tingling produced by a mild but painful interrupted current. This sensation increases rapidly in intensity and ultimately ousts the warm sensation from consciousness. Finally, an intense pain is produced, in which H. can recognize no element of heat. This would not be called hot but for the antecedent sensation of warmth and for the fact that, in ordinary life, this painful sensation usually arises in consequence of excessive heat.

At about 50° C. the pleasant feeling-tone of spot-warmth is still obvious, in spite of the presence of a tingling which contains an element of discomfort, scarcely to be called pain. These sensations are as distinct as if a hot test-tube and an interrupted current were being applied together. At 52° C., this tingling rises in intensity and becomes decidedly painful. As soon as the temperature of the test-tube falls again to about 48° C., the tingling lessens and the pleasurable spot-heat reasserts itself as if a covering had been removed.

The properties of heat-spots can be investigated only by working with temperatures which do not evoke this accessory tingling. This caution, so necessary for all who work on the normal skin, is equally

obligatory when examining parts in a condition of protopathic sensibility.

The highest temperature to which the cold-spots within the affected area reacted varied greatly. External cold, especially when associated with dampness and fog, greatly lowers the sensibility of the hand. No cold-spot reacted to temperatures above 26° C., even under the most favourable conditions, and few responded habitually to 25° C.

At first, during the earlier protopathic stages, no sensation of cold might be evoked by temperatures above 20° C.; but with rapid increase of this form of sensibility, the part became increasingly sensitive to temperatures up to 24° C. With this gradual improvement, the first-grade spots responded with increasing constancy to the same range of temperature.

Five years after the operation, an area between the knuckles of the index and middle fingers, though highly sensitive, still remains in a purely protopathic condition. Within its limits lie many active cold-spots, but not one of these reacts to temperatures above 26° C., and many scarcely react to 24° C.

When an area supplied with protopathic sensibility only is stimulated by means of a cold object, a sensation is evoked which differs greatly from that produced over the normal skin. When first the cold test-tube is applied, no result is produced; the sensation of cold makes its appearance after a short interval and slowly increases, until at last it possesses a quality of freezing, to an uncomfortable degree. On contact with a corresponding part of the normal skin the same tube is at once appreciated as cold. But the unpleasant quality does not reach the severity of that produced over the affected area. The difference between the response of the two parts consists, first, in the slower development of the sensation on the abnormal side, and, secondly, in the greater intensity of its unpleasant quality. This would certainly lead an ordinary patient to say that the sensation was " colder " on the affected side.

Not only has this sensation on a protopathic area a more unpleasant quality, but it is diffused over a wider extent. By stimulating a group of cold-spots with a drop of ether, it is possible to avoid all localization by way of deep sensibility. In this manner, we have obtained from a small group of spots the most intense sensation of cold not confined to the point stimulated, but affecting the greater part of the abnormal area on the back of the hand. This wide diffusion would also tend to make an unskilled observer say that the sensation produced from the protopathic area was " colder " than that from the normal skin.

Stimulation of an active heat-spot produced a response that could not be mistaken. The sensation seemed to flash up like a bright light in the darkness. From January, 1905, onwards, the area on the back of the hand was in a perfect condition for observing the difference between the effect of heat applied to these spots or to parts between them. Several first-grade spots lay in an area of about 5 cm. by 2 cm., which was totally insensitive to cotton wool after the hand had been shaved. Here no sensation was produced by heat, unless one of these spots was included within the area stimulated. Moreover, to be effective, the temperature must have been higher than 37° C.

But at this time the proximal part of the affected area on the back of the hand had already become sensitive to cotton wool and to von Frey's tactile hairs. Here a tube at 36° C. produced an immediate sensation of warmth; this gradually increased in intensity, and was strictly associated with the sensations of touch produced by the contact of the tube. Touch and warmth formed an entity, giving the impression of a single object.

Early in this research H. became conscious that he was frequently confused about the intensity of the cold of the stimulating object. A test-tube containing water at 20° C. would produce a sensation apparently colder than that caused by stimulating an active cold-spot with an ice-cold rod.

To investigate this condition, a group of active cold-spots was selected within a protopathic area, and one of them was stimulated with an ice-cold copper rod. After an interval, the bottom of a silver test-tube containing water at 19° C. was placed over the group of spots. H. invariably thought that the tube at 19° C. was "colder" than the iced rod. The two stimulations were repeated in irregular sequence, care being taken that a sufficient interval was allowed to elapse between them. Throughout these experiments H. was unable to recognize by means of his tactile sensations whether he was being stimulated by the tube or the rod; in one case, after the tube had been applied, he said, "That is a good spot," comparing it with the previous stimulation with the ice-cold rod. The test-tube in every case produced a far more extensive sensation, and H. said that this would certainly have been regarded as colder by the ordinary patient.

Within wide limits it would seem that the number of spots stimulated is of greater importance than the intensity of the cold by which the sensation is evoked. If the two objects are of equal area, the one which is of lower temperature will produce the more extensive

sensation, and will therefore be called "colder." But an ice-cold rod, which can stimulate one cold-spot only, will seem less cold than a tube containing water that is only cool to the normal skin.

Another factor, which tells in the same direction, is the wide extent of the referred sensation produced by stimulating a protopathic area. Stimulation of a single spot with an ice-cold rod may produce coldness in a remote part; but excitation of a group of spots, even with a temperature of 20° C., causes a still more extensive referred sensation of cold. This will usually be called "colder" than the sensation produced by stimulating a single spot, however intense may be the cold employed.

Owing to the scattered position of the heat-spots on the back of the hand we were unable to perform the analogous experiment with any certainty.

If active cold-spots are stimulated with heat, a vivid sensation of cold is produced, exactly resembling that caused by a cold rod. This is the familiar phenomenon known as "paradox-cold," and can be demonstrated on the normal skin. But, over parts in a condition of protopathic sensibility, this peculiar reaction can be studied with an ease impossible elsewhere. The scattered distribution of the heat-spots and the absence of all sensibility to heat in the intervening spaces makes it possible to find large areas where the only parts sensitive to thermal stimuli are the cold-spots. Stimulation of these cold-spots with the copper soldering iron at any temperature above about 44° C. will evoke a vivid sensation of cold. Moreover, the sensation has the same qualities as that produced by the cold rod; it is widely diffused and tends to be referred into remote parts. If a certain group of cold-spots has a tendency to produce a sensation in some definite part at a distance, the paradox-cold will be referred to the same part.

In common with all other observers, we have been unable to produce an analogous sensation of heat by stimulating the heat-spots with a cold object. But the experimental conditions are entirely different in the two cases. When the hand was in a protopathic condition large areas could be found sensitive to cold only; but there was no heat-spot that was not surrounded by a constellation of cold-spots. It was therefore impossible to apply cold to a heat-spot on the back of the affected hand without at the same time stimulating one or more of the cold-spots which lay so thickly around it.

We were unable to convince ourselves that the prick of a fine needle, accurately thrust into the site of an active cold- or heat-spot, produced any thermal sensation. The same may be said of other forms of mechanical stimulation.

We attempted to discover whether these spots responded to electrical stimulation, but were greatly hampered by the difficulty that the electrode was in itself a cause of thermal stimulation. However, we overcame this source of error by using the head of a small pin which had been warmed to about 30° C. One pole of the coil was connected with the pin, the other with a large flat electrode upon which H. rested the palm of his hand. A shunt-key was placed in the circuit and was controlled by R. The minute testing electrode was placed over one of the active spots and, after we were certain that no thermal sensation was produced, R. opened and closed the key without H.'s knowledge. In no case was any true sensation of heat or cold produced. We must therefore conclude that these temperature-spots are insensitive equally to mechanical and electrical stimulation.

In conclusion, we believe that all sensibility to heat and cold, present during the protopathic stage of recovery, is due to the activity of heat- and cold-spots. Within the twenty-five squares of 1 cm. on the back of H.'s affected hand, we found sixteen heat-spots and an average of fifty-one cold-spots. The heat-spots did not react to temperatures below 37° C., and we found no cold-spot that responded to a cold stimulus at a temperature above 26° C. But paradox-cold can be evoked from the cold-spots of the normal and protopathic skin with punctate stimuli at temperatures between about 45° C. and 50° C.

Any thermal sensation produced by an adequate stimulus to a protopathic area tends to be widely diffused and to be referred into remote parts. In the attempt to estimate the relative intensity of two stimuli, a less cold object covering a larger area of the skin may evoke a more vivid sensation than one of smaller size but of lower temperature. H. invariably thought the former was "colder" than the latter; and yet if the two stimuli covered approximately the same area, he could recognize which of them was at the lower temperature.

Section 4.—Hair-Sensibility.

The hairs within the affected area of the forearm and hand remained totally insensitive to all forms of stimulation until July 20, 1903, eighty-six days after the operation. We then discovered that, within the upper patch on the forearm, lay four hairs from which a sensation was evoked by pulling. At a distinct interval after the hair was pulled, H. experienced a slowly developing vague sensation which was neither definitely painful nor unpleasant. It died away, and recurred as a painful sensation

which faded, and again recurred as pain. The sensibility of these four hairs varied greatly ; but slow development and a tendency to recur were the most certain characteristics of the sensation evoked when they were stimulated. This mode of reaction of the hairs was the beginning of the gradual restitution of a certain form of sensibility.

On the forearm and over the thumb, the return of painful sensibility was developed earlier and more widely to prick than to plucking the hairs. Over areas where few hairs were painful we found innumerable points where prick was distinctly appreciated. But there was no doubt that the upper patch on the forearm with a larger number of painful hairs was also more sensitive to prick than the more distal parts of the limb, where these hairs were less numerous.

On October 3, 1903, 161 days after the operation, we found that the affected area was no longer completely insensitive to cotton wool. Three days later, sensibility had so greatly increased that a sensation was evoked by cotton wool everywhere over the forearm. So curious and abnormal was its character, that the borders of the original anæsthetic area could be marked out precisely, by noting the point at which the sensation changed when cotton wool was dragged across the arm from normal to abnormal parts.

Throughout the period during which the hairs of the forearm were regaining their sensibility, the skin of the back of the hand had remained entirely insensitive. But on December 3, 222 days after the operation, the thumb and adjoining portion of the first interosseous space seemed to be sensitive to cotton wool. Three days later (December 6), cotton wool produced a definite sensation over the basal and terminal phalanges of the thumb, and over the back of the hand this stimulus was distinctly appreciated in many situations, especially within the first interosseous space. When stimuli were repeated at intervals of a few seconds, a diffuse general painless tingling resulted ; if a longer pause was allowed to elapse between them, the general tingling died away and was slowly renewed. H. was then unable to say exactly at what point of time the stimulus had been applied which had caused this renewal of the sensation.

Within less than a week (December 13), a few scattered hairs in the first interosseous space caused a painful sensation when pulled.

This sensibility of the hairs on the back of the hand rapidly increased. On January 4, 1904, 254 days after the operation, no part of the affected area which possessed hairs failed to respond.

This response was of the same extraordinary character as that with which we became familiar when testing the hairs of the forearm, and

consisted of a general tingling. Not only was it diffused widely, but a sensation was evoked which seemed to lie over parts of the affected area remote from the point of stimulation. For instance, when the neighbourhood of the index knuckle was gently rubbed with cotton wool, a tingling was produced all over the metacarpal of the thumb. Moreover, if the hairs were pulled, the pain which resulted was also referred to the same remote parts as the sensation produced by stroking with cotton wool.

Here again we were face to face with the same tendency for a sensation to be referred to remote parts as was the case when a protopathic area was exposed to thermal or painful stimuli. Moreover, the sensation was referred to the same situation, whether the stimulus consisted of mechanical stimulation of the hairs, the prick of a pin, a hot or a cold test-tube.

Throughout the period during which the hairs of the forearm and hand had grown increasingly sensitive to pulling and to stimulation with cotton wool, the whole affected area had remained entirely insensitive to the careful application of No. 5 of von Frey's hairs. But if it was allowed to touch any part of the hairs which lay above the surface of the skin, the same diffuse tingling was produced as with any other mechanical stimulation.

Now, there is no part of the normal forearm or hand where No. 5 does not produce a sensation, if the point is placed on the windward side of a hair. For almost every hair is closely associated with one of von Frey's touch-points. The total failure of the affected area to react to No. 5 showed, either that the threshold was abnormally high, or that the hairs had become endowed with a form of sensibility independent of that usually called light cutaneous touch. The latter hypothesis seems to be the correct one. For when normal hair-clad parts are shaved, it is found that the skin, at any rate of the forearm and hand, remains sensitive to cotton wool.

But as soon as the affected area was shaved, cotton wool no longer produced a sensation of any kind, and the original anæsthetic borders could be marked out as accurately as on the day after the operation. The peculiar reaction we have described is therefore associated solely with the innervation of the hairs.

Fortunately, a small portion of the hairless skin of the thenar eminence was included within the anæsthetic area. In spite of the universal development of this tingling reaction to cotton wool over the hair-clad parts of the affected skin, this portion of the thenar eminence

remained throughout the whole of this period insensitive to cotton wool and to von Frey's tactile hairs. When cotton wool was applied in such a way that it was distinctly appreciated over the normal parts of the thenar eminence, all sensation was lost in the neighbourhood of the boundary of the affected area. On moving the cotton wool further in the radial direction, the typical tingling sensation was evoked and the cotton wool was again appreciated, but in a new way. This was particularly well seen in the region of the head of the metacarpal of the thumb, where some long hairs tend to lie athwart the axis of the bone. As soon as the tips of these hairs were reached, H. called out, "Hair stimulation." He said, "I recognize the extreme difference between the two conditions. The skin of the normal thenar eminence gives rise to a sensation different from that produced by stimulating normal hair-clad parts. During the observations described above, this sensation ceased entirely for considerable periods" (these coincided with the stimulation by R. of the hairless insensitive portion of the thenar eminence). "Suddenly an entirely new sensation made its appearance which I have learnt to associate with the stimulation of hairs within the affected area. This is characterized by a diffuse tingling, and by extraordinary reference to parts at a distance."

The part of the skin of the hand which lies between the knuckle of the index and middle fingers still remains in a condition of protopathic sensibility. So long as the hairs are intact, cotton wool causes an unusually intense tingling sensation, but as soon as the part is shaved it becomes entirely insensitive to cotton wool. Whether the hairs are intact or not, careful stimulation with von Frey's No. 5 fails entirely to elicit any sensation; and yet, before the operation, there were many spots in this situation which reacted to this stimulus.

In conclusion, we find that the period of recovery associated with the existence of protopathic sensibility brings to the hairs a capacity for reacting to mechanical stimulation. But the resulting sensation is tingling and diffused, and tends to be referred to parts remote from the point stimulated. Moreover, the return of this form of sensibility does not bring to the skin after shaving any power of reacting to stimulation with cotton wool or von Frey's No. 5.

Section 5.—The Sensibility of the Glans penis.

At an early stage in our observations on the consequences of injury to peripheral nerves, we began to search the body to see if perhaps some

part of the normal skin might exhibit protopathic characters. For if a protopathic response is associated with a more primitive form of sensibility, it was always possible that some area might have remained normally in this condition. We then discovered that the glans penis responded to cutaneous stimuli in that peculiar manner with which we were already familiar from our study of the first stage of recovery after nerve division.

On turning to von Frey's account of the glans penis ([9] p. 175) we found a brilliant description of a part endowed with protopathic and deep sensibility only. We can add nothing material to this remarkable description, but shall attempt to show how exactly in the case of H. the response of this organ to cutaneous stimuli corresponds to that of the highly protopathic area, which remains on the back of his hand.

The protected position of the glans hidden away under the foreskin has no fundamental bearing on the nature of its response. Observations on H. exactly corresponded with those obtained from another subject who had been circumcised many years ago.

The glans is entirely insensitive to stimulation with cotton wool and with the tactile hairs. This is expressed by von Frey in the statement that the threshold for mechanical stimulation has a high value; he continues: "Es stellte sich dabei heraus dass die hohe Reizschwelle bedingt ist durch das Fehlen der Druckpuncte. Der seinerzeit bestimmte Schwellenwerth ist die Schmerzschwelle."

As soon as hairs of greater bending strain, the so-called "pain-hairs," are used, the glans is found to be sensitive to from 70 to 90 grm./mm.^{2}. This produces a characteristic diffuse boring or stinging pain much more unpleasant than over the skin of the penis or foreskin; von Frey specially remarks that the pain is of a different character from that over the normal skin.

The abnormal behaviour of the glans to painful cutaneous stimuli is well shown by means of the algesimeter. When the needle was brought into contact with the skin, such as that of the body of the penis, H. was at once conscious that he was being touched with a pointed object. At a variable pressure of from 20° upwards, the sensation became one of pain. But when the instrument was applied to the glans no sensation was produced until it registered over 20°. Then, if a sensitive spot had been chosen, pain appeared and was so excessively unpleasant that H. cried out and started away. This pain was not localized, but radiated widely and seemed to be situated in the urethra as well as in

the glans. If the point impinged on a less sensitive spot, pain might not be caused until the instrument registered 40°. In this case a distinct sensation of deep touch appeared at about 30°, which merged gradually into the characteristic diffuse pain as the pressure was increased.

In the same way, an interrupted current almost painless on the normal skin causes an aching, tingling sensation over the glans which is extremely unpleasant. The characteristic "whirring" sensation is absent and is replaced by a slowly increasing diffused pain.

The most remarkable peculiarities are shown in the behaviour of the glans to heat and cold. In the case of H., there appear to be no heat-spots except in the neighbourhood of the corona; the body and tip of the glans are entirely insensitive to heat. But cold-spots abound and paradox-cold can be as easily evoked as from the protopathic hand.

We therefore made a number of observations in the following manner. The foreskin was drawn back, and the penis allowed to hang downwards. A number of drinking glasses were prepared containing water at different temperatures. H. stood with his eyes closed, and R. gradually approached one of the glasses until the surface of the water covered the glans but did not touch the foreskin. Contact with the fluid was not appreciated; if, therefore, the temperature of the water was such that it did not produce a sensation of heat or cold, H. was unaware that anything had been done.

From 0° C. to 21° C. a sensation of cold was always produced which seemed "colder" than over the skin of the penis. Between 21° C. and 26° C. the answers were not uniform; sometimes the water was said to be cool, sometimes H. did not recognize that he had been stimulated. Above this temperature he uniformly failed to respond, although 27·5° C. seemed cool as soon as the water reached the foreskin.

With warm water at temperatures below 38° C., no sensation of any kind was produced until the foreskin was reached. At 38° C. H. complained of a slight aching, which increased in intensity until at about 43° C. it became extremely painful. At 45° C. the sensation was usually said to be cold. This is that paradox-cold, so frequent a phenomenon over the protopathic area on the back of the hand.

But if the glass was carefully raised, so that the water reached the neighbourhood of the corona without stimulating the frenulum or the foreskin, the same temperature was called pleasant heat. In the case of the other subject, heat-spots are present in the neighbourhood of the meatus, and temperatures above 40° C. were uniformly said to be warm.

So intense and widespread may be the sensation of cold or of heat, that von Frey speaks of the corona and neck of the glans as the most sensitive parts of the body to temperature. But these parts do not react to temperatures between 26° C. and 37° C. The threshold, judged by the range of reaction, is obviously raised, but judged by the intensity of the response, the part would be called one of increased sensibility to heat and cold. This is exactly the condition with which we are familiar, from our observations on the affected hand. The surface of the glans penis is a region highly endowed with protopathic sensibility.

But, in addition, the glans seems to have many of the characters of a part innervated from the deep system. If the needle of the algesimeter is replaced by a small piece of cork, no sensation is produced, until the instrument registers between 30° and 40°. This pressure, however, causes a distinct sensation of touch, which is usually well localized. As soon as the cork is withdrawn and the sharp needle substituted, pain is produced by this pressure, and the point of application cannot be localized with any approach to accuracy. We became familiar with this phenomenon when protopathic sensibility returned to the back of the hand already innervated from the deep system of afferent nerves. But the localization of tactile pressure on the glans is not of such a high order as over the hand endowed with deep sensibility only.

Another feature in which the glans resembles a part endowed with deep and protopathic sensibility is the absence of any appreciation of the relative size of the stimulating object. H. could not distinguish from one another a point, a rod with a circular base 2 mm. across, and one of 2 cm. diameter. But, as soon as they were applied with different pressures, whatever the size of the object, the greatest pressure was at once recognized. During the first of these observations, H. noted that he had experienced no pressure sensations so clear and definite since the days when the hand was innervated from the deep afferent fibres only. The definiteness of these sensations arose from the fact that they were uncomplicated by any accessory tactile phenomena.

In conclusion, we believe that the glans penis is an organ endowed with protopathic and deep sensibility only. It is not sensitive to cutaneous tactile stimuli, but pressure is correctly appreciated and localized with fair accuracy. Sensations of pain evoked by cutaneous stimulation are diffuse and more unpleasant than over normal parts. Sensibility to heat and cold is dependent entirely on the presence of heat- and cold-spots. If the former are absent from any part of the glans, temperatures of 45° C. produce a sensation of cold, indistinguishable

from that caused by stimulation with a cold object. In every case the reaction appears to be more vivid than over normal parts, and yet the glans is entirely insensitive to temperatures between 26° C. and 37° C.

Chapter V.—Epicritic Sensibility.

Section 1.—*Tactile Sensibility.*

Throughout the first year after the operation, the sensibility of the affected area to protopathic stimuli steadily increased, the response to a prick became more uniform, and the heat- and cold-spots more numerous. But it was not until 365 days after the operation (April 24, 1904), that the proximal part of the forearm first became sensitive to cotton wool when shaved. Nearly a fortnight before (April 17, 1904), we had discovered six spots within this area which responded to No. 5 of von Frey's hairs, even when care was taken to avoid contact with the projecting stumps of the hairs.

From this date, the forearm became increasingly sensitive to all cutaneous tactile stimuli. Step by step with this change, the tingling and referred sensations gradually diminished, until it was no longer possible to mark out with certainty the borders of the affected area on the forearm by means of cotton wool.

This disappearance of the tendency to refer into remote parts was the most striking sign of returning sensibility to tactile cutaneous stimuli. When the sensory condition of the forearm went back during the winter of 1904-5, this phenomenon reappeared as clearly as before. During every subsequent summer the sensibility improved, and every winter it tended to fall back somewhat. But at the end of four years after the operation, sensation had so completely returned to the forearm that it was no longer possible, even during the following winter, to discover any material abnormality in this part of the affected area. Brushing the hairs with cotton wool no longer caused a diffuse tingling and this stimulus was appreciated, even when the forearm was carefully shaved. Moreover, within the whole area, a multitude of points responded even to No. 3.

Owing to the detailed nature of our previous observations, we were able to watch the consequences of returning sensation on the back of the hand with greater minuteness. Here the first signs of sensibility to cotton wool after shaving appeared 567 days after the operation (November 12, 1904), in the neighbourhood of the radial aspect of the

carpus and the proximal portion of the metacarpal of the thumb; these parts still remained insensitive to No. 5 (fig. 13). But though this response to cutaneous tactile stimuli was very defective, reference was profoundly inhibited. The sensation evoked was diffuse, but it was no longer situated in some remote part.

With the coming of the winter cold (December, 1904), the greater part of the recovering area on the hand again became insensitive to cotton wool after shaving, and the referred sensations were as definite as before.

It was not until March 26, 1905, that the small patch which had remained sensitive to tactile cutaneous stimuli, began to extend rapidly again in the direction of the thumb and first interosseous space. Over almost the whole of these parts, No. 5 was now appreciated. Steady improvement took place throughout the summer, and even the hairless portion of the thenar eminence which lay within the limits of the affected area became sensitive to tactile cutaneous stimuli.

Accurate localization of touches with cotton wool now became possible over the greater part of the back of the hand and the dorsal aspect of the thumb. Tingling and referred sensations ceased, except over the distal part of the affected area, which has not even now, five years after the operation, become sensitive to cotton wool after shaving (fig. 14).

At the present time, the back of the hand still presents two parts in different states of sensibility. The proximal part responds to cotton wool when shaved, to No. 5 and occasionally to No. 4 of the tactile hairs. This includes the basal phalanx of the thumb. The more distal portions of the affected area remain in a purely protopathic condition, entirely insensitive to cutaneous tactile stimuli (fig. 14).

In association with this gradual return of cutaneous tactile sensibility, H. regained the power of appreciating the "pointedness" of a needle or pin. Over normal parts of the hand, it is almost impossible to touch the skin with a sharp point, such as that of the algesimeter, without producing a sensation which betrays its pointed nature. This sensation is not painful, but conveys the impression that the stimulating object is sharp. It was totally absent from all parts in the purely protopathic condition. Even at the present time, the highly sensitive protopathic portion of the back of the hand is incapable of responding to the algesimeter, until it registers 30 or more degrees, and hairs of from 50 to 70 grm./mm.^{2} evoke sensation of pressure only.

This power of recognizing the sharpness of a stimulating object, underlying the discrimination of the head from the point of a pin,

is a function of the appreciation of relative size. It is restored to the affected skin together with the sensation of cutaneous touch and other functions of epicritic sensibility.

Thus, when a part previously in a condition of protopathic sensibility begins to respond to cotton wool after careful shaving, the diffuse tingling diminishes, the sensation is no longer referred to remote parts, and correct localization becomes possible. At the same time, the power of distinguishing the point from the head of the pin and the appreciation of relative size are gradually restored.

Section 2.—Thermal Sensibility.

Returning sensibility of the skin to tactile stimuli was associated with a profound change in the response to heat and cold. Temperatures to which the protopathic parts were insensitive now evoked a sensation, and both radiation and reference of heat and cold ultimately disappeared entirely.

These changes could best be studied over the back of the hand; for during the eighteen months which preceded the first signs of returning epicritic sensibility, we had become familiar with the position of all the principal heat- and cold-spots within this part of the affected area. We shall therefore begin our account of the effect produced by the return of epicritic sensibility with a description of the thermal reactions on the hand, dealing later with the similar changes which occurred in the forearm at an earlier date.

Before the skin in the neighbourhood of the wrist had become sensitive to cotton wool, we noticed that temperatures of 36° C. or even 34° C. occasionally caused a sensation of warmth (October 23, 1904). This differed materially from the response obtained by stimulating heat-spots; it was well localized and seemed to develop in close association with the touch of the stimulating object. Moreover, it was evoked from parts where no heat-spots had ever been discovered. By November 12, 1904, temperatures of 36° C. produced an undoubted sensation of warmth over an area which included the site of the most sensitive group of heat-spots on the hand. But we found that, although the parts around now responded to 36° C., the spots themselves still failed to react to any temperature below 38° C.

The results obtained by stimulating this area with low temperatures were less striking, but seemed to point to the conclusion that an analogous change was taking place in the sensibility of the hand to

cold. Temperatures of 26·5° C. and 25·5° C. were said to be cool in the neighbourhood of the wrist, although no other part of the affected area reacted at that time to anything above 24° C.

It was plain that certain parts of the back of the hand, especially in the neighbourhood of the wrist and over the metacarpal of the thumb, had become sensitive to temperatures, to which the remainder of the affected area, endowed with heat- and cold-spots only, did not respond. It was these same parts which about this time became sensitive to cotton wool when shaved.

Throughout the winter, the hand made little further progress towards recovery, and at one time seemed to fall back into an earlier condition. But, whenever the days were bright and the temperature more favourable, we were able to confirm the return of sensibility to temperatures between 33° C. and 37° C.

During this period, the hand was in an excellent condition for observing the difference between the sensations produced from a part innervated by heat-spots only and those due to stimulation of the recovering area with temperatures to which not even the most sensitive heat-spot reacted.

Over the centre of the back of the hand (26 and 25 B), lay a group of unusually active spots, within an area which did not otherwise respond to heat; here the skin was anæsthetic to cotton wool when shaved and to von Frey's tactile hairs. No temperature below 38° C. produced any sensation of heat, and higher degrees caused the characteristic response, radiating widely and referred to some remote part.

But, over the proximal portion of the first interosseous space and the head of the metacarpal of the thumb, lay an area sensitive to cutaneous tactile stimuli. Here 36° C. uniformly produced a sensation of warmth which was strictly associated with those of touch and pressure. Touch, pressure and warmth formed an entity, giving the impression of a single object. With higher temperatures such as 40° C. capable of stimulating the heat-spots in this region, this sensation of warmth merged gradually into pleasurable spot-heat. But this differed greatly from the response obtained on stimulating heat-spots over parts that had not entered on the final stage of recovery; for it was no longer referred to some remote part, but was closely associated with the other local sensations. The coming of the new reaction to warmth had not only increased the range of the sensitiveness of the skin to thermal stimuli, but had inhibited the tendency to refer into remote parts.

This part of the hand not only recovered its sensibility to less

intense degrees of heat, but when the weather was favourable, temperatures of 27° C. began to be appreciated as cool. Throughout the greater part of the period of this experiment, the external temperature was seldom above 20° C., and the hand was always adapted to cold to a varying degree. But during the summer, especially of 1906, we made several observations which showed that the proximal part of the affected area on the hand responded to temperatures such as 27° C., to which the cold-spots never reacted.

This increased sensitiveness to thermal stimuli was not associated with any increase in the number of the heat- and cold-spots. In fact, it became evident with the return of sensibility to cutaneous tactile stimuli that many of the cold-spots were less easily marked out than before. During the purely protopathic stage of recovery, no sensibility to heat and cold existed, except in the position of the spots. They were therefore easier to mark out than when the intervening portions of the skin had become sensitive to the intermediate degrees of temperature.

But, apart from this technical difficulty, it seemed as if the increased sensibility diminished the activity of the temperature-spots. First-grade spots could be discovered as easily as before, although they no longer produced a widespread referred sensation; but those of the second grade were less numerous over the proximal squares on the hand than before this part responded to minor degrees of heat and cold. This was not due to any general change in the condition of the back of the hand, for the temperature-spots in the distal squares showed no diminution.

The diminished vividness of reaction, the increased range of sensibility and the inhibition of reference into remote parts were not due to an increase of the sensibility which had previously been present, but to the advent of a new sensory factor. This was proved by the experiment first made in May, 1905, of cooling the hand. We found that the mechanism upon which this new form of response depended was peculiarly susceptible to external cold.

After an extended series of observations, we placed the palm of the hand upon ice for a few minutes. It was then withdrawn and laid upon a towel as usual, and those parts from which no referred sensations had been obtained were again tested with an ice-cold tube. In every case, a sensation was evoked in some remote part as vivid and distinct as in the days before the hand became sensitive to intermediate degrees of temperature. External cold had thrown back the recovering area into a protopathic condition.

Before cooling the hand.	*After cooling the hand.*
(5) Local cold.	All over interosseous space.
(10) Local cold.	Up the arm to the scar.
(3) Local cold.	Head of first metacarpal and base of first phalanx of thumb.
(9) A diffuse sensation around the spot touched.	Metacarpal of thumb.

(The numbers represent the part to which the stimulus was applied, as shown on fig. 21, p. 414.)

By again warming the hand, the previous condition could be revived; reference disappeared from this part of the affected area which regained its sensibility to intermediate degrees of temperature. Further experiments on these lines will be described in chapter VII.

The affected area on the forearm first began to respond to temperatures between 37° C. and 34° C. in June, 1904. The sensation produced was not referred to some distant part, but was that of warmth localized to the point stimulated. At the same time, that portion of the forearm which had become increasingly sensitive no longer responded so vividly to temperatures below 22° C. Stimulation with 20° C. was frequently said to be neutral over the proximal patch, although definitely cold over the distal part of the forearm.

As the general sensibility of the forearm increased, spreading slowly in a distal direction, the response to temperatures between 18° C. and 40° C. became very erratic. A stage was reached in which the protopathic hand gave more definite results and would have been considered more sensitive than the forearm which had already advanced another stage to recovery. This was due to the diminished ease with which the full reaction could be evoked from the cold-spots, inhibited by the newly developed sensory function.

This disturbing uncertainty slowly passed away and the whole of the affected area on the forearm has become uniformly sensitive to temperatures above 35° C.; even 33° C., under favourable conditions, produces a sensation of warmth.

In conclusion, we found that the return of sensibility to cutaneous tactile stimuli was associated with a tendency to respond to temperatures between 26° C. and 37° C. This increase in thermal sensibility was not accompanied by an increase in number of the heat- and cold-spots. Radiation and reference into remote parts steadily diminished, and the sensations excited by a hot or cold object became closely associated with those produced by contact at the point of stimulation. During

the recovery of epicritic thermal sensibility, the hand could be degraded by cooling into a purely protopathic condition; radiation and reference returned as vividly as before, to disappear on again warming the hand.

Section 3.—The Compass-Test.

Tactile discrimination was absent throughout the stage when the affected area of the forearm and hand was innervated by deep sensibility only. Two points applied simultaneously were not distinguished, and every application of the compasses was said to produce a single sensation. H. showed no tendency to speak of the contact of a single point as "two."

With the return of protopathic sensibility, the compass-records became extremely irregular; not only were two points said to be one, but one point was as frequently thought to be two. Over the normal skin, this tendency to "double ones" commonly appears just before the threshold is reached and a slight increase in the distance between the two points will produce a record entirely free from mistakes. But in the protopathic stage, however highly the skin is endowed with this form of sensibility, uncontrolled by epicritic impulses, the single point frequently produced a double sensation even although the double stimuli were made with the points 10 cm. apart.

At a later period of recovery, when part of the affected area had become sensitive to cutaneous tactile stimuli, this doubling of the single point rendered all attempts to obtain an accurate threshold impossible. We were, however, able to show that it was peculiarly liable to occur, when one point of the compasses fell over distal parts of the limb, which were in a less advanced stage of recovery. Thus, in the forearm better records were obtained when the single point was applied in the upper patch than in the lower (distal), although the double stimulations were always made over the same spots.

This phenomenon of "double ones," as it occurred during H.'s recovery, seemed to be based on several different conditions. Stimulation with a single point sometimes produced two equally distinct tactile sensations, or one was more distinct than the other. Lastly, the sensation was occasionally of wide longitudinal extent, and so gave the impression that it was caused by two points at a distance from one another.

At the same time, stimulation with two points was sometimes called "one," because it produced a single tactile sensation with no abnormal quality; or the sensation was that of one point which seemed abnormally

heavy. This was extremely puzzling, because its singleness compelled H. to call it "one," although the additional heaviness led him to think that it must have been produced by two points.

These abnormalities seem to be due for the most part to the radiation and reference so characteristic of protopathic sensibility. In the case of the hand, where one part still remains in a protopathic condition, the records are still bad in proportion as one point of the compasses falls within the limits of this area. Moreover, on those occasions when the sensibility of the skin fell back into an active protopathic state, in consequence of unfavourable external conditions, the records even at 8 cm. became almost worthless.

In spite, however, of the difficulty caused by these "double ones," we could watch the gradual return of epicritic sensibility in the lowering of the threshold at which one and two points produced an indistinguishable sensation. In November, 1903, when the forearm was still in a purely protopathic condition, this limit was reached at 6 cm. Together with the return of sensibility to warmth in June, 1904, a change for the better in this respect came over the compass-records, and in August of the same year, the threshold at which the compass-stimuli became indistinguishable had sunk to 5 cm. Finally, in June, 1905, a formula was obtained—

$$4 \text{ cm. } \frac{1 \mid 9 \text{ R. } 1 \text{ W.}}{2 \mid 9 \text{ R. } 1 \text{ W.}}$$

—almost comparable with that from a similar part of the normal forearm—

$$4 \text{ cm. } \frac{1 \mid 9 \text{ R. } 1 \text{ W.}}{2 \mid 10 \text{ R.}}$$

But, although the threshold at which the stimuli of the compasses became indistinguishable was greatly lowered, every application of the test even at distances of 8 or 9 cm. produced records containing an unusual number of errors, both in the recognition of one and of two points. Over the normal forearm, no mistakes were made, until within about 2 cm. of the distance at which every stimulus was called "one." But over the abnormal area, even when it had been sensitive for more than three years to cutaneous tactile stimuli and to warmth below 37° C., a large number of single compass-stimulations were thought to be double. For instance, on August 25, 1907, we obtained the following formulæ :—

Affected forearm.	Normal forearm.
$6 \text{ cm. } \frac{1 \mid 7 \text{ R. } 3 \text{ W.}}{2 \mid 10 \text{ R.}}$	$\frac{1 \mid 10 \text{ R.}}{2 \mid 10 \text{ R.}}$

	Affected forearm.	Normal forearm.
5 cm.	1 | 6 R. 4 W. 2 | 10 R.	1 | 9 R. 1 W. 2 | 9 R. 1 W.
4 cm.	1 | 10 R. 2 | 3 R. 7 W.	1 | 10 R. 2 | 10 W.

In conclusion, we believe that spacial discrimination, as tested by the simultaneous application of two compass-points, is a function of epicritic sensibility. A protopathic condition of the skin leads to intense confusion, in consequence mainly of radiation and reference. The first effect on the compass-records of the return of epicritic sensibility is the reduction of the distance at which one and two compass-points produce a similar sensation. Then the erroneous "double ones" are gradually reduced in number. But, even at the end of five years after the operation, many errors of this kind were still present when the compasses are applied, even at a distance of 8 cm. over the abnormal area of the forearm.

Section 4.—The Sensibility of the Triangle.

A month after the operation, we discovered that a small triangular portion of the affected area near the wrist was in a remarkable condition, insensitive to a prick but responding to cutaneous tactile stimuli. We failed to recognize its existence until May 25, 1903, partly because its sensibility was defective even to those stimuli to which it responded, but principally owing to the condition of the skin produced by the antiseptics. As soon, however, as all bandages were removed and the forearm thoroughly cleansed of the epithelial flakes, the remarkable condition of this part of the forearm became evident.

From the first, there was no doubt concerning the main sensory characters of this area. It had the form roughly of a right-angled triangle with the base (3 cm.) towards the hand and the hypotenuse (4·5 cm.) on the extensor aspect of the wrist. The third side measured about 4 cm. in length (fig. 5).

Like all the rest of the affected area, it was obviously endowed with deep sensibility. Tactile pressure was appreciated and well localized. The sense of roughness, measured by Graham Brown's æsthesiometer, was equal to that of a similar area on the sound wrist.

But, unlike any other part within the borders of the loss of sensation, the skin was undoubtedly sensitive to cutaneous tactile stimuli; No. 5 of von Frey's hairs and, to a less extent, No. 4, were appreciated. Cotton

wool produced a sensation indistinguishable from that over the normal skin, unaccompanied by tingling, diffusion or reference into remote parts. Gently blowing on the hairs through a tube was at once appreciated. Within this area, from the day of its discovery, the point could always be distinguished with certainty from the head of a pin, although the skin was entirely insensitive to cutaneous painful stimuli. Localization, not only of pressure but also of cutaneous tactile stimuli, was as good as on a similar part of the normal forearm.

The remarkable feature of this area was the complete absence of all sensibility to cutaneous painful stimuli. A prick produced no sensation of pain, although the stimulus was recognized as a point. Pulling the hairs, so sensitive to the slightest movement, caused no pain.

The anomalous condition could best be demonstrated by electrical stimulation. Strong interrupted currents unbearably painful over the normal skin produced the characteristic whirring sensation devoid of any element of pain. But if the coils were separated so that the current was just appreciated, the threshold was only slightly higher over the triangle than over the corresponding area on the normal skin. (Coil distance, normal 2·5 cm., triangle 4·5 cm.)

Thus, although this area responded to tactile stimuli, its sensibility was less than normal. Although No. 5 produced a distinct sensation within the triangle, No. 4 was frequently not appreciated; but over the normal wrist many spots responded, even to No. 2. A similar slight diminution of sensibility was shown in the results of the compass-test. Over the normal wrist, when the points were separated to 3 cm., H. made no mistakes in the twenty applications, and the threshold lay between 3 cm. and 2 cm. But, over the triangle under similar conditions, four mistakes were made at this distance:—

$$3 \text{ cm. } \frac{1 \mid 8 \text{ R. } 2 \text{ W.}}{2 \mid 8 \text{ R. } 2 \text{ W.}}$$

When we turn to the observations on the thermal sensibility of this triangle, we are face to face with many difficulties. Our earlier experiments were made with ordinary test-tubes of glass, and it was not until August 15, when the sensory condition had materially changed, that we used silver tubes. Again, it was difficult to prevent radiation to normal parts when testing an area of this size. Moreover, we were not at this time fully alive to the importance of the external temperature; we did not recognize that in the climate of this country the hands are usually adapted to cold.

But, in spite of these defects, we can say with certainty that the

triangle remained insensitive to all temperatures below 22° C., until the appearance of the first cold-spot (October 15, 1903). Careful and repeated examination with the cold rods and with test-tubes containing ice failed to elicit any sensation of cold from any part of this area.

Similarly, we could discover no signs of heat-spots until November 9, 1903. But one of the most remarkable features of this area was its response to heat, applied not to points but to areas of 1 or more centimetres in diameter. Temperatures of from about 42° C. to 48° C. were at once said to be warm. But if the tube was at 50° C. or above, it was either called a touch or was said to be slightly warm, passing quickly into neutral. Had the warmth, appreciated when the stimulus was at 42° C., been due to radiation, a tube at 50° C. or above would have produced it with even greater certainty. Time after time the relative temperature of two tubes at 44° C. and at 55° C. were compared, when the former was invariably said to be the hotter of the two.

So far the results of our observations are definite. But one of the greatest difficulties was the tendency which H. showed to call cold stimuli "warm" within the limits of the triangle. Whenever a thermal sensation was produced at all, it was one of warmth; some of the most satisfactory warm sensations were evoked by an ice-cold tube and yet, at this time, temperatures of 50° C. and above were not appreciated. Even in the later days, when the triangle had become sensitive to prick, these higher temperatures evoked a sensation of pain only.

The first change which occurred in the sensibility of this area was on July 10, 1903, seventy-six days after the operation; it then became sensitive to painful cutaneous stimuli, such as a prick and the painful interrupted current. But it did not respond with a sensation of cold to temperatures below 22° C. until October 15, 1903, 173 days after the operation, when the first cold-spot was discovered within its limits. The cold test-tube laid on the skin elsewhere within the triangle caused no sensation of cold. On November 9, 1903, 198 days after the operation, the first heat-spots made their appearance, and from that time onwards the return of sensibility took place rapidly.

But throughout the whole of this period, the sensations which returned were not diffused or referred into remote parts. They were not more but less vivid than normal and in no way resembled those evoked from the greater part of the forearm and hand which had assumed the protopathic condition.

Here, owing to a fortunate anatomical peculiarity, the operation had produced on a small area of skin a condition of dissociated sensibility

which was the converse of that of the protopathic parts. It was sensitive to cutaneous tactile stimuli, but insensitive to those which would normally produce pain. Cold was not recognized, and temperatures above 50° C. were not appreciated; yet 42° C. to 49° C. seemed to produce a sensation of warmth, and were always said to be hotter than those of 50° C. and above.

Chapter VI.—Trophic, Vasomotor, and Pilomotor Changes.

Section 1.—*Vasomotor and Trophic Disturbances of the Skin.*

Changes in the nutrition and vascular supply of the part are among the usual consequences of dividing peripheral nerves. But if the injury is accidental, motor and sensory fibres are commonly destroyed together and much of the atrophy is due to the paralysis of the muscles. Even changes in the growth of the nails may be produced by the consequent immobility of the limb (Head and Sherren [17], p. 263).

But in our experiment all these sources of error were eliminated. Afferent nerves were alone divided, and during the period when the arm was immobilized on a splint, H. could move his fingers freely.

Care had been taken during the operation to protect the back of the hand from mechanical injury and irritation by antiseptics. But four days afterwards (April 29), the analgesic portion began to assume a somewhat swollen appearance. The surface was rough and the skin appeared white owing to the adherence of epithelial scales; with a magnifying glass it had a peculiar translucent appearance. A week later, the skin over the radial half of the back of the hand and dorsal surface of the thumb had become inelastic and wrinkled like that of an old man. This want of elasticity produced a sensation as if the back of the thumb were covered with collodion. But in addition the superficial layers of epithelium had formed minute bran-like scales; the affected portion was drier than the normal skin and the cracks more evident. The whole area was of a slightly deeper red than the rest of the skin of the hand, and therefore showed clearly on the photograph taken at this time (fig. 1). The hairs were disordered and did not lie in sweeping masses; they stood up or lay in an irregular manner, each hair assuming a different direction. The extent of these changes corresponded exactly with the area insensitive to prick.

The insensitive parts did not sweat, and in the hot weather of July, 1903, the difference between the normal and affected portion of the hand was striking. The normal skin was soft, moist and velvety, whilst

the abnormal area was dry and inelastic. If a needle was dragged across the back of the hand, the white marks produced by the scratch disappeared rapidly from the normal skin; over the affected portion they remained sometimes for several days as white powdery lines. Midge-bites, which occurred five days before, were still evident as pinkish round swellings, although those on the rest of the hand were no longer visible.

This dryness and absence of sweating began to disappear from the proximal part of the affected area 112 days after the operation, and they were no longer present over the forearm after 136 days. But the skin of the hand remained in an abnormal condition and did not cease to be dry until about 189 days after the operation (November 1, 1903). With this return of sweating, the hand lost the peculiar bluish colour which had characterized it throughout the first five months of the experiment (October 6, 1903).

Evidently the vaso-constrictor fibres and those which govern the sweating of the skin began to function 107 days after the operation and had regained their function even over the hand within 190 days.

In spite of these changes in the skin, the operation in no way affected the growth of the thumb-nail. Before the operation, the nails of both thumbs were marked with nitric acid and were found to be growing equally. Afterwards, they continued to grow equally, even when the affected area was supplied with deep sensibility only and throughout the whole period of protopathic recovery. The actual amount of growth varied considerably at different seasons of the year, but this variation affected the nails of both hands to the same extent.

In July, 1903, as the sequel to an extensive series of observations on the sensibility of the frozen hand, we noticed that a sore had appeared in the centre of the affected area, evidently the consequence of a cold burn produced by ethyl chloride. It seemed to start as a vesicle which had contained a minute quantity of fluid; the surface of this blister was removed in the course of washing and a raw surface was exposed. If protected, this sore tended to heal, but broke down again in consequence of the small injuries of ordinary life. Thus, any act which tightened the skin, such as grasping an oar or the handle-bar of a bicycle, opened the sore again after it had formed a scab. By taking the skin between the finger and thumb, serum and even blood could be expressed from its edges.

In this condition the sore remained until 152 days after the operation (September 24, 1903). It then showed signs of healing and became dry and scaly. From the periphery, epithelium appeared to be growing

in. Speaking broadly, the surface which a fortnight before appeared callous and unlikely to heal was now healing soundly and normally. This was coincident with the return of sensibility to prick to that part of the skin within which lay the sore. But its extreme proximal edge still remained analgesic, and it was not until 185 days after the operation (October 27), that this part of the hand became sensitive to prick and this edge of the sore healed finally. The strict relation between the healing of this trophic ulcer and the return of sensibility to prick was evident.

Section 2.—The Pilomotor Reflex.

Throughout the period when the skin of the forearm and hand was completely insensitive, it was impossible to produce erection of the hairs within the affected area. Vigorous stimulation of the skin of the chest with ice or other means would start the condition known as "goose-skin" which usually spread to both arms (Mackenzie [21]). Over the sound limb, all the hairs would be more or less erected, but on the left forearm, those of the affected area remained unchanged; this probably accounted for their disordered appearance.

With the return of protopathic sensibility, we noticed that the hairs could again be erected by suitable pilomotor stimuli. The exact date of the return of this reflex was not noted; but we gradually became aware that pricking the skin, pulling the hairs, or the application of the cold tube would occasionally give rise to a condition of "goose-skin" within the area we were testing.

As protopathic sensibility increased, this reflex could be evoked more easily from the affected area than from the normal skin. The iced tube placed on any active protopathic part might produce a widespread erection of the hairs over both the flexor and extensor aspect of the forearm which not infrequently spread beyond the limits of the area of defective sensibility. Even brushing the hairs with cotton wool in this stage of recovery would start a pilomotor reflex.

With the gradual return of epicritic sensibility to the forearm, this increased response died away, and at the present time it is no more easy to produce a pilomotor reflex from the affected area of the forearm than from other parts.

It is evident that the existence of a high degree of protopathic sensibility renders it easier to evoke a pilomotor effect. This excessive response is inhibited on the return of epicritic impulses.

Although stimulation of a protopathic area evoked a stronger pilomotor response, the erection of the hairs within this area was no greater

than elsewhere, if the reflex was a general one produced by placing ice upon the chest. The increased effect caused by stimulating a protopathic area must therefore have been due to physiological conditions affecting its afferent impulses and not to any structural change in the central mechanism. Absence of that control usually produced by the coincident activity of epicritic impulses allowed those from the protopathic area to exercise a greater influence upon the central pilomotor mechanism. Had the excessive reaction been due to an anatomical change in the centre, a reflex evoked by general means, such as ice applied to the chest, would have produced a greater erection of hairs over the affected area than elsewhere; this was not the case.

During the period when the back of the hand was in a condition of active protopathic sensibility, we noticed that a referred sensation was liable to be associated with erection of the hairs over the remote area in which it was situated. Thus, pricking the region near the wrist would produce not only a sensation, but also erection of the hairs of the forearm near the scar. If the stimulus produced a severe protopathic reaction, this pilomotor reflex would become general; but if slighter, it tended to appear at the site of the referred sensation.

Whilst engaged on these experiments, we discovered that the "thrill" called forth by æsthetic pleasure is accompanied by erection of the hairs. In H.'s case, it started in the region of the neck and spread rapidly down the arms, over the trunk, the thighs and outer aspect of the legs. If he sat with his arms bared to the shoulder in a carefully warmed room he could evoke the reflex by reading aloud some favourite poem. At a certain point he would call out that the thrill was beginning and shortly afterwards the long hairs on both forearms were seen to be erected, and the characteristic acuminate appearance was noticed upon the skin. This general pilomotor reflex was no greater over the highly protopathic area than elsewhere on the arms.

Chapter VII.—Adaptation to Heat and Cold.

After we had convinced ourselves by repeated experiment that the affected hand behaved differently in the winter and in the summer, we attempted, by changing its temperature, to alter its reaction to thermal stimuli. We found that, by laying the palm of the hand upon ice, we could throw back the greater part of the affected area into the protopathic condition. Cold had so reduced the sensibility of the skin that

parts, which had almost returned to the normal condition, reacted as if they were in an earlier stage of recovery.

This led us on to examine the behaviour of the affected area when adapted to moderate degrees of heat and cold. If one hand is dipped into warm water, the other into cold, the same object at an intermediate temperature will seem cold to the former and warm to the latter. This is the well-known experiment on adaptation. We modified it by adapting both hands to the same temperatures and comparing the sensation produced by the same object over normal and abnormal parts.

The majority of these observations were made at sittings between December 2, 1906, and March 24, 1907. By a fortunate chance, the external temperature was on every occasion almost exactly the same; the highest reading was 14° C., the lowest 13° C. All these experiments, therefore, were begun with the hands adapted to a temperature of from 13° C. to 14° C.

Throughout the following experiments, two regions within the affected area were distinguished by their behaviour: (1) a purely protopathic part in the neighbourhood of the second metacarpal and occupying the space between the knuckles of the index and middle fingers; (2) that portion of the affected area, already far on towards recovery, which lay over the wrist and first metacarpal bone. But, since the latter behaved throughout like a normal area of lowered sensibility, attention will be directed mainly to the sensations produced from the protopathic parts of the affected hand.

The simplest form of the experiment was carried out in the following way. By preliminary observations, we found that a copper block at a temperature of 29° C. did not appear hot or cold over any part of either hand. Both hands were then placed in a basin of water at 50° C. After a time, they were removed, dried and placed in the usual position for testing. The stimulus at 29° C. now seemed cold when applied to the right hand and to the normal parts of the left, and cool over the metacarpal portion of the affected area. But elsewhere over this part of the hand, it produced no sensation of either heat or cold. So definite was this absence of sensation, that it could be used to mark out the boundaries of the affected area.

The hands were then put into water containing melting ice. When they were removed, the copper block at 29° C. seemed warm over the right hand and over normal parts of the left. Within the affected area, it produced no thermal sensation, excepting over the metacarpal portion, where it seemed to be warm.

This experiment shows that the thermal sensibility of protopathic parts did not undergo that shifting of threshold, which can make a temperature of 29° C. seem at one time hot and at another cold.

But the threshold of thermal sensibility over protopathic parts may shift, although not to this extreme degree. We therefore carried out a series of observations of which the most complete were made on March 2, 1907. The external temperature was 14° C. The hands were adapted to water at 45° C., removed from the basin and dried; after a few observations, they were returned to the basin, within which the water was kept at a constant temperature. Thus, they could be maintained in a condition of warm adaptation for the long period necessary for the following observations. In this condition 33° C. was found to give a neutral sensation over the normal hand and over normal parts of the left hand; temperatures of 30° C., 31° C. and 31·5° C. were called "cool neutral," and 29° C. seemed definitely cold. But over the protopathic area, none of these temperatures gave any thermal sensation. Cold was not evoked until the temperature was reduced below 24° C.

Over the right hand and normal parts of the left, 35° C. was said to be "warm neutral"; but 37° C. seemed definitely warm, even at a distance from heat-spots. Within the affected area, no sensation of heat was produced, until the stimulus reached 41° C., when it caused a characteristic outburst over the group of heat-spots in squares 26 B, 26 E, and 25 D; elsewhere it caused no sensation.

Thus, when the hands were warm-adapted (45° C.), the neutral point over normal parts seemed to lie at about 33° C. Temperatures of 29° C. were said to be definitely "cold," and 31·5° C. was called "cold neutral." At the opposite end of the scale, 35° C. produced a sensation of warmth which rose to definite heat at 37° C. But over protopathic parts, no temperature above 24° C. caused a sensation of cold, and no sensation of heat was produced by any temperature below 40° C. Moreover, whether the stimulus seemed to be hot or cold, the sensation had the characters of that evoked from spots.

When the hands were adapted to water at 13° C., 27° C. was found to be neutral everywhere over normal parts; 28° C. and all temperatures above seemed definitely warm. But over the protopathic area, no sensation of heat was produced until the stimulus reached from 39° C. to 41° C. A temperature of 20° C. evoked a sensation of cold from both normal and affected parts of the hand.

If the water in which the hands are adapted was lowered to 10° C., it occasionally happened under suitable conditions that a temperature of 22° C. seemed neutral over normal parts, but caused a definite outburst of

spot-cold when applied to the affected area. We thus produced the paradoxical result, that parts of low general sensibility reacted definitely to temperatures which produced no sensation over the normal skin.

These experiments on cold adaptation are more difficult to carry out than those in which the hand is warmed. Throughout a great part of the year, the external temperature is so low that the exposed parts of the body are permanently adapted to cold. An attempt further to lower the temperature of the hand may cause it to become blue and cold, and lead to a serious diminution of general sensibility which frustrates the object of the experiment. Even 18° C. may then produce no sensation of cold over the affected area or any other part of the hand, the cold-spots may react feebly to temperatures that are usually effective and the intensity of the referred sensation is diminished.

Thus, dipping the hand into cold water may produce three separate conditions according to circumstances. Firstly, over normal parts a simple shifting of threshold may take place ; secondly, a part on the way to recovery and showing definite signs of epicritic sensibility may be thrust back to a purely protopathic condition as described on p. 396. Thirdly, especially in winter when the hand tends to be constantly cold-adapted, the application of severe cold may produce a condition of lowered general vitality, which diminishes the reaction, even of protopathic parts.

When the normal hand is adapted to heat, 33° C. becomes the neutral point, 35° C. seems to be warm and 31° C. cool. Carefully adapted to cold, the neutral point shifts to 27° C. and all temperatures above 28° C. are said to be warm.

Now, the highest temperature to which the cold-spots reacted was 26° C., and most of them did not respond to 24° C. Even when the hand was adapted to heat, no sensation was produced by any higher temperature. It is therefore evident, that some mechanism other than the cold-spots must exist in the normal skin by which a sensation of cold is evoked with temperatures between 24° C. and 31° C.

In the same way, when carefully adapted to cold, 28° C. may seem warm to the normal hand ; yet the purely protopathic part never responded to temperatures below 37° C. and most heat-spots are insensitive to temperatures below 40° C. It is equally evident that there must be a mechanism other than the heat-spots by which sensations of warmth can be evoked with temperatures between 28° C. and 37° C.

These observations remove the difficulty experienced by Head and Sherren ([17], p. 224) in proving the existence of the sensation of coolness, apart from the reaction of cold-spots. Under the usual

conditions, working with hospital patients, they could obtain no sensation of cold with temperatures above 24° C., and they found that even protopathic parts would respond to such stimuli under favourable conditions. But we have shown that, by adapting the hand to heat, there is a range of at least 5° C. above the highest limit of the cold-spots, within which stimulation of normal parts may produce a sensation of cold.

These observations may be summed up in the following conclusions :—

(1) Over normal parts, the neutral point of thermal sensibility shifts according as the hand is adapted to heat or to cold.

Over protopathic parts, no such change occurs. The heat-spots do not react to temperatures below 37° C., even when the hand is adapted to cold, nor does adaptation to heat raise the highest limit of the cold-spots above 26° C.

(2) It follows that some innervation other than protopathic must exist in the normal skin, which renders it sensitive to temperatures between 26° C. and 37° C., and that this mechanism is capable of adaptation within a wide range.

(3) By carefully adapting the hand to cold, a paradoxical condition can be reached, in which a temperature of 22° C. produces no sensation of cold over normal parts, although it evokes a definite sensation from the affected area. This is due to the fact that protopathic parts are incapable of adaptation to any material extent, and the cold-spots continue to react to 22° C., although it produces little or no sensation over the normal cold-adapted hand. By this experiment, parts in a condition of defective sensibility have been rendered apparently more sensitive to the specific stimulus of cold.[1]

[1] The significance of these experiments depends upon the supposition that the normal and abnormal parts of the hand do not assume materially different temperatures after cooling and warming. To investigate this not improbable source of error we obtained the help of Dr. Bayliss, who kindly carried out with us a series of experiments on the temperature of the skin with a thermo-electric junction, in the Physiological Laboratory at University College. We tested the temperature of the dorsal surface of the hands after they had been warmed in water at 45° C. and cooled in water at 15° C. Two areas were chosen on each hand, one in the first and the other in the fourth interosseous space. By this means we tested on the left hand the behaviour of a normal against an abnormal area of skin; but, lest these two spots should naturally behave differently to warming and cooling, we carried out a series of tests over similar spots on the right hand. The results showed that the small differences in the temperature of the normal and abnormal parts after warming and cooling, lay within the limits of experimental error. The following table gives the results obtained in the most satisfactory series :—

	First interosseous space.	Fourth interosseous space.
Left hand.		
Cooled in water at 15° C.	19·2	19·2
Warmed in water at 45° C.	30·4	31·4
Right hand.		
Cooled in water at 15° C.	20·1	19·4
Warmed in water at 45° C.	31·8	31·6

CHAPTER VIII.—LOCALIZATION AND SPACIAL DISCRIMINATION.

Among the many curious facts elicited by this inquiry, none are more remarkable than those bearing on localization. At the time when the affected area was innervated by the afferent fibres of muscular nerves only, tactile pressure was localized accurately, although two points simultaneously applied to the skin could not be discriminated. Then followed the period when protopathic sensibility returned, and cutaneous stimuli began to be localized over some area at a distance from the point of impact. Slowly, with the return of epicritic sensibility, the power of accurate localization of cutaneous stimuli was restored.

Each of these conditions has been described in its proper place; but many of our observations are of such psychological interest, that we have deemed them worthy of more detailed consideration.

(1) *Deep Sensibility.*

After division of all the nerves to any area of the skin, the part is supplied solely with deep sensibility. A touch made with a certain amount of pressure can be localized with remarkable accuracy. At first, our observations were complicated by the unsatisfactory condition of the skin; but as soon as the œdema and swelling had passed away, we could not discover any obvious difference in the accuracy with which tactile pressure could be localized over corresponding parts of the two hands. H. visualizes strongly [1] and his accurate localization over the affected area was best shown when he was asked to mark the spot touched on a life-sized photograph of his hand (figs. 15 and 16.) Moreover, when allowed to indicate the place that had been touched, his answers were as accurate on the one hand as on the other, though his eyes remained closed throughout.

But in spite of this he could not discriminate two points applied simultaneously to the skin, even when separated to the greatest distance possible over the affected area on the back of the hand. Two points applied successively were at once recognized, even when 1·5 cm. distant from one another.

All appreciation of size and shape was lost over this area; the flat of

[1] On p. 343 stress was laid on the difficulties which arise, in consequence of the inability of a strong visualizer to reproduce cutaneous sensations. But throughout these experiments on localization and spacial discrimination, H. localized every sensation on a visual picture which corresponded remarkably with the proportions of the normal hand. This gave his answers a definiteness and security, unattainable when the quality of the sensation was in question.

a knife could not be distinguished from its edge, nor the head from the point of a pin. When a very large surface was applied to the back of the hand, H. thought it seemed to him large, because he had a visual picture of his hand upon which were certain points of reference such as the index knuckle and head of the first metacarpal. It was not possible to apply a large surface to the affected area in such a way that these points of reference would be stimulated simultaneously ; and even a small interval between the moments at which different parts of the stimulating surface came into contact with the skin was sufficient to evoke the picture of two points. If these points were widely distant from one another, H. judged that the object must be of large size. But the more nearly the various distant parts of the affected area were touched at the same moment, the less was he able to recognize the extent of the surface stimulated.

Deep sensibility conveys the power of appreciating the locality of the part pressed upon, but not the ability to discriminate two points applied to the skin simultaneously. Nor does it convey any of those sensory qualities which underlie the appreciation of size and shape.

Head and Sherren ([17], p. 214) were able to show that, if a part possessed deep sensibility only, the position and movements of the joints could be accurately recognized. This question did not come to direct experiment in the case of H., but we can be certain from cases of accidental injury that the presence of deep sensibility enables the patient not only to localize the spot touched but to recognize the position of his limbs in space.

(2) *Protopathic Sensibility.*

So long as the affected area was innervated by the afferent fibres of muscular nerves only, the position of a touch was well localized. But with the first signs of returning protopathic sensibility, localization became gravely disturbed. This disturbance took two forms. The sensation seemed to be diffused to a varying extent round the point actually stimulated, and for this phenomenon we have throughout this paper used the term " radiation." In the other form there was produced a sensation also diffuse, but situated in a region remote from the point stimulated; this phenomenon we term " reference." Cold or a prick applied to the forearm not only radiated widely but produced a sensation in the thumb, and H. could no longer recognize which part of the affected area had been stimulated. With the return of cutaneous

painful and thermal sensations, the power of localization, previously sufficiently accurate, was greatly disturbed.

As protopathic sensibility improved, the radiation greatly increased, and the tendency to refer the sensation into remote parts became more definite. H. was conscious of a struggle between the local sensations, evoked by the pressure of a cold tube, and the coldness which seemed to be situated in some part at a distance from the point stimulated. In the early days of returning protopathic sensibility, the former was dominant, and correct localization was possible, in spite of the radiating and remote sensations of tingling, cold or pain. Later, when protopathic sensibility had reached a high stage of development, this was no longer the case, unless the tube was applied with considerable pressure to the skin.

To evade the localization due to deep sensibility, we employed minute drops of ether or of ethyl chloride, instead of the ice-cold tube; the characteristic radiating and referred sensations of cold then appeared unhampered by the consequences of pressure. Such a stimulus applied to the wrist might cause the whole affected area on the back of the hand, including the greater part of the thumb, to become icy cold, and stimulation of a group of spots on the forearm was followed by an intense coldness over the whole dorsal surface of the thumb.

In these experiments, H. was in every case unconscious of the actual place of stimulation. He sat with his eyes closed, and in consequence of the even temperature of the room experienced no spontaneous sensations from the hand. Gradually out of this state of quiescence arose a more or less definite sensation of cold, entirely free from any element of touch, pain or tingling. This seemed to be situated over an area of considerable size, and was never limited to a point corresponding with that actually covered by the stimulus. There was no consciousness of anything in contact with the skin; the sensation was one of pure cold, and corresponded with nothing previously experienced by H.

The relative intensity of the radiating sensation and of that referred to some remote part varied greatly. But in every instance, the stimulus, however little tactile its character, was accompanied by some diffuse sensation in a situation approximate to the point stimulated. In some cases this might be so faint compared with the vivid reference that it scarcely aroused consciousness; on the other hand, the disturbance around the site of the stimulus might be so great that the remote sensation would have escaped notice without careful introspection.

To test the constancy of this reference, eleven situations were chosen over the back of the hand and marked on a life-sized photograph.

These situations were repeatedly tested between January, 1904, and the end of 1907 with every form of stimulus to which protopathic sensibility responds (fig. 21).

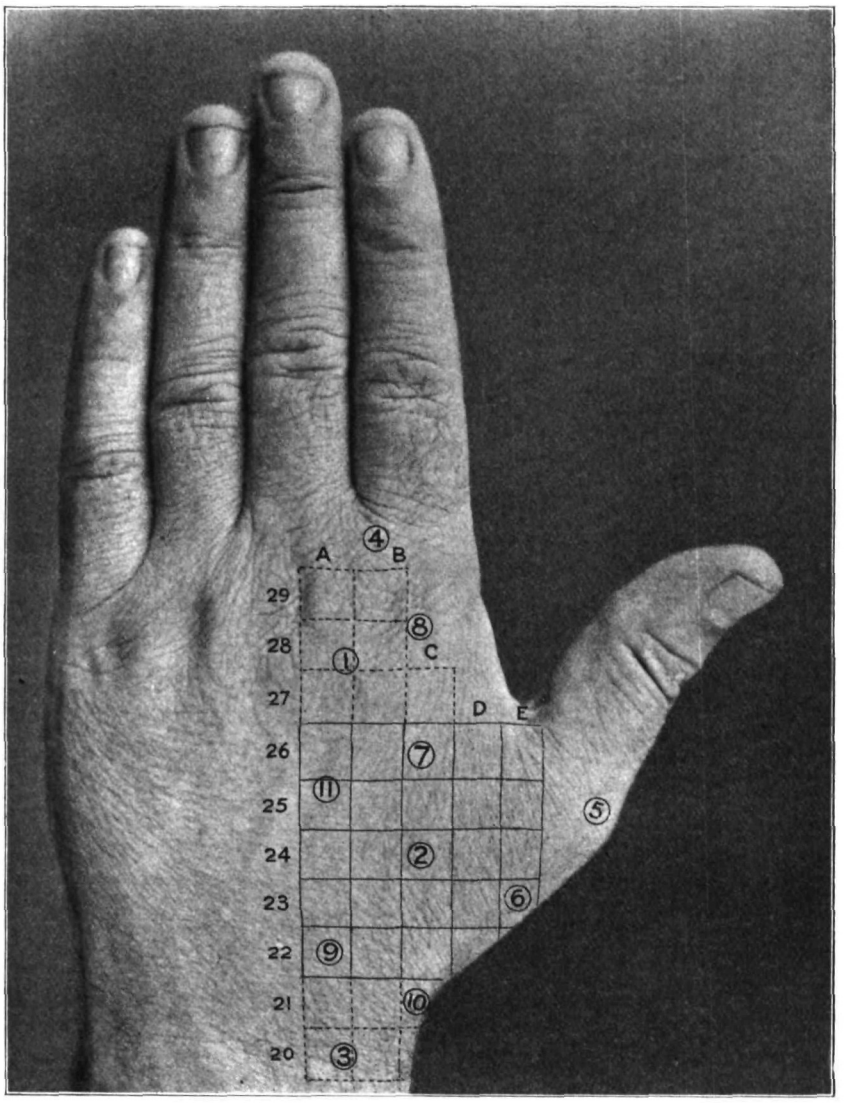


FIG. 21.

The circular numbered areas show the spots habitually stimulated when investigating the position of the referred sensation.

The squares marked in unbroken lines are those used throughout the whole research. Those enclosed within dotted lines were used to determine the position of the referred sensation when stimulating isolated heat- and cold-spots.

The back of the hand was also marked out into squares, and the position of the referred sensation determined for each square centimetre (fig. 21).

Of all stimuli, cold gave the best results; for it could be applied exactly to any point, whilst with cotton wool the rubbing backwards and forwards was liable to stimulate hairs which belonged to areas not directly over the situation desired. Pricking was also unsatisfactory, because of the duration of its after-effect and the prolonged diminution of sensibility by which a vigorous reaction to this stimulus was followed. Pulling the hairs was also comparatively unsatisfactory for the same reasons.

The eleven situations selected within the affected area on the back of the hand were tested on thirty-seven occasions with cotton wool, thirty-five times by stimulation with an ice-cold tube, six times with the prick of a pin, and four times by pulling hairs.

As a general rule, the constancy of reference was greater in the case of the cold tube than with cotton wool; this probably depends on the difficulty in limiting the latter mode of stimulation in every case to the same spot. In order to study reference, cold was always evoked by placing the flat end of the silver tube on the skin, so that the area covered was well defined and accurately limited to the region it was intended to stimulate. Cotton wool, however, had to be swept over the skin with some vigour, in order to elicit a sensation of sufficient intensity to provoke distinct reference, and, though every endeavour was made to limit the extent of the stimulus, it must have been usually wider than the area covered by the bottom of the cold tube. Further, even if the spot actually touched with cotton wool were strictly limited, the area of skin affected would be considerably larger, owing to the slope of the hairs; for a touch on one spot may, by moving a hair, actually stimulate a part of the skin 1 cm. or 2 cm. distant. The extent of the referred sensation was usually greater with cotton wool than with the cold tube, although the latter was a more intense stimulus. This must certainly have been due to the larger area stimulated by the cotton wool.

Of all the situations chosen (fig. 21), No. 10 lying close to the extensor tendons of the thumb, produced the most constant referred sensation. When stimulated with cotton wool, a characteristic tingling was produced in that part of the forearm which has been called the upper patch and lies in the neighbourhood of the distal end of the scar. Radiation was present around the wrist, but reference occurred invariably

to the forearm. A cold test-tube produced equally constant results; on the twenty occasions upon which a referred sensation was evoked, it was situated in the same part of the forearm. Here no confusion was possible between radiation and reference. The one sensation seemed to be widely distributed over the back of the wrist within the affected area, whilst the other lay in the proximal part of the forearm.

No. 1, lying between the knuckles of the index and middle fingers, was another area from which reference to a remote part was almost constant. Forty-four times (twenty with cotton wool and twenty-four with cold) some portion of the thumb or its metacarpal was the seat of the referred sensation; twice only was it said to be over the radial aspect of the first interosseous space.

Stimulation of the two neighbouring situations, No. 8 and No. 4, gave results of almost equal constancy. In the case of the former, reference took place to the metacarpal of the thumb in forty-six instances (twenty-two with cotton wool, twenty-four with cold), and ten times to the radial aspect of the interosseous space, whilst stimulation of No. 8 was followed in fifty-three cases (twenty-six with cotton wool, twenty-seven with cold) by reference to the metacarpal or some part of the thumb; eight times to the radial aspect of the space and once to the wrist.

The two phalanges of the thumb lay outside the situations originally chosen, but have lately been the subject of an extended study in connexion with the conflict of referred and local sensations. The terminal phalanx is in the case of H. entirely devoid of hairs and could not be stimulated with cotton wool in its purely protopathic condition. But with cold and with heat, the referred sensation was in every case situated over the region between the knuckles of the index and middle fingers.

Reference from the basal phalanx of the thumb took place invariably to the same part; but when the fold of skin over the interphalangeal joint was stimulated, the sensation was referred occasionally to the wrist or to the index knuckle.

Less constant results were produced by stimulating the remaining situations on the back of the hand. One cause of this discrepancy, especially in the earlier observations, was the failure to distinguish between radiation and reference. As H. was in all cases ignorant of the actual position of the point stimulated, except in as far as he was guided by accompanying sensations of pressure, he was frequently unable to distinguish the two sensations. But, if the radiation and reference were

widely separated, as when stimulation of the index knuckle produced a sensation in the thumb, no confusion was possible; it was from such situations that the answers were found to be most constant.

Moreover, several of the chosen situations seem to lie within areas which may refer to two different places. This is well illustrated by the results obtained from stimulating No. 3 on the dorsal surface of the wrist. On twenty-two occasions, the remote sensation seemed to be situated in the first metacarpal, and twelve times in the basal phalanx, making in all thirty-four times to some part of the thumb. But a definite referred sensation to the forearm was produced nineteen times from the same spot. We found that by shifting the tube slightly we were able to change the position of the referred coldness from the thumb to the forearm. Evidently No. 3 lay in the neighbourhood of two areas, one of which tends to be associated with reference to the thumb, the other to the forearm.

By combining all our observations, made by stimulating chosen situations or squares marked on the back of the hand, it appears that reference takes place somewhat as follows. The area on fig. 22 I. refers usually to some part of the forearm, that on fig. 22 III. tends to refer mainly into the thumb, and the whole thumb including a small portion of the radial half of the first interosseous space is associated with reference to the region of the index knuckle. In the same way, stimulation of the proximal patch on the forearm (fig. 22 IV. A) tended to evoke a sensation in the back of the hand, and the distal area (fig. 22 IV. B) was similarly associated with the skin over the base of the metacarpal of the thumb.

As far as we could tell, the various specific sense-organs, cold-spots, heat-spots and pain-hairs situated in any small area of the skin were associated with sensations referred to the same remote parts. Heat-spots were so scattered and so few in number that the material for such a generalization was scanty. But whenever the heat-spot was active, it was found that the sensation of heat was referred to the same area as the coldness produced by stimulating the adjacent cold-spots.

Stimulation of the area on the dorsal aspect of the thumb, shown on fig. 22 II., caused a sensation referred to the distal and ulnar aspect of the affected area on the back of the hand. Conversely, stimulation of this region of the skin (fig. 22 III.) caused a referred sensation in the thumb. So constant was this cross reference that it could be utilized for a series of experiments on inhibition.

During the earlier stages of recovery, we were not sufficiently aware of

the constancy of this cross reference. But we were repeatedly struck with the tendency of the proximal part of the affected area on the forearm (fig. 22 IV. A) to be associated with the area on the back of the hand; similarly, stimulation of the distal portion of the affected forearm (fig. 22 IV. B) tended to be associated with a sensation over the meta-

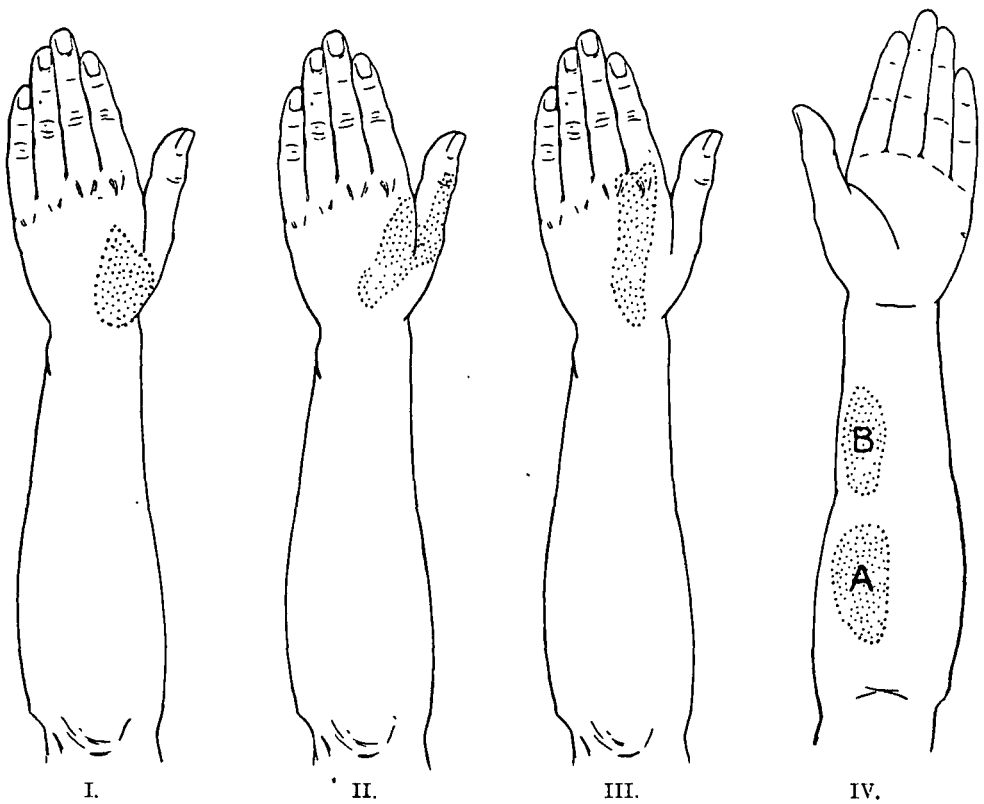


FIG. 22.

By marking out the whole of the dorsum of the hand with squares we found that stimulation of the area shown on I. caused a referred sensation in the forearm in the neighbourhood of IV A.
Stimulation of the area shown on II. caused a referred sensation in the region of the index knuckle.
Stimulation of the area shown on III. caused a sensation in the thumb.
Stimulation of the area marked A on IV. evoked a sensation over the dorsal surface of the hand near the wrist and that of B caused a referred sensation in the thumb.

carpal of the thumb. We were, however, unable to work out this relation so completely on the forearm as on the hand, for by the time reference from the hand to the forearm was fully established, recovery had so far advanced that the forearm no longer produced a referred sensation.

Throughout this long series of observations, reference was always to a part within the affected area; it never lay over any normal part of the hand. Long after the forearm had returned so nearly to a condition of normal sensibility that stimulation with cold was no longer associated with reference, it was still possible to produce a sensation in the forearm by stimulating the back of the wrist. The parts over the metacarpal of the thumb have so far regained sensibility that no remote sensation can now be induced by stimulating the skin. But this part of the hand is still the seat of vivid referred sensations, whenever the ulnar and distal portions of the affected area are stimulated with cold or with cotton wool.

Throughout the whole period of protopathic recovery, localization was profoundly changed. At the same time, all spacial discrimination was absent, including all recognition of relative size. The results obtained with the compass-points were even less accurate than when the hand was innervated by deep sensibility only. Then the contact of a single point was rarely said to be two; but in the protopathic stage this occurred repeatedly. The application of a single point not only evoked a widespread tingling, but also in many cases a distinct remote sensation which greatly confused the answers to the compass-test.

(3) *Epicritic Sensibility.*

With the first signs of returning epicritic sensibility, reference occurred less frequently and radiation became diminished.

In the early part of November, 1904, when the shaved hand first became sensitive to cotton wool, it was found that a change had come over the nature of the reaction to an ice-cold tube; the sensation radiated widely around the spot stimulated, but was referred less than usual to remote situations. From those parts, however, which showed no return of epicritic sensibility, such as the neighbourhood of the index knuckle, the referred sensation was as vehement as ever.

In December of the same year, the sensibility of the hand went back in consequence of the winter cold; radiation and reference were as vivid as in the purely protopathic condition, and little if any of the affected portion of the hand was sensitive to cotton wool after shaving. In February, 1905, there was not a single situation within the affected area from which we did not obtain a referred sensation. From No. 10 near the wrist it was projected into the upper patch on the forearm as intensely as before.

With the coming of spring (April, 1905), seven out of the twelve

situations gave local radiation without reference on stimulation with the ice-cold tube. There was coincident improvement of sensibility to cotton wool, and the results of the compass-test were the best so far recorded.

In June, 1905, the hand had further improved and a referred sensation was obtained on stimulation of the parts near the index knuckle only. Sensibility of the shaved hand to cotton wool had greatly increased, and the compass-test gave good results at 4 cm. when the points were placed longitudinally so as to fall as much as possible within the area of partial recovery.

Sensibility again degraded during the winter of 1905-6, accompanied by the reappearance of the phenomena of reference and widespread radiation. We therefore had the opportunity of confirming and amplifying our previous observations. But it is not necessary to wait for these annual fluctuations of temperature; artificial cooling will produce similar changes in the sensibility of the recovering parts. On July 6, 1905, reference was almost entirely absent and radiation greatly diminished. But after the palm of the left hand had been laid upon ice for a short time a referred sensation could be evoked from every situation within the affected area; even stimulation of the parts near the wrist was associated with coldness or tingling in the forearm. Similar changes were observed throughout the long series of experiments on adaptation made during the winter of 1906-7.

The inhibition of reference and radiation, which accompanies the return of epicritic sensibility, is evidently due to the opening up of fresh paths in the peripheral nervous system. The mechanism associated with protopathic sensibility is not gradually educated into something higher; but the consequences of its peculiar activity are checked in the central nervous system by the coincident existence of epicritic impulses. Inhibited and controlled, they are ready to burst out in the form of radiation and reference, as soon as the activity of the dominant mechanism is diminished by cooling the hand.

We therefore determined to test this control, by placing an ice-cold tube partly within and partly without the protopathic area on the back of the hand. The distal part of the affected area was still in an actively protopathic condition during the winter of 1907. It was separated from normal skin by a well-defined border almost coincident with the line of the third metacarpal bone. Here we could place an ice-cold tube so that the circular area of its base might be distributed in varying proportion between parts of normal and abnormal sensibility. When the tube was placed so that one half fell on the normal, the other on the abnormal

side of the border in the region of square 27 A, a vivid coldness appeared in the thumb which disappeared, and was replaced by an entirely local sensation. Reference was wiped out as completely as if a current had been switched off. Sometimes the remote sensation reappeared in a fainter form to be abolished again completely.

This control of radiation and reference cannot be definitely said to be associated with any one factor in epicritic sensibility. The change occurred with the first signs that the affected hand was sensitive to warmth and to cotton wool after shaving. The compass-test still gave poor results at 6 cm.; but it must be remembered that the extent of skin to which epicritic sensibility was returning was at first so situated that the two points of the compasses could not be placed simultaneously within it. Later, we always found that row D gave uniformly better results than row B, which shows that with returning sensibility to warmth and to cotton wool after shaving came an increased power of spacial discrimination. This is the only new spacial faculty restored by the recovery of epicritic sensibility. Tactile localization and the sense of passive position were present from the beginning of the experiment; spacial discrimination alone was absent. If therefore the disappearance of radiation and reference is to be associated with any one element of epicritic sensibility, it is probably spacial discrimination which is responsible for the cessation of the abnormally wide diffusion of protopathic sensations.

The results at which we have arrived in this chapter may be summed up as follows:—

(1) Accurate tactile localization is possible even when the part is supplied with deep sensibility only, provided the pressure is sufficient to stimulate the deep afferent system.

Accurate localization of cutaneous stimuli does not return until the skin becomes sensitive to von Frey's tactile hairs and to cotton wool after shaving.

(2) It is possible to recognize the position of the parts in space and to appreciate the movement of the joints even though the limb is innervated by deep sensibility only.

(3) Tactile discrimination, the recognition of two compass-points applied simultaneously to the skin, is impossible in the absence of epicritic sensibility, except at distances enormously in excess of the normal.

(4) The protopathic condition is associated with a tendency to produce sensations in parts remote from the point of stimulation. If care

is taken to avoid tactile pressure, it may be impossible to recognize to what part of the skin the stimulus has been actually applied.

The existence of epicritic impulses inhibits this tendency to refer into remote parts. Thus, the first signs of returning sensibility to cutaneous touch and to minor degrees of heat led to a diminution of these referred sensations. In the same way, the return of sensation to prick and to the extremes of heat and cold to a part such as the triangle, previously sensitive to cutaneous tactile stimuli, was not associated with any tendency to reference. Even coincident stimulation of an adjacent part in the normal condition seems to have an inhibiting effect on this tendency of the protopathic skin.

(5) Localization is in all probability the sum of two sets of sensations, one of which arises from deep, the other from cutaneous stimulation. But with the remaining spacial elements the conditions are somewhat different. Deep sensibility is responsible for our knowledge of the position of our limbs in space, whilst stimulation of the epicritic system is necessary to evoke the power of spacial discrimination. Each of the two systems brings its addition to the impulses which underlie localization; but sense of position in space depends on deep sensibility alone, spacial discrimination on the activity of the epicritic system only.

Chapter IX.—Intensity.

Throughout the previous chapters, we have repeatedly dwelt on the vivid response of protopathic sensibility to painful stimuli. A prick, which on the normal skin gives rise to little more than a sensation of sharpness, may in the protopathic condition produce a response so unpleasant that it would in ordinary language be said to be much more painful.[1] We have little doubt that the trained psychologist experiencing the two sensations would say that the pain in the second case was of greater intensity, and, if speaking in terms of the sensibility of the skin, he would say that in the protopathic condition, it was more sensitive. On exact examination, he would expect to find that the skin

[1] All unpleasant protopathic sensations are associated with an unusually disagreeable feeling-tone. Those which are pleasant, such as the heat evoked by stimulating heat-spots, are unusually agreeable. Thus a temperature of 40° C. applied to a part devoid of heat-spots is less distinctly pleasant than when it is brought to bear on a group of active heat-spots in a protopathic area. Conversely, pain evoked even from a protopathic area of defective sensibility is more disagreeable than that produced by the same stimulus applied to the normal skin. In addition to pain, which is a measurable sensation, we must distinguish discomfort ("Unlust"). In cases of injury to the spinal cord discomfort may be produced over a totally analgesic area by potentially painful stimuli (*vide* Head and Thompson [18], p. 644).

had a lower threshold for pain, *i.e.*, that pain would be produced with a smaller stimulus than over normal parts.

Observations made with the algesimeter and with von Frey's pain-hairs have shown that this is not the case. The increased response to painful stimuli may even occur with a threshold considerably raised.

For, during a considerable part of the five years that have elapsed since the operation, the back of the hand was in a condition of low protopathic sensibility. Not only was the skin insensitive to such stimuli as light touch and warmth, but even painful sensations had a higher threshold than over normal parts. Yet in spite of the incomplete restoration of protopathic sensibility, the response to painful cutaneous stimuli was greater than normal. If attention is paid to the character of the sensation resulting from an equal stimulus to similar parts on the two hands, the affected area would seem to be more sensitive on account of the greater painfulness. But if the sensibility of the skin was measured by the threshold of stimulation, the affected area would be called less sensitive than normal.

This difference came out clearly, when the point of a pin was dragged across the back of the hand from normal to protopathic parts. The change was so sudden and the new sensation so painful, that the border could be marked out to within 2 mm. And yet at the same time the threshold for painful stimuli was higher than normal over the affected area.

It might be supposed that the exaggerated response of protopathic pain was due to some incomplete restoration of the functions of the mechanism for painful sensations, which would diminish or pass away with the lowering of the threshold to the normal. But this is not the case. Fortunately, a small part of the affected area still remains in a purely protopathic condition. Here the threshold for painful cutaneous stimuli does not materially differ from that over a similar part of the normal hand. But the sensations evoked from the affected area are still both more unpleasant and of greater extent than normal. The approximation of the threshold for painful stimulation to that over normal parts, far from decreasing, seems actually to have increased the vividness, the extent and the unpleasantness of the resulting sensation.

And yet H., like all patients in this condition, never for a moment doubts that the protopathic area is one of defective sensibility. Over normal parts of the hand, it is almost impossible to touch the skin with a sharp point, however lightly, without producing a sensation which he knows if increased will gradually pass into pain. The normal skin

responds to a point with a sensation which is not painful, but which conveys the impression that the stimulating object is sharp. This is absent over protopathic parts. When the needle of the algesimeter is applied carefully, even over a highly sensitive protopathic area, the pressure can be increased without evoking any response until the scale shows about 20°. Then a sensation of pressure is evoked in consequence of the stimulus to deep sensibility. Increase the pressure further and at about 30° to 35° pain is produced, either suddenly or as a gradually increasing ache.

The sensibility of the protopathic area in the neighbourhood of the index knuckle (fig. 14) has so greatly increased, that the threshold for cutaneous painful sensations, tested with von Frey's hairs, is now the same as that of a similar part of the normal hand. But although the threshold for pain over this highly protopathic part has sunk to the normal, the sensibility of the two areas, tested by means of a sharp point, is fundamentally different. From the skin in a protopathic condition, pain is evoked without the preliminary painless sensation of a point.

These observations show that we must readjust the usual psychological conception of intensity, at any rate as far as painful sensibility is concerned.

On turning to the phenomena of thermal sensibility, many facts point to an equal need for revision of the usual views on intensity. On comparing the sensations from normal and protopathic parts, the same cold tube at 20° C. is commonly said to be colder over the affected area. But, if the threshold be determined in the usual way by lowering the temperature of the stimulus from neutral to the just perceptibly cold, it will be found that the protopathic region will seem to be by far less sensitive. A temperature of 30° C. or even 31° C. may be called cool over normal parts under favourable conditions, but 27° C. never produced a sensation of cold over any portion of the affected area. A part which reacted with a more vivid sensation of cold when stimulated with 20° C. was incapable of responding to temperatures well within the range of the normal skin.

Return of epicritic sensibility diminishes the vividness of response to protopathic stimuli. The part of the affected area in the neighbourhood of the first metacarpal has become sensitive to light touch after shaving and responds to minor degrees of heat; sensibility is almost completely restored. Temperatures of 26° C. and 27° C. produce a sensation of coldness and, measured by all the usual criteria, it is a highly sensitive

part. But a tube at 20° C. seems less cold than over the neighbouring purely protopathic area.

The same condition was repeatedly observed throughout the period during which the forearm was recovering. Thus, on December 1, 1906, 26° C. seemed cool to the affected area on the forearm but produced no sensation of temperature over the back of the hand; but 23° C. was said to be cool over the forearm and intensely cold over the back of the hand. On August 7, 1904, 20° C. produced a cool sensation ("poor cold") only over the proximal part of the affected area on the forearm, "good cold" over the distal patch and "tremendous spot-cold" over the back of the hand.

At this time stimulation of the protopathic area in the neighbourhood of the wrist uniformly caused a sensation of cold, referred to the proximal patch on the forearm in the neighbourhood of the scar. By this means, a colder sensation could be produced than by applying the same tube directly to that part of the forearm. We are thus face to face with the following significant anomaly. A cold stimulus evoked a sensation of cold over a certain part of the forearm; but, when this stimulus was applied to a protopathic part on the hand, it produced a sensation referred to the same area of much greater coldness than that which followed direct application of an identical stimulus to the same part.

By carefully adapting the hand to cold, a condition can be produced in which 22° C. continues to cause a vivid sensation of cold from the protopathic area, but seems neutral to normal parts of the hand. An area of undoubtedly lowered sensibility then reacts with a specific sensation to a temperature, incapable under the circumstances of evoking a sensation from the normal skin.

An interesting example of failure to recognize this ambiguity with regard to intensity in the case of protopathic sensibility is given by von Frey's statement that the glans penis is the most sensitive part of the body to temperature. Now we have shown that this organ reacts to thermal stimuli like the skin in the protopathic stage after nerve division. It is a part of the body which is normally devoid of epicritic sensibility. A tube of 20° C. placed on the corona of the glans penis is said to be decidedly colder than on the adjoining skin; but tubes of 27° C. and 28° C., which produce obvious cold on the skin, evoke no such sensation from the glans. A region which has been called the most sensitive part of the body is as a matter of fact one of low sensibility, if tested by the customary measure of the threshold.

In the case of heat the results are the same; but, owing to the

narrow range of temperature at our disposal, their demonstration is not so easy. Merely judged by the vividness of the response, a protopathic region would be called more sensitive than normal. A tube at 40° C. placed over a group of spots within the protopathic portion of the back of the hand seemed hotter than over normal parts; yet this area did not respond to any temperature below 37° C. When a silver tube containing water at 47° C. was rolled across the hand from normal to abnormal parts, it becams "hotter" over the affected area. But a tube at 35° C., obviously warm over the normal skin, no longer caused any sensation of warmth as soon as the protopathic border was passed. Judged by the standard of threshold, the protopathic area was less sensitive, although a temperature of 47° C. seemed hotter than over the normal hand.

At an early stage of recovery, the hairs regained a peculiar form of sensibility to contact. Stroking a hair-clad part with cotton wool produced a widespread tingling referred to parts at a distance, identical with those for the sensations evoked by painful and thermal stimuli. This tingling seemed to be more intense than the sensation which follows the brushing of normal hairs with cotton wool. But, when the roots of the hairs were tested by von Frey's method, not one of them was found to react to No. 5, although over normal parts the majority are sensitive even to stimulation with No. 3; and if the skin of the affected area was shaved, it became entirely insensitive to all cutaneous tactile stimuli.

Whatever the effective stimulus applied to an area in a condition of high protopathic sensibility, the specific sensation evoked will seem to be more vivid than that over normal parts. A prick will seem more unpleasant, cold will appear to be colder and brushing the hairs will cause a widespread tingling apparently more intense than any sensation produced by brushing the normal hair-clad skin.

Yet in every case the protopathic area is one of defective sensibility in spite of its more vivid response. Stimulation of the normal skin with a needle produces almost at once the sensation of a pointed object, which with increasing pressure passes gradually into pain. Thus, even if the threshold for painful stimuli may have sunk approximately to normal over protopathic parts, they still fail to respond to the antecedent sensation of a point. In the case of heat and cold, it can be shown that the threshold is always higher than over the normal skin. Even the tingling evoked by touching the hairs of a protopathic part, requires a stronger stimulus than when the skin is endowed with epicritic sensibility.

All forms of sensation evoked from protopathic areas have a high threshold, whether the condition be normal as in the case of the penis, or a stage in the recovery of sensibility after nerve division.

The most striking feature of the response from protopathic parts is its wide extensity. Each strictly local stimulation is followed, not by a localized sensation, but by an outburst of pain, heat, cold or tingling which may extend over the greater part of the affected area.

How large a part is played by this wide extent of the sensation, in our judgment of the relative coldness of a stimulus applied to protopathic parts, is shown by the following experiment. After the cold-spots had been marked out carefully, the protopathic area was stimulated with the flat circular bottom of a silver tube 1·25 cm. in diameter containing water at 20° C. This produced a sensation of cold. One active spot within the area covered by the tube was then stimulated with a copper rod 1 mm. in diameter which had been cooled to the temperature of ice. This caused a sensation, apparently "less intense" than that from the tube at 20° C., and the result was not altered by changing the order of the two stimuli. In these observations, H. was unable to recognize whether the smaller or the larger object was being applied; in one case when the tube had been used he said, "That is a good spot," comparing it with the previous stimulation with the rod only.

Increasing the area of stimulation produced the same effect as increasing the intensity of the stimulus. H. would have said that the tube at 20° C. was uniformly "colder" than the rod, had he not recognized that in many cases the coldness was not greater. Yet, although the resulting sensation was not more "icy," it was so much more extensive that his natural tendency was to call the tube a stimulus of greater intensity. This he might have corrected, had he been able to recognize that a larger area of skin was stimulated by the tube than by the rod; since this was impossible over a purely protopathic area, his only guide to the intensity of the stimulus was the extent of the sensation evoked.

But it must not be supposed that he was entirely unable to appreciate a difference in intensity between two stimuli of equal extent applied to a protopathic area. A tube containing ice will produce a colder sensation than the same tube containing water at 20° C. applied to the same parts. But, if once the stimulus is of a temperature low enough to excite the cold-spots to a full explosion of activity, the extent of the stimulus is of greater importance than its intensity.

In considering the direction in which the current notion of intensity might be revised, we must limit the application of the term in its strict sense to epicritic and to deep sensibility. In protopathic manifestations, there is undoubtedly a "more-or-lessness," which is of the same nature as that denoted by the term intensity, though it is liable to be obscured by variations in the extent of the stimulus.

It would even seem as if sometimes a less cold object applied to a larger surface will cause a sensation more intensely cold than the stimulation of a single spot by an iced rod.

Thus, even when we confine ourselves rigidly to the consideration of actual more-or-less coldness, a more extensive stimulus at a higher temperature may produce a definitely colder sensation, apart altogether from the fact that it radiates over a wider aaea.

From these facts, it follows that Weber's law or other expressions of exact quantitative relations between stimulus and sensation must undergo revision. In the case of the protopathic system, it is clear that there can be no question of any such exact relation. In the sensations from a protopathic area, there may exist a more-or-lessness which can be called intensity. But this is of so indefinite a character, and its relation to the intensity of the stimulus may be so obscured by differences in the extent of stimulation, that there can be no question of any such definite association between stimulus and sensation, as those formulated in Weber's law or Fechner's formula. As far as Weber's law holds good for the temperature-sense of the skin, we should expect it to be the expression of epicritic thermal sensibility. That is to say, it should be demonstrable, more particularly between 26° C. and 37° C., the highest point of the cold-spots and the lowest to which the heat-spots reacted. Further, the discriminative sensibility as revealed by the just-perceptible difference or the difference-threshold should be greater between these limits. It is remarkable that two of those who have investigated the validity of Weber's law for the temperature-sense have given figures corresponding closely with those to be expected on the basis of our view that the law holds true of epicritic sensibility only. Lindemann [20] found the discriminative sensibility to be greatest on the hand between the temperatures of 26° C. and 39° C.; the just-observable difference within these limits was 1·20° C. Nothnagel [24] found the most delicate discrimination between 27° C. and 33° C.; the just-perceptible difference was slightly larger only up to 39° C. and was also fair between 27° C. and 14° C. These observations help to support

our view that, as far as the skin is concerned, Weber's law applies to epicritic sensibility only.

The results at which we have arrived in this chapter may be summed up as follows :—

(1) Parts in a condition of protopathic sensibility respond more vividly than the normal skin to all stimuli capable of evoking a sensation.

(2) This sensation is usually more intense and always of much greater extent than over normal parts.

(3) For all effective stimuli, the threshold is high in a protopathic area, and, in spite of the vivid response, it is obviously one of defective sensibility. Epicritic sensibility with its low threshold must be present, before the sensory complex resembles that from the normal skin.

(4) An effective protopathic stimulus of low intensity, but covering a larger area, may produce a sensation of greater apparent intensity than a more restricted stimulation of greater strength. Not only is the sensation more extensive, but at times it may seem to be specifically more intense.

(5) The usual psychological view that an increased sensory reaction corresponds to a lowered threshold must be readjusted. It is true in the strict sense only of epicritic and deep sensibility.

Chapter X.—Punctate Sensibility.

Although our observations on the distribution and functions of the cold- and heat-spots agree substantially with those of previous observers, we differ from them fundamentally in our views of the nature of punctate sensibility. Blix ([4] and [5]) was the first who examined the skin minutely with stimuli of small extent, and discovered the heat- and cold-spots. He was followed by Donaldson [6] and later by von Frey ([7], [8], [9], [10], [11]) with a superb series of observations which greatly extended the original conception of punctate sensibility.

In consequence, it became a matter of general belief that the skin was endowed with sensitive spots, each of which reacted to a specific stimulus. Not only were there spots for cold and for heat, but also for pressure and for pain. To the activity of this mechanism were attributed all the sensory impulses arising from cutaneous stimulation.

But this minute concentration on the functions of the skin led to a neglect of those forms of sensation produced by the coarser stimuli, such as pressure. Any object, however light or heavy, was thought to be appreciated in consequence of impulses from the " pressure spots," so

long as no movement of muscles or joints occurred. So soon, however, as the weight was supported by muscular effort, the "muscle-sense" came into action, based on afferent impulses conducted from the tendons, joints and other subcutaneous structures.

But division of all the nerves to the skin in our experiment showed that this deep innervation played a greater part in the sum of sensory impulses from the periphery than had been previously suspected. Much of what is commonly called "touch" is due to the activity of this afferent mechanism, and not to stimulation of the cutaneous "pressure-spots" only.

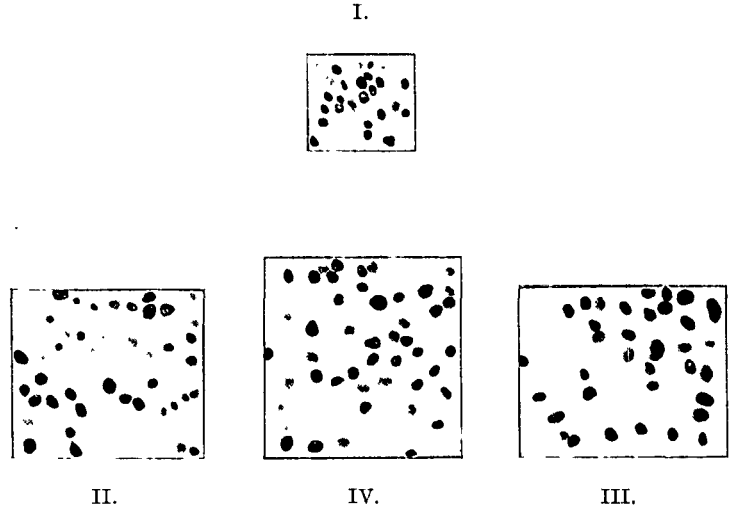


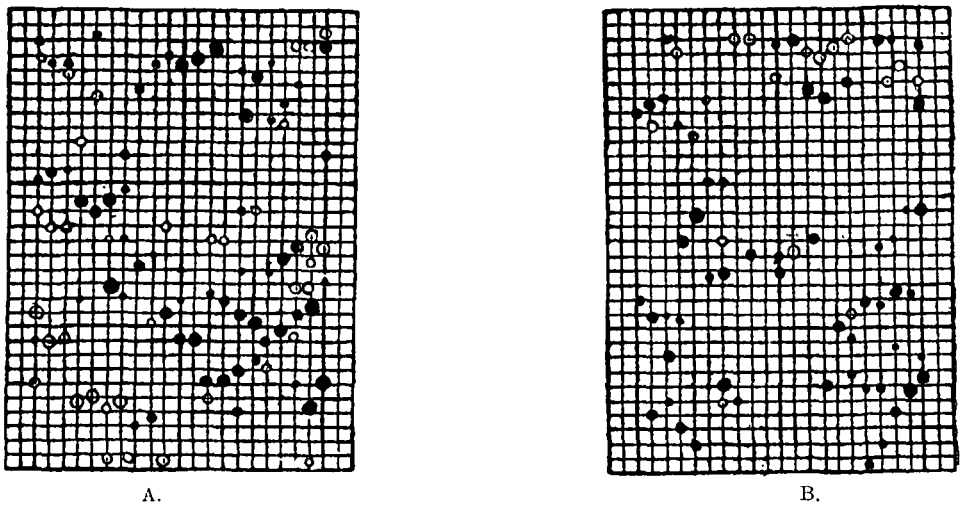
FIG. 23.

Photographed from Blix [4].
In the original the black dots are red and correspond to the heat-spots. The lighter dots are green and represent the cold-spots.
I.—An area on the dorsal aspect of the left hand at the base of the middle finger.
II.—An area on the wrist.
III.—An area on the arm ("Armlänge").
IV.—An area on the dorsal aspect of the left hand of another observer.

Excessive pressure was also found to produce pain when the cutaneous nerves were divided, and it is therefore certain that the "pain-spots" of the skin are not responsible for all painful sensations from the periphery. The pain of pressure and rending is due to the stimulation of end-organs of the deep afferent system.

It is therefore obvious that, of the sum of afferent impulses starting from the periphery, a large number arise from the activity of

organs situated elsewhere than in the skin. On this side our observations are accessory to, but do not trench on, those of von Frey and his fellow workers. But even when we confined our attention to the skin, we found that the sensory spots did not account for all the afferent impulses of cutaneous origin which reached the central nervous system. It is therefore obligatory on us to show in how far we agree with, or differ from, the conclusions of previous observers with regard to punctate sensibility.



A. B.

FIG. 24.

Somewhat enlarged from Donaldson [6].

The black dots indicate cold-spots. The larger ones represent the spots which gave a strong reaction, the smaller those which gave a weak one. Circles represent the heat-spots.

A. represents the distribution of the temperature-spots over six squares each of 1 cm. on the back of the left hand. B. represents a similar map of a symmetrical part of the right hand. Thus each map is 2 cm. broad and 3 cm. in height.

The upper boundary is peripheral, the lower central; the left of the observer corresponds to the ulnar aspect, the right to the radial.

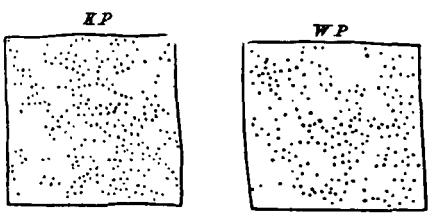
Section 1.—*Heat- and Cold-Spots.*

The existence of heat- and cold-spots has not been seriously called in question since they were first described by Blix [4]. They are easily demonstrable, scattered irregularly over the surface of the body (fig. 23). The cold-spots preponderate greatly; according to Blix there are from two to four cold-spots to one heat-spot. It is difficult to compare his results numerically with our own, because the size of the area chosen for investigation in different parts of the body evidently varied greatly, and he does not state whether his maps were drawn strictly to scale.

Donaldson [6] marked out six squares of 1 cm. on the dorsal surface of each hand; in these six squares he found on the right fifty-six cold-spots, and on the left fifty-nine. Within the same limits the heat-spots numbered seventeen and thirty-seven (fig. 24).

The area on the back of the affected hand most closely investigated by us consisted of twenty-five squares each of 1 cm. Here we found about sixty-eight cold-spots, and from fourteen to sixteen heat-spots. Some of these were more constant than others, and a certain number were discovered at every examination throughout the four years which followed their reappearance (*cf.* p. 377 and figs. 19 and 20).

Similar results were obtained by Sommer [26]; von Frey gives no maps of these spots, but from observations made by him on H.'s hand



A. B.

FIG. 25.

Photographed from Goldscheider [15], Tafel 1.
In the original the cold-spots on A. are red, whilst the heat-spots on B. are blue.
Each area represents 4 cm. from the back of the hand.
It is obvious that both heat- and cold-spots vastly outnumber those recorded by other observers.

both before and after the operation, we can state that our results are numerically in complete accord with those obtained by his methods.

This remarkable harmony in the results of most observers is disturbed by the statements of Goldscheider [15] only. His maps reproduced in fig. 25 differ so greatly from the results of all other workers, that we can only assume he was not dealing with punctate sensibility as generally understood.

These spots respond to stimulation in a strictly specific manner. Thus, stimulation of the cold-spots with temperatures of 45° C. produces a sensation of cold. We have been unable to stimulate either the cold- or heat-spots with the interrupted current, provided all precautions are taken to exclude thermal stimuli and the effect of suggestion; in this we are at variance with Blix. We differ also from Goldscheider [15] in

that we have been unable to evoke a sensation of heat or of cold by mechanical irritation of these spots, if the stimulating object be maintained at a neutral temperature.

Our observations have shown (chapter IV., section 3, p. 383) that the reaction of these spots is peculiar and characteristic. When sensibility to heat and cold depends on the existence of spots alone, any effective stimulus tends to produce a more vivid response than from the normal skin. Not only is the sensation evoked from a protopathic area of wider extent than normal, but at times it seems to be actually colder (*cf.* p. 422). Yet, in spite of this greater vividness, such parts as the affected area on the back of the hand and the normal penis did not respond to temperatures between 26° C. and 37° C. The degree of temperature necessary to stimulate individual spots varied greatly ; but no heat- or cold-spot on the back of the affected hand responded to temperatures between these limits. This combination of an abnormally vivid response to effective stimuli, with failure to react to temperatures capable of exciting the normal skin, is a characteristic feature of all parts, where thermal sensibility depends on the existence of heat- and cold-spots only.

Moreover, so long as the thermal sensibility of a part depends entirely on these spots, it is incapable of that wide range of adaptation which is an inherent function of the normal skin (*cf.* p. 406). Soaking the hand in water at 45° C. does not cause the cold-spots to respond to temperatures above 26° C., and careful cooling does not increase the range of sensitiveness of the heat-spots. And yet, under such circumstances on the normal hand, adaptation would occur and the same intermediate temperature would appear at one time cool and at another warm.

It might be supposed that the vivid response, the high threshold and the want of adaptation so characteristic of punctate thermal sensibility on the affected parts were due to defective regeneration of the mechanism of the heat- and cold-spots. But the normal glans penis is unable to respond to temperatures between 26° C. and 37° C., not only when the stimulus is punctiform, but also when the whole organ is immersed in water. But so vivid are the sensations evoked by effective thermal stimuli, that von Frey calls it the most sensitive part of the body.

It is therefore certain that the cold- and heat-spots cannot account for all the thermal sensibility of the normal skin. Some other nervous mechanism must be present, which endows the skin with the power of reacting to intermediate degrees, and is capable of thermal adaptation.

But when all the cold- and heat-spots have been marked out on the normal skin, considerable spaces remain between insensitive to punctate thermal stimuli. These, if sufficiently extensive to be tested with a tube, will be found to be sensitive to water above 26° C. and below 37° C., especially after the part has been suitably adapted.

We therefore believe that the skin is endowed with two thermal mechanisms, one of which reacts to punctate stimuli and has a high threshold judged by the inability to respond to temperatures between 26° C. and 37° C. Its end-organs are strictly specific and are dotted about irregularly throughout the skin, in such a way that large spaces may be entirely devoid of heat-spots.

The second mechanism is incapable of reacting to punctate stimulation, but responds readily to temperatures above 26° C. and below 37° C., when applied over an area of some extent. The nature of this response depends on the temperature to which the part is adapted. At one moment 30° C. may seem warm, at another cold according to whether the skin has been previously adapted to cold or to heat respectively.

Section 2.—Pain-Spots.

Blix [5] denied that sensibility to pain was associated with any mechanism analogous to the heat- and cold-spots. But in consequence of the widely extended observations of von Frey on various forms of punctate sensibility, the idea has gradually grown up that pain-spots exist in the skin in every way comparable to, but more numerous than, the cold- and heat-spots. Thus Thunberg ([28], p. 651) says: "Erst v. Frey fand dass die Verhältnisse hier (for pain) ganz analog denjenigen der anderen Sinnespunkte liegen."

But no observations by von Frey bear such an interpretation. His great contribution to the subject of skin-sensibility was the introduction of measurable mechanical stimuli, not only for touch but for pain. He selected a large number of hairs of different sectional area and bending strain, and showed that as soon as a certain pressure per unit area was exceeded, pain was produced. This threshold for pain of cutaneous origin differed greatly in various parts of the body. If a test-hair was chosen which just exceeded this amount, it formed a minimal pain-stimulus for that particular part of the body. Such a hair will be found to cause the characteristic pricking sensation at a few points only. These are von Frey's "pain-spots" (Schmerzpunkte). But by increasing the

strength of the stimuli, *i.e.*, by using hairs of greater bending strain, many more points can be discovered from which pain can be evoked; at last, the number of such points within any square centimetre becomes so great that it is scarcely possible to map them with accuracy.

Suppose, however, that one or more square centimetres has been examined exhaustively and that these minimal pain-spots have been marked on the skin. On subsequent examination, even an hour or two later, it will be found that many of the spots no longer respond to the same stimulus; for instance, those which had previously reacted to 75 grm./mm.^{2} may be insensitive to hairs of less than 150 to 200 grm./mm.^{2}. Moreover, many unmarked places will be found to respond even to hairs which exert a comparatively low pressure per unit area. Whatever ultimate view we may take of the nature of pain-spots, experimental observations on their distribution are much less conclusive than those on the heat- and cold-spots.

The true nature of cutaneous painful sensibility cannot be settled by examination of the normal skin. But the answer is given at once when we turn to the permanently protopathic area on the back of H.'s hand. Here the skin responds to temperatures below 26° C. and above 37° C. only, and painless stimulation of the hairs produces the characteristic diffuse sensation; pain extending widely, and referred to remote parts, can be evoked by stimulation with the stiffer test-hairs. Such an area is usually supposed to be in a low state of sensibility. But on testing with graded hairs, the threshold for pain is found to be the same as that for the normal skin. Sometimes, owing to the greater technical ease of the observations, this protopathic area gave a painful response to hairs of a lower grade than was the case over an equivalent part of the normal skin. Far from being a region of defective painful sensibility, the threshold for cutaneous pain was here as low (1908), and possibly even lower than normal. This we can affirm, not only from our own observations, but from a careful examination made by Professor von Frey of that part of H.'s hand.

But, although fully sensitive to pain, this area is entirely insensitive to the tactile test-hairs. Pain, instead of developing gradually out of the sensation of contact with a pointed object, arises without warning as soon as the force exerted by the "pain-hair" exceeds the threshold for the particular spot to which it is applied.

Within this protopathic area, in spite of the simpler condition, we find exactly the same inconstancy of reaction to cutaneous painful stimuli as in the normal skin. By using hairs which just exceed the

pain-threshold, two or three spots can be marked out in each centimetre; these are the minimal pain-spots of von Frey. Even these are inconstant in reaction, and by using hairs of greater bending strain, a multitude of further spots can be discovered within each square.

Thus it would seem, that the pain-spots within any square centimetre are extremely numerous and possess widely different thresholds. Moreover, they are inconstant, varying in sensitiveness from time to time.

This variability and inconstancy of reaction they share with the heat- and cold-spots. Within the twenty-five squares on the back of H.'s hand, lay sixteen points where at one time or another heat was evoked by punctate stimulation; of these, thirteen were marked out as the site of heat-spots on ten or more of the eighteen photographic records, that is to say three heat-spots were so inconstant that they were frequently missed.

But even amongst those spots which could be discovered without difficulty, the threshold was by no means the same. Two of them usually reacted to 38° C., but a large proportion did not respond to temperatures below 40° C.: in order to be certain that every spot had been fully tested, we always employed an iron at about 45° C.

When we examine the records of the more numerous cold-spots, the proportion of inconstant ones greatly increases. In fact, the photographs are so diverse that we have been compelled to confine our attention to those which are accompanied by an explanatory key recording the constancy of response. Among the sixty-eight spots, thirteen only are present in all three sets of maps and photographs.

The small number of the heat-spots and the complete absence of sensibility to heat in the intervening spaces of the protopathic skin make it easy to settle their number and to record their position. This is more difficult with the cold-spots and, with the further increase in number shown by the pain-spots, becomes an impossibility. Moreover, it is easy to be certain that no active cold-spots have escaped, by using a rod at the temperature of melting ice. But, with the pain-spots, a great increase in the strength of the stimulus leads to such deformation of the skin that the stimulus no longer acts in a punctiform manner.

But in spite of the technical difficulties in mapping out the pain-spots, they are evidently closely allied in origin and function to those for heat and cold. After division of a peripheral nerve, the three sets of organs recover their functions approximately together, and a part may remain for a long period sensitive to painful and to the more extreme degrees of thermal stimulation only. Sometimes, regeneration may

stop short at this protopathic stage, and the hairless skin will then be sensitive exclusively to stimuli capable of exciting the pain-, heat- and cold-spots. This is not due to defective restoration of the nerve-mechanism of the spots themselves, for the cutaneous sensibility of the glans penis depends entirely on the activity of these spots; it is a part of the skin which has remained normally in a protopathic condition.

Moreover, so long as the skin is innervated through these spots only, the sensation is widely diffused, and referred into some remote part which is constant whatever stimulus be applied, provided the area stimulated is the same.

Thus, it is obvious that the cutaneous mechanism which underlies painful sensibility belongs to the same order as the heat- and cold-spots, both in the period at which it regenerates and in the nature of its response to stimulation.

The heat- and cold-spots form a thermal mechanism with a high sensory threshold, incapable of responding to temperatures between 26° C. and 37° C. But a cutaneous painful sensation can be evoked from a highly developed protopathic part as easily, and in some cases even more easily, than from the normal skin. It would seem at first sight as if protopathic sensibility was not in this case associated with a high threshold.

But careful analysis of the effect produced by stimulation with graduated hairs shows that, although pain is produced as easily over highly protopathic parts as over the normal skin, the complex of sensations is different. When a hair of between 70 and 100 grm./mm.^{2} is applied to the protopathic area, a sensation of localized pressure is produced, followed by the gradual development of the characteristic stinging pain. Over the normal skin, the first sensation, when the hair is applied, is one of a circumscribed pointed object; to this, a definite painful element is gradually added. At pressures incapable of producing pain, the sensation of a point warns the patient that the stimulus, if increased in strength, may become painful. This recognition of the pointed nature of the stimulus is due to the power of appreciating relative size, a faculty which depends on impulses arising in the epicritic mechanism.

Pain is always a high threshold sensation as shown by the fact that it is not evoked by punctiform stimuli until the pressure exceeds 70 grm./mm.^{2}. The low threshold contribution to the sensory complex, introduced by the existence of epicritic sensibility, consists in the power of recognizing that the stimulus is pointed, before the pressure is sufficient to cause pain.

In conclusion, we believe that the sensibility of the skin to painful stimulation depends upon organs analogous to the heat- and cold-spots; and just as the latter are more numerous than the former, so the pain-spots exceed the cold-spots in number. With this excess is associated a wide diversity of threshold and a greater inconstancy of response, so that it is experimentally impossible to mark out with certainty all the pain-spots in a given area. Von Frey's pain-spots comprise those of the lowest threshold only, which react to the minimal punctate pain-stimulus for any particular area of the skin.

The pain-spots resemble those for heat and cold in that the threshold of even the most sensitive is remarkably high. Stimulation of the skin with graduated hairs produces a widely diffused sensation of pain, with no antecedent appreciation of the pointed nature of the stimulus. This faculty first returns with the restoration of the low threshold impulses of the epicritic system.

Section 3.—*Touch-Spots.*

So far we have considered the reaction to punctate stimuli of three sets of end-organs, which recover their function early within approximately the same period after nerve division. A portion of the skin, innervated by these organs only, shows sensory peculiarities which we have called protopathic and is entirely insensitive to cutaneous tactile stimuli, provided the hairs are not disturbed.

But it is universally recognized that on the normal skin, punctate stimuli produce a sensation of touch. Blix described what he called "Druckpunkte," points in the skin peculiarly sensitive to touch, in close relation to the roots of the hairs. These observations were amplified by von Frey, who found that these "Druckpunkte" possessed a remarkably low threshold. He was, however, unaware of the phenomena of deep sensibility and did not recognize that comparatively slight pressure could produce a localized sensation, although the skin was entirely insensitive. This name is therefore unfortunate, and we shall speak of "touch-spots," whenever we allude to these sensitive cutaneous points ("Druckpunkte").

These spots belong to a different order from those for pain, heat and cold. They regain their function at a much later period of regeneration, if the nerve has been completely divided. Thus the proximal patch on H.'s forearm became sensitive to prick 56 days after the operation; sensibility to cold returned in 112 days, and in 161 days this part

responded to heat. But it was not until 366 days after the operation, that the same area when shaved became sensitive to cutaneous tactile stimuli.

Should any part of the skin happen to remain permanently in a protopathic condition, it will show all the properties of punctate sensibility to pain, to heat and to cold, but will be devoid of touch-spots. This is the normal condition of the glans penis.

Conversely, the skin of the "triangle" was sensitive to cutaneous tactile stimuli and was endowed with touch-spots resembling in function those of the normal skin. But no pain-, heat- or cold-spots could be found anywhere within this area.

We have already described the close association between the returning response to cutaneous tactile stimuli and the recovery of sensibility to intermediate degrees of temperature, more particularly to warmth. Thus, a part such as the back of the hand may remain for a long while innervated by pain-, heat- and cold-spots only, insensitive to temperatures between 26° C. and 37° C. and to painless stimulation with von Frey's test-hairs. As soon, however, as the touch-spots reappear, the part will be found to have regained in addition its sensibility to intermediate degrees of temperature.

Moreover, the return of function to the touch-spots is closely associated with recovery of the power of accurately localizing cutaneous tactile stimuli. Before this group of sensory functions has reappeared, discrimination of two points applied simultaneously is impossible. But with the recovery of sensibility to von Frey's tactile hairs, accurate localization and discrimination become possible. The wide radiation and reference into remote parts, so characteristic of the unchecked activity of heat-, cold- and pain-spots, ceases and is replaced by a less vivid sensation, restricted to the immediate neighbourhood of the point of contact. Thus, the return of function to that sensory mechanism of which the touch-spots form a component, actually diminishes the sensations associated with the activity of those organs, which are universally accepted as the type of cutaneous sensory spots.

Over hair-clad parts, these touch-spots are strictly associated with the roots of the hairs; they express the sensibility to mechanical stimuli of that part of the hair which lies beneath the surface of the skin. Almost every hair is a delicate tactile sense-organ; any movement of its tip is transmitted to its root with the increased power of a lever, setting up tactile impulses. It is not remarkable, therefore, that mechanical stimulation, applied directly to the hair-root, produces similar tactile

sensations. But owing to the want of leverage, this method of stimulation is less effective, and the force required to produce a sensation is higher than when the free portion of the hair is disturbed.

Even when care is taken to touch no part of a hair lying above the skin, the threshold for punctate tactile sensibility is extremely low. Out of 303 touch-spots on von Frey's forearm, 221 reacted to a force of or below 1 grm./mm. (8 grm./mm.^{2}); sixty-six required 2 grm./mm. (12 grm./mm^2), and there was not one which did not respond to 4 grm./mm. (21 grm./mm.^{2}). Such threshold values are roughly one-fourth of those required over the same parts to produce a painful sensation.

But it must not be supposed that these touch-spots are the same as those for pain. The majority of the pain-spots lie between hairs, whilst on hair-clad parts touch-spots correspond almost exclusively to hair-roots. It must not be forgotten that a hair-root may be found to be the seat of both a touch- and pain-spot owing to the sensibility of many of the hairs, both to tactile and to painful stimuli. But, whereas the spaces between the hairs contain many pain-spots, touch-spots are almost entirely absent. Von Frey discovered three touch-spots only which were not definitely associated with the hair-roots, in a space of seven 1 cm. squares on the calf of the leg. Within the same area he marked out seventy-seven touch-spots connected with the hairs ([11], p. 233).

Almost all the observations on touch-spots have been made on hair-clad parts of the skin; here, as von Frey has shown, they correspond to the subcutaneous portions of a hair. But the tips of the fingers are even more sensitive to the test-hairs than any hair-clad part. Thus the finger responds to 3 grm./mm.^{2}, but the back of the hand requires 12 grm./mm.^{2}. Here the existence of definite touch-spots cannot be demonstrated with certainty, so numerous are the points sensitive to stimulation with test-hairs.

We have shown that when any part of the skin, whether endowed with hairs or not, becomes sensitive to punctate tactile stimuli, it shortly regains its sensibility to temperatures between 26° C. and 37° C. Yet the heat-spots are not increased in number and do not react to thermal stimuli below 37° C. This return of function must be due to some mechanism of a different order from the heat-spots.

In the same way, we believe that the return of cutaneous tactile sensibility is coincident with the restoration of function to a set of end-organs of a different order from the heat- and cold-spots. On hairless parts of the skin, such as the finger-tips, they are so thickly scattered

that it is impossible to demonstrate their punctate distribution. But over hair-clad parts they are associated peculiarly with the hairs, and every hair-root therefore becomes a sensory spot.

The conclusions arrived at in this chapter can be summed up as follows:—

(1) The skin is supplied by two anatomically distinct systems which have been called protopathic and epicritic, and regenerate at different periods after complete nerve division. Moreover, a part of the skin may be supplied by one of these systems only. Thus, the cutaneous sensibility of the normal glans penis is protopathic, closely resembling the present condition of a small portion of the affected area on the back of H.'s hand. Conversely, the "triangle" was sensitive to tactile test-hairs and to warmth, but was completely devoid of heat-, cold- and pain-spots.

(2) Protopathic sensibility depends upon specific end-organs gathered together within the skin to form sensory spots; the spaces between are insensitive to cutaneous stimuli, if the part is endowed with protopathic sensibility only.

Owing to the sparseness of the heat-spots, their characteristics can be easily demonstrated; cold-spots are more numerous and correspondingly difficult to investigate. The pain-spots are so closely distributed throughout the skin that it is impossible to study them with the accuracy of the heat- and cold-spots; but the character of their response, and the period at which they regenerate, show that they belong to the same order.

(3) Whenever the skin is supplied by protopathic end-organs only, any sensation evoked radiates widely and tends to be referred to remote parts. These are the same, whichever kind of spot be stimulated, so long as it lies within the same area of the skin.

Radiation and reference are abolished, as soon as the part becomes sensitive to cutaneous tactile stimuli and to intermediate degrees of temperature.

(4) Any part of the skin, innervated by heat- and cold-spots only, is incapable of that wide adaptation to external temperatures so characteristic a function of the normal skin.

(5) Cutaneous tactile sensibility is due to the activity of a sensory mechanism of a different order from the heat-, cold-, and pain-spots. It regenerates much later after complete nerve-division. The restoration of cutaneous tactile sensibility is closely associated with the return of the capacity to appreciate temperatures between 26° C. and 37° C., with the

power of accurate cutaneous localization and with the discrimination of two points.

Its end-organs become susceptible of investigation with punctate stimuli over hair-clad parts, owing to their close association with the roots of the hairs. But these "touch-spots" (Druckpunkte of Blix and von Frey) are not analogous to those for heat, cold, and pain.

(6) All protopathic sense-organs have a high threshold; the heat-spots do not react to temperatures below 37° C., the cold-spots do not respond to temperatures above 26° C. and the pain-spots on the back of the hand are insensitive to pressures below about 70 grm./mm.^{2}.

All epicritic sense-organs have a low threshold. They respond to temperatures between 26° C. and 38° C., and the back of the hand is sensitive to 12 grm./mm.^{2}.

A protopathic part, whether it be the normal glans penis, or the affected part of H.'s left hand, is in a condition of high threshold sensibility. When the normal skin is stimulated, the defects of protopathic sensibility are corrected and compensated by the simultaneous activity of the low-threshold epicritic system. Temperatures between 26° C. and 37° C. can produce sensory impulses, and the epicritic mechanism is highly adaptable. The threshold for painful sensations is the same over normal and over highly protopathic parts, but on the normal skin the approach of pain is preceded by the sensation of contact with a pointed object. This is absent over protopathic parts. The power of recognizing the pointed nature of the stimulating object depends on the existence of epicritic sensibility, and belongs to that group of sensations by which we estimate relative size.

Chapter XI.—General Theoretical Conclusions.

Section 1.—The Integration of Afferent Impulses.

Throughout this paper we have spoken of three forms of sensibility, and in the previous chapter we gave our reasons for the belief, that they were associated with the activity of three anatomically distinct systems.

Johannes Müller believed that on stimulating the body-wall a specific impulse was initiated, which passed unaltered to the brain, forming the basis of a specific sensation. In the same way Blix [4], when he discovered the heat- and cold-spots, thought that the impulses arising in these specific organs passed unchanged through the nervous system to underlie all sensations of heat and cold.

But we have been able to show that the process is one of much greater complexity. Under normal conditions there are no "protopathic" or "epicritic sensations." These terms may be justly applied to two anatomically distinct peripheral systems, or to the sensibility with which the skin becomes endowed by the preponderating activity of one or other nervous mechanism. They can also be used to distinguish two groups of impulses set free by stimulation of the end-organs in the skin. But sensations must be described solely by their specific qualities, and not by these names which apply to the peripheral physiological level only.

For, as soon as they reach the first junction in the central nervous system, sensory impulses are transformed into more directly specific groups. Both protopathic and epicritic end-organs may be stimulated by heat applied to the skin and the resulting impulses will travel by separate peripheral paths to the spinal cord. There they become united and pass on, as a single isolated group, to underlie, in the highest centres, specific sensations of heat.

A similar fusion of originally separable elements occurs when the skin is stimulated with cold, and the intramedullary path transmits an equally specific group of impulses.

In the same way, the physiological basis of a sensation of pain may be compounded of elements due to stimulation of the end-organs of the skin and of the deep afferent system. These, when united, pass up together in the same isolated paths devoted to the transmission of sensory impulses evoked by painful stimuli.

Epicritic tactile impulses become combined with those arriving by way of the deep afferent system into a single tactile group. Once past the first synaptic junction, epicritic impulses, evoked by the lightest perceptible touches, become simply the minimal physiological elements in a tactile group, of which the maximal constituents, produced by pressure, arrive by way of the deep afferent system.

But pressure acting on the end-organs of this deep system may cause sensations of pain in addition to those of touch. Under such circumstances, the tactile impulses evoked by pressure will arrive at the spinal cord in company with those which underlie pain. On reaching the first synaptic junction, these two elements become separated. The tactile impulses are combined with those arriving by way of the epicritic system; whilst those associated with the painful aspect of pressure pass into a secondary path, in conjunction with impulses arising from stimulation of the pain-spots in the skin. When once the secondary afferent

system has been reached, no traces remain of the original grouping in the peripheral path (Head and Thompson [18]).

This integration takes place on a physiological level; the whole process remains entirely outside consciousness. Throughout their passage from the periphery to the highest centres, these impulses undergo redistribution from the complex elementary grouping to something simple and specific.

The process, so far as we have yet considered it, has been one of sorting only. Impulses, originated by similar aspects of the same stimulus, have been gathered together, although they arose in end-organs of different systems. When, however, we consider that a temperature of 45° C., applied to the normal skin, can be shown to stimulate the heat-spots, the cold-spots and the epicritic thermal mechanism, it is obvious that some of these peripheral impulses must be inhibited; they never reach the highest centres to form the basis of a sensation. It might be objected that under normal circumstances the cold-spots are not stimulated by a temperature of 45° C.; but, provided the heat is applied directly to a cold-spot, paradox-cold is easily evoked from the normal skin. As soon, however, as a heat-spot is stimulated at the same time, the cold sensation disappears, giving place to one of heat. Evidently, the impulses produced by the action of 45° C. on the heat-spots and epicritic thermal mechanism are dominant to those evoked from the cold-spots. During the protopathic stage of recovery, it was possible to find parts where the thermal mechanism consisted of cold-spots only. Here even tubes containing water at 45° C. caused a sensation of cold.

The behaviour of the penis forms an excellent example of such inhibition. In the case of H., the tip happens to be devoid of heat-spots but is sensitive to cold and to pain. When, therefore, it was dipped into water at 40° C., no sensation of heat was produced, but H. experienced an unusually disagreeable sensation of pain. When the water was raised to 45° C., this was to a great extent displaced by a vivid sensation of cold. But, as soon as the water covered the corona without reaching the foreskin, both cold and pain disappeared, giving place to an exquisitely pleasant sensation of heat. The corona is richly endowed with all forms of protopathic sensibility; but the impulses, which must have been evoked from the end-organs for pain and for cold by contact with the water at 45° C., were inhibited by those consequent on stimulation of the heat-spots. Moreover, we can estimate the relative dominance of the impulses evoked by any particular temperature. At

45° C., those which form the basis of sensations of pain are controlled by those evoked from stimulation of the cold-spots, and both recede before the impulses which underlie a sensation of heat. But a further rise in the temperature of the stimulus to about 50° C. causes a sensation of pain together with one of heat, and the only inhibited impulses are those from the cold-spots.

The following experiment on H.'s hand shows this inhibition in a still more remarkable manner. A portion of the affected area in the neighbourhood of the index knuckle remains in a purely protopathic condition, and adequate stimulation of the skin still causes a vivid sensation of cold referred to the dorsal aspect of the thumb. If this part of the thumb was brought into contact with a large vessel containing water at between 40° C. and 44° C., H. experienced a pleasurable sensation of heat. A cold tube was then applied to the neighbourhood of the index knuckle, and the impulses which would normally have evoked a sensation of cold in the thumb were neutralized by contact of this part of the skin with the warm vessel. All sensations of heat at once disappeared from this portion of the thumb, and gave way to a new sensation, that of pain. As we know from experiments on the penis, temperatures of from 40° C. to 44° C. can evoke pain in the absence of the thermal mechanism. Evidently, therefore, the warm vessel stimulated the pain-spots in the thumb, but the impulses so caused were inhibited by those which underlay the sensation of heat. When these impulses were neutralized by the application of cold to the region of the index knuckle, those evoked from the pain-spots were no longer blocked, but passed onwards to form the basis of a painful sensation.

Throughout the first or protopathic stage of recovery in our experiment, the vividness and extent of the reaction became greater with the gradual return of sensibility to pain and the increasing number of heat- and cold-spots. This tendency to evoke a sensation, in parts remote from the point of stimulation, was curtailed or even abolished, at the height of its development, with the first signs of returning sensibility to cutaneous touch and to minor degrees of heat. Had the recovery of sensation taken place by gradual increments, we should have expected the steady increase in protopathic sensibility to be associated with a simultaneous decrease in radiation and reference. But in no part of the affected area was this form of sensibility so high and reference so vivid as in the patch on the back of the hand, which still shows no signs of epicritic recovery (autumn of 1908). The return of epicritic impulses diminishes protopathic activity, as expressed in the sensations evoked by stimulation of the end-organs of this system.

This is proved by the behaviour of the recovering hand after it had been cooled. Epicritic sensibility is liable to be affected by external cold, especially before it has been completely restored. At a time when almost the whole of the back of H.'s hand had so far recovered that referred sensations could no longer be produced, it was rapidly cooled; it thereupon ceased to respond to cotton wool when shaved. Radiation and reference returned as vividly as of old, and the hand was thrown back into a purely protopathic condition. The newly recovered activity of the delicate epicritic mechanism was disturbed by the cold, and protopathic impulses previously inhibited now passed through uncontrolled.

This control[1] can be exerted even by epicritic impulses from the adjacent normal skin. If a cold tube was placed so that it fell wholly within that part of the affected hand which remains in a protopathic condition, a vivid referred sensation was always experienced in the thumb. But when the base of the tube fell partly within the abnormal area and partly on the neighbouring skin, reference was abolished; the only sensation produced was one of coldness around the spot on the back of the hand in contact with the tube (*vide* p. 420).

The first stage of recovery after complete division of all the peripheral nerves to any part of the skin is occupied in the restoration of protopathic sensibility. Throughout this period, protopathic impulses are not inhibited; owing to the absence of the epicritic system and the sensations of pain, heat and cold are not only more vivid, but are referred into remote parts. But none of these phenomena accompanied the return of sensibility to the heat-, cold- and pain-spots within the "triangle." This area on the back of the wrist was from the first sensitive to cutaneous tactile stimuli, and two points applied simultaneously within it could be discriminated; but we were unable to discover any signs of punctate sensibility to pain, heat or cold. Gradually these spots reappeared; but the sensations evoked when they were stimulated were no more vivid or extensive than normal. The existence of epicritic sensibility throughout the period of protopathic regeneration controlled the aberrant manifestations of this system.

Section 2.—Sensory and Non-sensory Afferent Impulses.

Some afferent impulses never reach consciousness at all, but carry out their functions reflexly on the physiological level. To this group

[1] This control can be explained by the hypothesis of drainage put forward by McDougall [23]. We hope to deal with this question and with dominant activity of low-threshold sensibility in a subsequent paper.

belong those which influence muscular tone, and control the condition of the vessels.

But many impulses capable of forming the basis of a sensation are prevented under normal conditions from reaching the highest centres; or, if their forward path is not completely barred, they pass on in a profoundly modified form, in consequence of the concurrent activity of other sensory end-organs. The utility of this arrangement is obvious, especially in the case of those impulses which underlie sensations of pain. Temperatures of from 40° C. to 45° C. normally cause a pleasurable sensation of heat, although, in the absence of the heat-spots and epicritic thermal mechanism, pain is produced. Such temperatures are adequate stimuli to the pain-spots, at any rate on the back of the hand, but the impulses evoked are prevented from reaching the highest centres by the effects of coincident stimulation of the thermal end-organs. As the temperature rises, these potentially painful impulses increase in strength, until they can no longer be inhibited; they then form the basis of a sensation of pain. In this case, consciousness is not disturbed, until impulses are produced, not only in themselves of adequate strength to evoke a sensation, but able to overcome the inhibitory effect of the activity of other specific end-organs.

In a similar way, the return of epicritic sensibility reduces the amount of pain caused by cutaneous stimuli, without at the same time raising the threshold. Radiation and reference are inhibited, and the pain produced by a prick is restricted to the immediate neighbourhood of the spot stimulated. This diminution in extent reduces the amount of pain suffered by the patient, although the measured threshold for painful sensations may be actually lower than during the preceding protopathic stage.

So long as a part of the body is innervated by the end-organs of the deep and protopathic systems, two incompatible forms of localization are possible. Painless pressure will be localized in the neighbourhood of the spot to which it is applied; but the sensation evoked by purely cutaneous stimuli will radiate widely, and be referred into some remote part. Both forms of localization may be present in consciousness together. When a cold test-tube is applied to the permanently protopathic area on the back of H.'s hand, the pressure of the tube is localized in the neighbourhood of the point of contact, but the cold sensation is said to lie mainly in the thumb. Thus, the existence of comparatively accurate tactile localization, due to the deep afferent system, does not seem to inhibit or control the impulses produced by

stimulation of protopathic end-organs. But, when once a part of the body is endowed with epicritic sensibility, reference ceases entirely.

It has been suggested (von Frey [14]) that protopathic sensibility is due to anatomical changes which have taken place within the central nervous system, in consequence of the abnormal state of the injured nerve. On the other hand, we believe that this condition is due to the uncontrolled passage of a set of impulses, which normally undergo modification or inhibition before they reach the highest centres. This view is supported by the existence of a normal protopathic surface, such as that of the glans penis.

Most of the characteristic reactions obtained from a part in a condition of protopathic sensibility undergo modification with the return of epicritic impulses; reference alone is completely abolished. It may be asked why a function apparently so useless remains, though in a condition of permanent suppression. The answer to this question is given by the existence of referred pain in disease of the internal organs. These parts are probably innervated, like the glans penis, from the deep and protopathic systems. But, unlike the glans, their sensibility is extremely low; heat- and cold-spots must be scanty or even absent from most parts of the stomach and intestines. Moreover, pain cannot be produced by such stimuli as the prick of a pin, adequate to evoke sensations from protopathic parts on the surface of the body. Internal surfaces cannot respond to artificial stimuli, to which they have never been exposed during the life of the individual or the race.

Even if a stimulus is adequate to evoke impulses from these sheltered parts of defective sensibility, it does not usually produce a sensation, in consequence of the concurrent activity of the sensory organs of the skin. But a sensation may be produced, whenever these visceral impulses become sufficiently strong to overcome this inhibition, or when the central resistance to their passage is in any way lessened. Once the path has been opened, the resistance to potentially painful impulses is lowered, and a weaker visceral stimulus will evoke a sensation. To this diminished resistance is probably due the production of pain by otherwise inadequate stimuli in cases of long-continued visceral irritation.

Since the internal organs are totally devoid of epicritic sensibility, a sensation produced within the visceral area will tend to show the same peculiarities as one evoked from a part supplied with deep and protopathic sensibility only. If the stimulus consists of pressure or of the movement of muscles, the patient will recognize to some extent its true

locality, in proportion as the part is supplied with end-organs from the deep afferent system. When, however, the stimulus evokes pain the sensation will tend to be referred into remote parts.

Now, just as one part of the affected area on H.'s hand seemed to be linked with some other remote portion, so visceral sensory surfaces seem to be closely associated with somatic segmental areas. When pain is evoked, it is not localized in the organ stimulated, but is referred to some area on the surface of the body.

Thus, the retention, on the primary level, of afferent impulses, which, if not inhibited, would lead to incorrect localization, has a protective object. To the normal organism they would be worse than useless, but in disease they underlie widespread pain and uncontrollable muscular reflexes.

The sensory processes discussed in this chapter take place on the physiological level. Psychological analysis fails entirely to disclose the struggle of sensory impulses revealed by our experiment. Integration occurs as impulses pass from the periphery towards the higher centres; the change is a constant one from a complex to a simpler and more specific grouping. Sensation, the final end of the process, assumes forms simpler than any sensory impulses.

We believe that the essential elements exposed by our analysis owe their origin to the developmental history of the nervous system. They reveal the means by which an imperfect organism has struggled towards improved functions and psychical unity.

References.

[1] Alrutz. "On the Temperature-Senses," *Mind*, 1897, vol. vi., New Series, p. 445.
[2] *Idem*, *Mind*, 1898, vol. vii., New Series, p. 141.
[3] *Idem*. "Ueber d. sog. perversen Temperaturempfindungen," *Skand. Archiv f. Physiol.*, 1906, Bd. xviii., S. 166.
[4] Blix, Magnus. "Experimentelle Beiträge zur Lösung der Frage über die specifische Energie der Hautnerven" (1 and 2), *Zeitschr. f. Biol.*, 1884, Bd. xx., S. 141.
[5] *Idem* (3, 4, and 5), *Zeitschr. f. Biol.*, 1885, Bd. xxi., S. 145.
[6] Donaldson. "On the Temperature-Sense," *Mind*, 1885, vol. x., p. 399.
[7] Frey, Max von. "Beiträge zur Physiologie des Schmerzsinns," *Berichte ü. d. Verhandlungen d. k. Sächs. Gesellschaft d. Wissensch.*, 1894, II., S. 185.
[8] *Idem*, 1894, III., S. 283.
[9] *Idem*. "Beiträge zur Sinnesphysiologie der Haut," 1895, II., S. 166.
[10] *Idem*, 1897, IV., S. 462.
[11] *Idem*. "Untersuchungen u. d. Sinnesfunctionen d. menschlichen Haut." Erste Abhandlung: "Druckempfindung u. Schmerz," *Abhand. d. math.-phys. Classe d. k. Sächs. Gesellschaft d. Wissensch.*, 1896, S. 175.
[12] *Idem*. "Ueber den Ortsinn der Haut," *Sitzb. d. phys.-med. Gesellschaft zu Würzburg*; Sitzung vom 9. November, 1899.

[13] FREY, MAX VON. "Ueber den Ortsinn der Haut," *Sitzb. d. phys.-med. Gesellschaft zu Würzburg;* Jahrgang 1902.

[14] *Idem.* "The Distribution of Afferent Nerves in the Skin," *Journ. Amer. Med. Assoc.*, September 1, 1896, vol. xlvii., p. 645.

[15] GOLDSCHEIDER. "Gesammelte Abhandlungen," Bd. i., Leipzig, 1898.

[16] HEAD, RIVERS, and SHERREN. "The Afferent Nervous System from a New Aspect," *Brain*, 1905, vol. xxviii., p. 99.

[17] *Idem* and SHERREN. "The Consequences of Injury to the Peripheral Nerves in Man," *Brain*, 1905, vol. xxviii., p. 116.

[18] *Idem* and THOMPSON. "The Grouping of Afferent Impulses within the Spinal Cord," *Brain*, vol. xxix., p. 537.

[19] HENRI, VICTOR. "Ueber die Raumwahrnehmungen des Tastsinnes," Berlin, 1898.

[20] LINDEMANN. "De Sensu Caloris," 1857. Quoted by THUNBERG, "Nagel's Handbuch d. Physiologie," Bd. iii., S. 687.

[21] MACKENZIE, JAMES. "The Pilomotor or Goose-skin Reflex," *Brain*, 1893, vol. xvi., p. 513.

[22] McDOUGALL. "Reports Cambridge Anthropological Expedition to Torres Straits," Cambridge, 1903, vol. ii., Pt. 2, p. 189.

[23] *Idem.* "The Nature of Inhibitory Processes within the Nervous System," *Brain*, 1903, vol. xxvi., p. 153.

[24] NOTHNAGEL. "Beiträge zur Physiologie u. Pathologie des Temperatursinns," *Deutsch. Archiv f. klin. Med.*, 1867, Bd. ii., S. 284.

[25] SHERRINGTON. "On the Anatomical Constitution of Nerves of Skeletal Muscles; with Remarks on Recurrent Fibres in the Ventral Spinal Nerve-root," *Journ. of Physiol.*, 1894-5, vol. xvii., p. 211.

[26] SOMMER. "Über d. Zahl d. Temperaturpunkte der äusseren Haut," *Sitzb. d. phys.-med. Gesellschaft zu Würzburg*, Sitzung vom 22. November, 1900, S. 63.

[27] STRUMPELL. "Ueber d. Bedeutung d. Sensibilitätsprüfungen mit besonderer Berücksichtigung d. Drucksinnes," *Deutsch. med. Wochenschr.*, September 22, 1904, Jahrgang 30, No. 39, S. 1411; No. 40, S. 1460.

[28] THUNBERG. "Physiologie d. Druck-, Temperatur-, und Schmerzempfindungen," "Nagel's Handbuch d. Physiologie," Bd. iii, S. 647.