THE EFFECT OF ODOURS IRRITANT VAPOURS, AND MENTAL WORK UPON THE BLOOD FLOW

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THE EFFECT OF ODOURS, IRRITANT VAPOURS, AND MENTAL WORK UPON THE BLOOD FLOW.*

PLATES I–VII.

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INTRODUCTION AND DESCRIPTION OF APPARATUS.

ATTEMPTS have been made from time to time to determine the effects produced by various sensations on the circulation of the blood. In 1877 a series of experiments was conducted by MM. Couty and Charpentier, under the direction of M. Vulpian,† in the hope of obtaining a more exact determination of these disturbances. They used curarized dogs with artificial respiration and recorded the results on a kymograph in the usual manner by means of a mercury manometer in connection with an artery. On stimulating the various organs of special sense they obtained cardio-vascular reactions similar in many respects to those usually obtained by stimulating sensory nerves, but differing markedly from these in their greater variability in both form and intensity under the same stimuli.

Both pneumogastric nerves were then severed. Sensory stimulation continued to produce its usual effect on arterial tension, but ceased to produce any effect on the heart. This convinced them of the fact that the heart disturbances and vasomotor changes were mediated by distinct mechanisms.

The cerebral cortex of fresh subjects was then shut out by pressure, by injection, and by light doses of chloral hydrate. In every case stimulation of the organs of sense failed to produce any effect, either on the heart or on arterial pressure, while the direct stimula-

* A thesis submitted to the Johns Hopkins University for the degree of Ph. D.

† De l'influence des excitations des organs des sens sur le cœur et sur les vaisseaux (recherches exp. faites dans le lab. de M. Vulpian), note de MM. Couty et Charpentier, presentée par M. Vulpian. *Comptes Rendus*, t. lxxxv, No. 3, p. 161.

tion of a peripheral nerve, such as the sciatic, continued to produce its usual effect. From these facts they concluded that the cardio-vascular disturbances accompanying sensory stimulation are not due directly to sensation itself, but to a contingent cerebral activity which they called emotion.

Experiments of this nature, however valuable in themselves, will hardly be regarded as sufficient data from which to draw conclusions as to the nature and extent of the cardio-vascular changes accompanying sensations in man. Even if it be granted that cerebral activity is the immediate cause of the cardio-vascular changes in both man and dog, it does not follow that these changes will be the same in the two cases.

In 1880 Dogiel * attempted, by means of the plethysmograph, to study the effects of music on the circulation of the blood in man. The apparatus used contained so many sources of error that even the meagre results obtained can scarcely be regarded as reliable. It is to Mosso's † researches that we are chiefly indebted for what definite information we possess concerning the correlation of cerebral function and cardio-vascular changes in man, but our literature on the whole subject of the changes produced in the circulation in response to various sensations is still very meagre. This is particularly true of olfactory sensations. The present research was undertaken in the hope of throwing some light on this problem.

The form of plethysmograph devised by Mosso was first used, and the volume changes in the arm recorded on a drum kymograph; but it soon became evident that several sources of error would have to be eliminated before accurate measurements could be obtained. The possibility of moving the arm into or out of the cylinder during the experiment must be removed. It is not sufficient to request the subject to sit quietly, nor even to support his head and arm, as Dogiel ‡ did. The voluntary effort required to sit immovable is itself a disturbing factor in the circulation of the blood. Besides, it is impos-

* *Archiv für Anat. und Physiol., Physiol. Abthlg.*, 1880, S. 420 ff.

† Kreislauf des Blutes im menschlichen Gehirn. Von A. Mosso, Leipzig, 1881.

‡ *Op. cit.*, pp. 419 et 429.

sible to prevent movement of the arm for any considerable time, since normal respiration moves the arm. Mosso's * plan of suspending the cylinder from the ceiling and allowing it to follow the movement of the arm is much better, but even here the inertia of the cylinder filled with water offers sufficient resistance to the movements of the arm to produce quite a perceptible error. I think it probable that the respiratory waves † often obtained by the plethysmograph are due in greater measure to this movement of the arm than to the changes in its volume of blood. During the early part of the present research I frequently obtained marked respiratory waves, but in every case I was able to trace them to this movement of the arm, and when the movement was prevented the respiratory waves were very much diminished if not entirely suppressed.

A second source of error lies in the fact that every increase of pressure in the cylinder tends to force the arm out of it, and every diminution of pressure exerts an opposite influence. The play of these opposing forces is felt very distinctly on the inclosed arm during each pulse beat, and when the resulting movement of the arm is prevented the record of the pulse wave is very much amplified. This source of error is still more marked in sudden large vasomotor changes, nor can it be eliminated by making the rubber sleeve so tight that it will not slip on the arm; for apart from the two obvious objections to this mode of procedure—that the arm should be oiled ‡ to prevent it from absorbing water, and that a tight sleeve interferes with normal circulation—the elastic sleeve itself lengthens and shortens in response to changing pressure in the cylinder.

There is still another source of error connected with this mode of closing the cylinder which remains even after all movements of the arm into or out of the cylinder have been prevented. If the arm does not fit the mouth of the cylinder snugly the portion of the elastic sleeve between the arm and the cylinder will yield to each change of pressure in the cylinder. The panting of this membrane in response to the pulse may be seen by the unaided eye. If the mouth

* *Op. cit.*, p. 44.

† Dogiel, *op. cit.*, p. 130.

‡ The oil, of course, increases very much the tendency to slip.

of the cylinder be large enough to allow the elbow to enter, it will usually be found much too large to fit the upper arm. This was very conspicuously the case in the cylinder used by Dogiel.* If the cylinder terminates over the large muscles of the forearm, as it does in Mosso's arrangement, it can be made to fit the arm snugly, but another source of error appears. Every movement of the inclosed fingers withdraws muscle from the cylinder or introduces muscle into it.

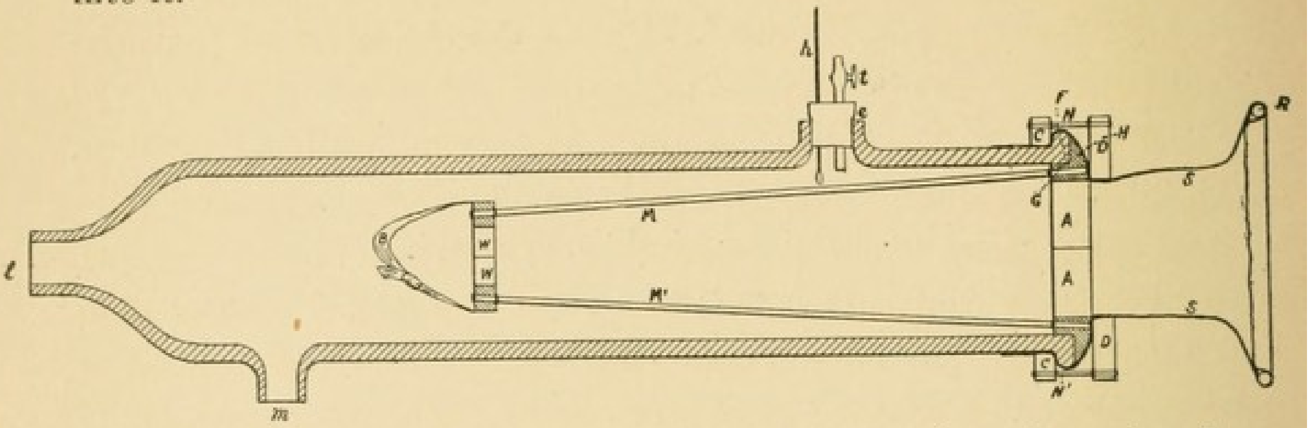


FIG. 1.—S, rubber sleeve; R, ring cemented into end of rubber sleeve; A, arm ring; G, shoulder in same; H, bevelled face of arm ring supporting rubber sleeve; C, D, rings making arm holder rigid to cylinder; N N', rods connecting the rings C and D; W, wristlet; B, band for same; M, *e*, *l*, smaller openings in arm cylinder; *h*, thermometer; *t*, stopcock; M M', metal rods, making wristlet rigid to arm ring.

Fig. 1 is a sketch of a device for removing these sources of error The same is shown in Plate II. The lettering is the same in both.

One end of a suitable-sized rubber sleeve, S, is drawn over the arm cylinder and fastened in position by a ligature. A metal ring, R, large enough to pass readily over the flange is cemented into the other end of the sleeve. By the aid of this ring the sleeve is easily doubled back over the flange of the cylinder, where it remains until the arm has been put into position in the cylinder. A hard-rubber wristlet, provided with a hinge and clasp, fits round the wrist. A soft band, B, passes from one side of this wristlet between the thumb and index finger and is buckled to the other side of the wristlet as tightly as comfort will permit. A second hard-rubber ring, A, provided with hinge and clasp, fits the arm above the elbow. This ring is rigidly connected with the wristlet by two metal rods, M, M'. A

* *Loc. cit.*

shoulder, G, is cut into one face of this ring so as to make it fit into and against the mouth of the cylinder. The face, H, of the ring is shaped so as to keep the rubber sleeve taut down to the point where it meets the arm. When the arm has been introduced into the cylinder and the arm ring fitted into its place, the rubber sleeve is drawn down over it. Two hard-rubber rings, C and D, rigidly connected by two metal rods, N, N′, and provided with hinges and clasps, are then fastened outside the rubber sleeve. One of these rings, C, rests against the flange of the cylinder; the other, D, fits tightly against the outer surface of the arm ring.

This arm holder reduces to a minimum, if it does not entirely remove, the sources of error discussed above. All movements of the elastic sleeve are rendered impossible. The arm holder is made absolutely rigid to the cylinder. The wristlet, with its tight band between thumb and index finger, prevents the arm from moving in the holder. As the inclosed arm can not bend, no muscle can be withdrawn from the cylinder or introduced into it.

The arm was now found to change in volume about one cubic centimetre at each pulse beat. This introduced a new difficulty in the recording apparatus. It will be remembered that in Mosso's * plethysmograph the volume changes were recorded by means of a test tube suspended in a beaker of water or some liquid of suitable specific gravity. The test tube was counterpoised by a weight carrying the recording needle and connected with the test tube by two threads passing over a pulley. However well this arrangement may serve for recording slow changes, its inadequacy for recording such changes as we are here dealing with is evident. The introduction and withdrawal from the test tube of a cubic centimetre of water fifty to one hundred times a minute sets up considerable agitation in the water in the beaker, where every motion is a source of error. Besides, the system has a period of its own which sometimes neutralises the pulse effects and at other times combines with them to produce greatly exaggerated excursions of the test tube, as happens in

* MM. A. Mosso et P. Pellacani. Sur les fonctions de la vessie. *Archives italiennes de biologie*, vol. i, p. 98.

the production of tone beats. The great inertia of the system also prevents it from recording accurately such rapid changes in volume.

The method adopted by Bowditch * of suspending the test tube from a spiral spring is more convenient. This removes the error which, in Mosso's plan, arises from the motion of the water in the beaker. It also materially lessens the inertia of the system. But the great inertia still remaining, and especially the periodicity of the spring, compelled me to seek some other method of recording. I had recourse to a water manometer of large bore connected with the cylinder by a wide, indistensible tube. A light and buoyant float † was used to carry the recording needle. This system, being rigid, and having no period of its own except that due to the float, gave a fairly accurate record of the changes occurring in the volume of the arm; but it introduced a new source of error which compelled me to abandon its use. The level of the water in the manometer tube determines the pressure which the water in the cylinder exerts on the arm. At the beginning of the experiment the manometer may be set so as to exert the proper pressure. But in the course of the experiment every change in the volume of the arm will cause a change of pressure on its surface. The arm sometimes changes twenty or thirty cubic centimetres in volume in a few seconds. This, of course, causes a corresponding change in the level of the water in the manometer tube, which in turn alters very considerably the pressure on the arm; nor can this factor be neglected. I found that the change of pressure due to an alteration of a few centimetres in the level of the water in the manometer caused a very large change in the volume of blood in the arm. That is what we would expect from the low blood pressure in the capillaries and veins.

Lehmann ‡ gives the following account of the apparatus used by him in investigating the effects of sensory stimulation. I quote

* *Proceedings of the American Academy*, May 14, 1879.

† Howell and Warfield. *Studies from Biological Laboratory, Johns Hopkins University*, vol. ii, p. 235.

‡ Die Hauptgesetze des menschlichen Gefühlsleben. Von Dr. Alfr. Lehmann, Leipzig, 1892.

his description in full, as I shall have occasion to refer to the results obtained later on.

" Wir haben nun die Aufgabe auf die Bestimmung der Atembewegungen, des Herzschlages und des Volumens eines einzelnen Gliedmasses, z. B. eines Armes, reduciert. Die erste Bestimmung ist mittels des Pneumographen leicht auszuführen, während die beiden letzten sich mittels Mosso's Plethysmographen zusammen ausführen lassen. Dieser besteht aus einem am einen Ende geschlossenen Rohr, das eben weit genug ist, den Arm zu umschliessen, der durch einen Gummiärmel wasserdicht mit dem Rohr verbunden wird. Durch ein Seitenrohr wird das ganze Rohr, nachdem der Arm in die rechte Stellung gebracht ist, mit Wasser gefüllt, und hierauf wird das Seitenrohr durch einen Gummischlauch mit einem Mareyschen Schreibapparat (*tambour enregisteur*) in Verbindung gebracht. Jede Veränderung des Armvolumens bewirkt eine Hebung oder Senkung des Wassers, durch welche die Luft im Schlauch und im Schreibapparat beeinflusst wird, und die Bewegung wird dann vom Stift des Schreibapparats auf eine rotierende Walze (das Kymographion) gezeichnet."

Lehmann's apparatus seems to be a Mosso hydrosphygmograph * in which the bottle for keeping the pressure constant has been omitted so as to compel the tambour to register both pulse and vasomotor effects. In both these forms of apparatus the pressure on the arm is too high. The air cushion is at the top of the cylinder. The whole arm is consequently under a positive pressure of some centimetres of water. The under surface of the arm can scarcely be under a pressure of less than twelve centimetres. If the cylinder be large enough to extend above the elbow, as it should do in order to escape a source of error mentioned above, this pressure is likely to be still higher.

The form used by Lehmann introduces another grave source of error. In dispensing with the pressure bottle, the tambour and cylinder are rendered a closed system in which every change of volume in the arm alters the pressure on its surface. If, as some-

* Diagnostik des Pulses. Von Dr. A. Mosso, Leipzig, 1879.

times happens, twenty-five or thirty cubic centimetres of blood be added to the volume of the arm, the distention of the membrane of the tambour necessary to make room for this increased volume of blood would exert a considerable pressure on the arm.

Besides the sources of error enumerated in connection with each of the forms of apparatus discussed above, there is a defect common to them all. We have seen that the changes in volume of blood in the arm are due to at least two distinct sources—changes in the heart's action and changes in the calibre of peripheral vessels. It is therefore highly desirable that the record of these two effects be kept as distinct as possible. Whenever, as is the case with each of these forms of apparatus, the same writing point is made to record the pulse and the gross volume changes, these effects partially mask each other and do not stand out as distinctly as they should. This is illustrated very well by many of the curves published in Lehmann's work. I have a large number of similar curves in my own possession which I obtained by the use of these forms of apparatus.

From what has been said, it is evident that an efficient apparatus for recording the volume changes in the arm must at least meet the following three requirements: First, the pulse and vasomotor effects should be recorded separately; second, the apparatus for recording the rapid and rhythmic changes of volume due to the pulse should have very little inertia and no periodicity; third, the pressure exerted on the arm should be as nearly normal as possible, and must remain constant during all changes of volume which may occur in the arm. These requirements are met fairly well by the following arrangement:

A long metal tube, A′ (Plate I), is slipped over an upright, U, to which it is fastened by a clamp, C. The top of the upright is held in position by two metal rods, M, M′, which make it rigid to the wooden screen interposed between the subject and the kymograph. A short metal tube, B, is supported in a vertical position by two clamps, D, D′, which make it rigid to the upper end of tube A. One end of a long close spiral, S, of No. 5 piano wire is slipped over the lower end of the tube, B, and fastened to it by a clamp, E. Two wires, F, F′, pass down from the free end of the spiral, and are fastened by two small binding screws to a light hard-rubber ring, R, one inch in diameter. By suitable cork collars, test tubes of various sizes may be suspended from this ring. The slipping of the wire under clamp E permits the length of spiral to be so adjusted that the level of the water in the suspended test tube will remain constant while the quantity of water in the test tube varies. One arm of a long glass siphon, G, is passed down through tube B, thence through the centre of the spiral S, and dipped a few millimetres beneath the surface of the water in the test tube T. The siphon is centred and held in position by six set screws passing through tube B. An indistensible tube, H I, connects the other end of the siphon with the arm cylinder. The four-way J interposed in this tube will be described later.

This is essentially the same as the apparatus described by Bowditch, to which reference has already been made. Its inertia unfits it for recording the changes in volume due to the pulse. Its periodicity combining with the rhythmic pulse at times neutralizes the pulse effects, and at other times combines with them to produce greatly exaggerated excursions of the test tube. The pulse and vasomotor effects also partially mask each other. The pulse effects are the disturbing factor in each case; if they be removed from the test tube and recorded separately, the instrument is well adapted for registering the vasomotor effects.

By the following device this separation of the pulse record from the vasomotor record may be attained, the pulse wave being recorded by a tambour the tension of which remains practically constant except for the variation with each pulse wave and the vasomotor changes being recorded by the test tube and spiral spring already described, which are so arranged that only the slow vasomotor changes in the volume of the arm cause any perceptible movement of the system, the quicker changes due to the heart beat disappearing from this record. A wide glass piston tube (K, Fig. 2 and Plate I; P, Plate II) is supported in a vertical position beside the arm cylinder, with the bottom of which it communicates freely. The

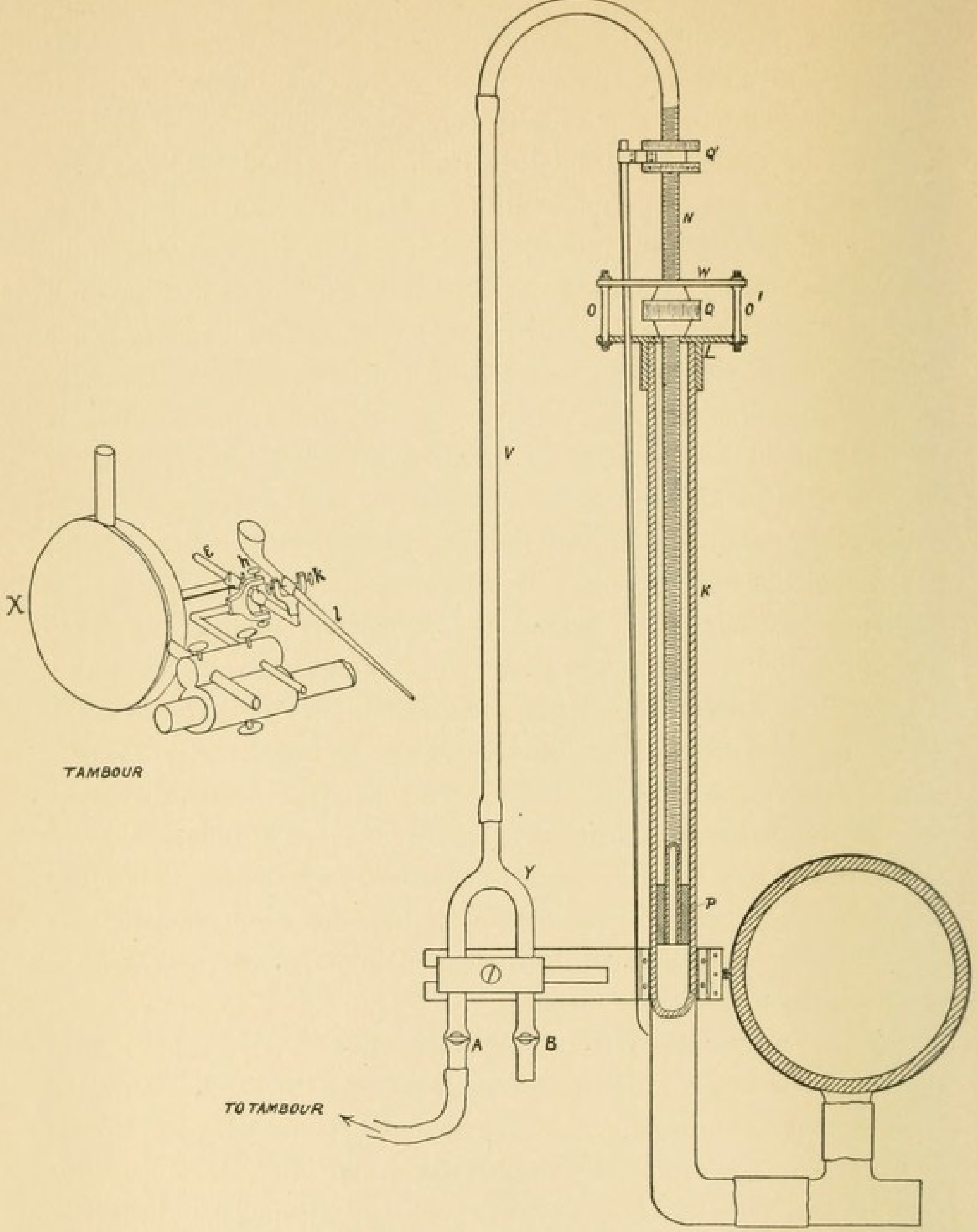


FIG. 2.—K, piston tube;* P, piston; N, piston rod; Q, milled nut for adjusting level of piston; Q', milled nut for adjusting indicator; *g*, metal cap of piston tube; W, washer, giving support to nut Q in lowering piston; O, O', rods supporting washer; *v*, tube connecting with tambour; Y, T-way; A, B, stopcocks on same; X, tambour; *e*, tambour lever carrying horizontal pivot; *k*, horizontal pivot; *h*, vertical pivot.

* The vertical piston tube allows the pressure of the water on the arm to be regulated at pleasure. The piston in this tube serves to keep the volume of the air between the water and the tambour constant.

upper end of the tube is incased in a metal cap, L (Fig. 2), which is perforated to allow free play to the hollow piston rod, N, and free communication between the air in the upper end of the piston tube and the atmosphere. From this cap two metal rods, O, O′, parallel with the piston tube extend upward about one inch and hold in place a washer, W, which encircles the piston rod. Between the washer and the cap a milled nut, Q, fits on the piston rod, which is threaded from end to end. The piston rod, N, is a metal tube one eighth of an inch in diameter, which extends through an otherwise air-tight piston, P, in the piston tube. A small indistensible tube, V, connects the upper end of the piston rod with a Marey tambour, X. A T-way, Y, provided with two stopcocks, A, B, interposed in the course of this tube, permits connection between the air cushion below the piston and the tambour or the atmosphere to be made or broken as desired. A milled nut, Q′, fitting the piston rod above the washer, carries an indicator, which passes down through a perforation in the washer, thence through a perforation in the flange of the metal cap, and terminates below the level of the piston. The distance between the point of the indicator and the lower surface of the piston measures the vertical height of the air cushion in the piston tube. It can be set at any desired distance by means of the nut Q′. Since the indicator is carried by the piston rod, the distance between its point and the piston remains constant whatever alterations may be made in the level of the piston. The level of the water in the piston tube when the air cushion is in communication with the atmosphere indicates the pressure exerted by the water on the surface of the inclosed arm. For convenience in registering this pressure a centimetre scale is affixed to the side of the piston tube.

The arm cylinder is of the usual form (see Plate II). A flexible metal band, Y, encircles the cylinder near one end and is closed over the upper surface of the cylinder by a nut and bolt. To this bolt are also fastened two chains which pass round the cylinder in opposite directions, and thence through a ring, *d*, which is suspended some distance above the cylinder. The chains are doubled back and hooked on themselves at desired lengths. The other end of the cylinder is suspended in a similar manner from the same ring. These chains serve to keep the cylinder in a horizontal position and to prevent it from rotating. A fifth chain, from which the ring *d* is suspended, passes through a pulley fastened to the ceiling, thence down to a ratchet which is supported at convenient height. By turning this ratchet the cylinder is raised or lowered to suit the comfort of the subject.

Besides the opening through which the arm is introduced, the cylinder is provided with three other smaller orifices. Through one of these, *l*, situated on the end of the cylinder, communication is made with the suspended test tube used to record the vasomotor changes. A second orifice, *e*, provided with a tight-fitting rubber stopper through which two perforations have been made, is located on the upper surface of the cylinder. A glass stopcock, *t*, is fitted into one of these perforations. The bulb of a thermometer, *h*, is introduced through the other. On the under surface of the cylinder is a third orifice, M, into which is fitted one branch of a large T-way. A second branch of this T-way communicates with the lower end of the piston tube. The third branch is connected with the tube *k* for filling and emptying the cylinder.

I have found the following method convenient for filling and emptying the cylinder, for regulating the temperature and pressure of the water, and for adjusting the instrument:

The piston is raised or lowered by turning the milled nut Q until the point of the indicator stands at the level to which it is desired to bring the water in the piston tube. Two supply jars, P, Q (Plate I) —one filled with hot water, the other with cold water—are placed on a shelf attached to the screen above the level of the test-tube siphon, G. Two siphons connect these jars with two branches of a large three-way stopcock, *w*, which permits the hot and cold water to be mixed in the desired proportions. The bulb of a thermometer for indicating the temperature of the water is placed in the tube, which conducts the water from the three-way *w* to one branch of a second large three-way, *z*. A tube connects a second branch of this three-way with the arm cylinder; another tube leads from its third branch to the sink. This three-way allows the water to pass from the three-way *w* to the cylinder, or from the cylinder to the sink, or from a hydrant tap to the supply jars, as may be desired.

The four-way J, each branch of which is provided with a stopcock, is made rigid to the tube A, at a level somewhat lower than that of the arm cylinder. One of these stopcocks (1) opens into the test-tube siphon ; a second (2) communicates with the arm cylinder; a third (3) is connected by a siphon with one of the supply jars; a tube from the fourth (4) leads to the sink.

When the subject's arm has been coated with vaseline and placed in the arm cylinder, as directed above, stopcock *t*, on the upper surface of the arm cylinder, is opened to allow the air to escape. Stopcocks A and B (Plate I and also Fig. 2) are closed to cut off connection between the air cushion of the piston tube and the atmosphere and tambour. Stopcocks 1 and 2, on the four-way, are opened, and stopcocks 3 and 4 closed. Three-way stopcocks *w* and *z* are adjusted so as to allow water of the proper temperature to enter the arm cylinder. When the cylinder is within a few cubic centimetres of being full the supply of water from this source is shut off, and a strong clamp placed on the supply tube at the point where it meets the cylinder, to prevent any possible error that might otherwise arise from leakage or from distention of the supply tube. Stopcock 3, on the four-way, is now opened and water allowed to flow into the cylinder until it is filled, when the stopcock at the top of the cylinder (*t*, Plate II) is closed to prevent air from re-entering the arm cylinder. Stopcock 2, on the four-way, is closed at the same moment to prevent increase of pressure on the arm while the test-tube siphon is being filled. When the test tube is partially filled, stopcock 3 is closed and stopcock 2 opened. If the test tube is too full at any time, water may be drawn off by opening stopcock 4. Stopcock B is now opened, thus establishing free communication between the air cushion and the atmosphere. The water in the piston tube will now rise to the same level as that in the test tube. Tube A′, carrying the test tube and its appurtenances, is slowly raised or lowered on the upright until the level of the water in the piston tube reaches the point of the indicator. Stopcock B is then closed and stopcock A opened, thus putting the air cushion in communication with the tambour. The lever of the tambour will now give a magnified record of the changes in the level of the water in the piston tube. If the resistance offered by the long narrow tube, H I, to the rapid passage of water between the test tube and the arm cylinder is not sufficient to prevent the changes of volume due to the pulse from moving the test tube, this resistance is increased to the desired extent by partially closing stopcocks 1 and 2 on the four-way. The small and rapid changes of volume due to the pulse are consequently recorded by the tambour alone, while the slower and larger volume changes, freed from pulse waves, are recorded by the motions of the test tube, on the same principle that the height of the tide is recorded by the level of the water in the vertical pipe of the tide gauge, while the separate waves are prevented from influencing this level by the resistance which the holes in the bottom of the pipe offer to the rapid passage of water.

This form of apparatus reduces very much the sources of error discussed above. The suspended test tube is entirely freed from the error due to the periodicity of the spring. The inertia of this system ceases to be a grave source of error owing to the slowness of the motions which it is now required to execute. The tambour, relieved for the most part from the disturbing factor of large volume changes, gives a fairly accurate record of the pulse waves. The chief source of error remaining is the pressure exerted by the water on the arm. It is, of course, impossible to have an arm immersed in water under perfectly normal pressure. I have found the conditions to be most favourable when the level of the water in the piston tube is that of the middle of the arm, the lower half of the arm being then under a positive pressure of a few centimetres of water, and the upper half under a like amount of negative pressure.

Each pulse wave is accompanied by a slight change of pressure on the arm, due to the resistance which the water in the cylinder offers to the entrance of the wave. This resistance is made up of several factors: First, the inertia of the volume of water to be moved; second, the force of gravity to be overcome in slightly raising the level of the water in the piston tube; and third, the resistance offered by the air cushion in the piston tube to change in the level of the water in the tube. The last-named resistance is due to the tension of the membrane of the tambour and to the inertia and friction of the recording lever. These sources of error are quite small, but they still exist, and should be taken into account in calculating results. The resistance offered by the air cushion has been rendered very slight by reduction in the weight and friction of the recording lever, and by the delicacy and low tension of the tambour membrane. The inertia of the mass of water to be moved may be reduced somewhat by so changing the form of the arm cylinder as to diminish the distance between the surface of the water in the piston tube and the point where the expansion of the inclosed arm first occurs. The wider the piston tube, the less the change in the level of the water caused by the pulse wave; but the pulse recorder becomes proportionally more sensitive to vasomotor changes. When there is a sudden large change in the volume of the arm, the vasomotor recorder can not take care of it rapidly enough. There is, in consequence, a temporary variation in the level of the water in the piston tube, which interferes somewhat with the pulse recorder and changes the pressure on the arm. The influence of this disturbing factor, which I have not yet been able entirely to eliminate, will receive attention when we come to discuss the results.

In the early part of the investigation, I used a Ludwig drum kymograph, with smoked paper for recording the curves. It soon became evident, however, that this plan of recording presented another grave difficulty.

Spontaneous changes, or at least changes not due to sensory stimulation, were continually appearing in both vasomotor and pulse curves. It was, therefore, necessary to have a continuous record of the changes going on in the arm for some time before and after stimulation, in order to be able to differentiate them from any sensory reactions that might appear. This is impossible with the Ludwig drum kymograph, for if it be made to travel fast enough to bring out the pulse curve, the paper will be used up in three or four minutes, and it will be necessary to stop and put on fresh paper. An ink record on a continuous band of paper is evidently what is needed. The chief difficulty in obtaining such a record is the resistance to be overcome in moving the vasomotor and pulse pens. I was unable to reduce this sufficiently in the case of vertical kymographs for continuous paper, and accordingly built a horizontal kymograph, the general arrangement of which is shown in Plate I. By special contrivances for suspending and moving the pens the resistance was reduced within the limits of that offered by the smoked paper.

A light plate of aluminium foil is cut in the form of a cross. The two ends of the transverse beam widen out and are bent so as to clasp tightly the tube of a glass pen. The ends of the other beam of the cross are bent into hooks, from one of which a thread passes over a pulley adjusted to the side of the kymograph, and is held taut by a small weight. From the hook on the other end of the beam a thread passes under a pulley adjusted to the other side of the kymograph, and thence vertically to a violin key, which turns in a cork holder cemented to the bottom of the test tube used for recording the vasomotor changes. This key is turned until the pen rests over the centre of the paper. A thread fastened to the bulb of the pen passes vertically to a similar violin key, which is supported in proper position. The tube of the pen, at a point somewhat beyond where it leaves the holder, is bent downward through an angle of about 45°. The key to which the vertical thread supporting the bulb of the pen is fastened is turned until the point of the pen just touches the paper. The pulleys are so adjusted that the upper portion of the pen will be about horizontal. The thread passing between the pulleys is horizontal also, except for the sag in the middle, caused by the weight of the pen. As the pen moves from either pulley toward the other it describes a curve, due to the sag in the horizontal thread. This curvilinear motion is neutralized in the point of the pen by the pendular motion of the bulb, due to the thread from which it is suspended, the factors in this adjustment being the extent of the sag, the length of the pendular thread, and the respective distances of the point and bulb of the pen from the horizontal thread. The extent of the sag is controlled by the size of the weight on the end of the thread. The length of the pendular thread is regulated by raising or lowering the key holder from which it is suspended. The distance of the ends of the pen from the horizontal thread is controlled by moving the pen in its holder.

The friction between the point of this pen and the paper is very small, since the point need not actually touch the paper, the capillary attraction between the paper and the meniscus being sufficient to cause the ink to flow if the pen be properly made. But even when the point of the pen actually touches the paper, it does so very lightly. If the point of the pen be lifted by a finger until the sag leaves the horizontal thread, half of the weight of the tube of the pen will rest on the finger. If the finger be now gradually lowered, the weight on it will be found progressively to diminish and finally to disappear, having been thus shifted to the horizontal thread. This gives very great buoyancy to the point of the pen and reduces friction to a minimum.

The pulleys are large and very light, and are pivoted in a manner similar to the balance wheel of a watch. Their friction is thus rendered very small. The inertia due to the pen, its aluminium holder, and the light weight on the end of the horizontal thread, is relatively a very small addition to that of the test tube partially filled with water; but the inertia of this whole system, large as it is, has very little influence on the accuracy of the record, owing to the slowness of the motions which it describes.

The tambour, *x* (Fig. 2 and Plate I), of the pulse recorder is supported with its membrane vertical. The motions of this membrane are communicated to one end of a light aluminium lever, *e*, which just after passing through a pivot, *h*, whose axis is vertical, bends upward at a right angle, and after running in this direction about one inch supports a second pivot, *k*, whose axis is horizontal and perpendicular to the long axis of the paper. A light glass pen, *l*, with a long tube is passed through this pivot and fastened to it when the bulb of the pen is directly over the axis of the first pivot. The motion of the membrane will now impart a magnified horizontal movement to the point of the pen, while its bulb, being in the axis of the pivot, only undergoes a very slight rotary motion. The second pivot allows the pen to move freely in a vertical plane. Ink is now poured into the bulb of the pen until the point of the pen barely rests on the paper. The friction here is very slight.

The pens for the pneumograph (to record the respiratory movements), the time marker, and the signal marking the time of application of the stimulus, are pivoted in a slightly different manner, but one which involves the same principle. The bulb of the pen with the ink which it contains acts in each case as a counterpoise to the long tube of the pen, thus causing the point to rest on the paper as lightly as desired. A horizontal movement is imparted to the point of the pen by a fork of the tambour lever or of an armature of an electro-magnet, as the case may be. For this purpose the pen must be free to move round two axes, one vertical and the other horizontal.

The points of the five pens are adjusted so as to fall in a line perpendicular to the long axis of the paper. The test tube used in the vasomotor recorder was of such a calibre that three cubic centimetres of water moved it one centimetre. The paper travelled from right to left; the time record is nearest the test tube, and consequently at the bottom of the paper. Movement of vasomotor or pulse pen toward the bottom of the paper represents diminishing volume of arm, and conversely. I used the time record as base line in calculating the volume changes. If d represents the initial distance in centimetres between the point of the vasomotor pen and the base line, and d' its distance in any subsequent position, then $(d' - d) \times 3 = V$, where V is the volume change in cubic centimetres. If at any time during the experiment the test tube is becoming overfilled, stopcock 2, Plate I, on the four-way, is closed and stopcock 4 opened until the desired amount is drained off. Stopcock 4 is then closed and stopcock 2 opened, and the fact noted on the paper. The point of the pen, of course, records the volume drawn out, which must be added in calculating subsequent changes. If the test tube is in danger of being emptied, water is introduced through stopcock 3 in a similar manner, and the amount subtracted in all subsequent calculations. Specimens of the curves traced by this instrument may be seen in Plate III.

Being thus enabled to obtain what I believed to be a fairly accurate record of the changes which actually occur in the volume of the arm, I proceeded to study the influences which determine these changes in the hope of being able to eliminate some of them and to differentiate the changes which would remain from any odour reactions I might obtain.

I first determined empirically what temperature of water and what pressure on the arm would maintain the most constant volume of blood in the arm. The most favourable pressure, as has already been stated, is that which is exerted when the level of the water in the piston tube was about that of the middle of the arm. When I used pressure lower or higher than this the arm exhibited a tendency to increase or diminish in volume. The proper temperature of water I found to be between 30° and 34° C, according to the temperature of the room and of the arm of the subject. I found that this temperature kept the volume of the arm more constant than any other, and I found also that the temperature of the water in the cylinder remained constant throughout the experiment, whereas, if the temperature be higher at the beginning, it will sink during the experiment, and conversely, if the initial temperature be lower.

After the experiment had been continued for about half an hour, large and frequent changes of volume usually occurred, which I attributed to the discomfort of the subject, who up to this time had been seated on a wooden chair. These disturbing factors were removed by putting the subject in an invalid chair which could be adjusted to any desired position. He could rest here comfortably, with all his muscles as completely relaxed as if he were in bed. This rendered the volume of the arm much more constant. But the most conspicuous of the disturbing factors still remained. This is the mental reaction. Apparently, every thought that flits across the subject's mind records its presence by a change of volume in the arm. Talking in the room, the entrance of a stranger, the striking of a clock, or a noise in an adjoining room, is usually accompanied by a change of volume in the arm, and this sometimes even when the subject is asleep. This is what was to be expected from the correlation which Mosso has shown to exist between cerebral function and the volume of the arm.* Nor do I see any way in which this disturbing factor can be eliminated while working with sensory stimulation. The only course open seems to be to confine it within as narrow limits as circumstances will permit, and to endeavour by control experiments to differentiate what mental reactions may remain from the sensory reactions under investigation.

The odours were at first administered to the subject by holding a bottle under his nose and allowing him to smell its contents. This was the plan pursued by Lehmann,† but it is open to several obvious objections. The disturbance of mental equilibrium occasioned by such a procedure is itself sufficient to condemn it. Any sudden or unexpected movement of the operator produces a mental reaction in the subject. On the other hand, I soon found that when he anticipated my movement a reaction appeared. When he saw me reaching for the odour bottle, even when I did not apply the stimulus, a reaction appeared which was often very similar to that accompanying the sensation itself. It is evident, then, that the subject should be isolated, and everything that could attract his attention as far as possible removed. To attain this end a screen was placed between the subject and the kymograph, so as to prevent him from perceiving the recording apparatus or any of my movements, and a special apparatus was devised for administering the odour without exciting or disturbing the subject.

The apparatus used for applying the odours is shown in Plate I. By means of an aspirator, *a*, attached to a hydrant tap, air and cold water are mixed together and poured into a large bottle, *t*. The water is drawn off by a siphon. The air is forced out through a

* Kreislauf des Blutes im mensch. Gehirn.

† *Op. cit.*, p. 82.

small tube, *b*, which connects with a coil of lead pipe immersed in a warm bath of constant temperature. This gives us a constant current of washed air of any desired size at a constant temperature and in constant hygrometric condition. A tube, *w*, conducts this current of air into a metal pipe, *y*, fastened to the front of a drawer in the kymograph table. A series of thirteen metal stopcocks open along the upper surface of this pipe. In the front of the drawer is arranged a series of thirteen bottles, each containing a small portion of odoriferous substance. A pair of small glass tubes perforate the stopper of each bottle and terminate at its lower surface. One of each of these pairs of tubes connects with a corresponding stopcock on the metal pipe. Each of the other tubes communicates with a corresponding glass tube which passes down through the bottom of the drawer, bends over to the screen, and runs up to about the level of the subject's head, where it terminates after passing through the screen. Thirteen flexible tubes connect these glass tubes with thirteen short metal tubes which are screwed into a terminal plate, the odour plate, Z′, and end on a level with its distal surface. A tube, 14, which does not make connection with any odour bottle, leads directly from the stopcock on the end of the metal pipe to a fourteenth metal tube in the odour plate. This permits a current of odourless air to be administered when desired.

The odour plate (Z′, Plate I and Fig. 3) is a copper disk, eight inches in diameter, supported from its centre on a universal holder, which allows it to be adjusted in any desired position. Through this plate are bored five series of fourteen holes each, arranged in five concentric circles. The odour tubes terminate in the inner circle of holes. The lumen of a short portion of the terminal end of these metal tubes is less than half the diameter of that of their proximal end. Thirteen of these tubes are provided with electric valves constructed so as to work noiselessly and to leave the face of the plate as free as possible. This prevents the subject from perceiving the opening or closing of the valves, except by his sense of smell, and removes from the face of the plate all objects to which odours might cling.

Fig. 3 shows the construction of one of these valves. A metal disk, A, faced with rubber dam is placed in the large end of the tube. The diameter of the disk is less than the large lumen of the tube and greater than its small lumen. A small wire, *b*, passes from the centre of this disk out through the small lumen of the tube, and a few millimetres from the face of the plate is fastened to a metal rod, *c*, which, after running outward parallel with the face of the plate for a short distance, bends back at a right angle, passes through a perforation in the plate, and is adjusted by two nuts to one end of an armature lever, *d*. This armature lever runs outward parallel with the plate, and terminates over an electro-magnet, *e*. It is supported on a pivot, *b'*, situated a short distance centrally to the magnet. A small spiral spring, *g*, fastened to the odour plate is adjusted

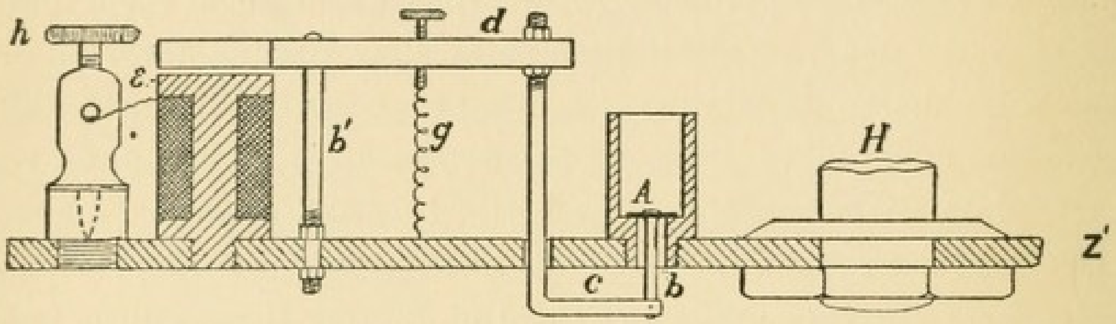


FIG. 3.—Z, terminal plate (odour plate); H, holder; A, metal disk for closing odour tube; *b*, wire from centre of disk A to rod C; C, rod connecting wire of valve to armature; *d*, armature lever; *e*, electro-magnet; *b'*, pivot of armature lever; *g*, spiral spring from armature lever to terminal plate; *h*, insulated binding screw.

to the central arm of the lever by a small nut and bolt, which allow the tension of the spring to be regulated at pleasure. One wire of the electro-magnet makes contact with the plate; the other passes to an insulated binding screw, *h*, fastened to the plate beside the coil. The tension of the spring is so adjusted as to hold the valve closed except while a current is passing through the magnet, and to prevent the armature from touching the magnet at any time. This prevents noise, and the rubber-dam face renders the valve itself noiseless. The movement of the wire on the face of the plate in opening or closing the valve is so small that it escapes the notice of the subject.

A wire from one pole of a battery makes contact with the metal pipe on the face of the kymograph drawer. Each of the thirteen stopcocks on the upper surface of this pipe is provided with a platinum contact, which, when the stopcock is open, dips into a corresponding mercury well situated on the upper surface of the drawer between the stopcock and its odour bottle. A wire passes from each of these mercury wells to a corresponding binding screw, thence through the coil of the electro-magnet to the terminal plate. A wire in contact with the copper terminal plate passes to the magnet of the signal pen, and thence back to the other pole of the battery.

The opening of any of these thirteen stopcocks, therefore, sends a constant current of air through the corresponding odour bottle, and, by completing the electric current, opens the terminal end of the corresponding odour tube near the subject's nose, and marks the instant of stimulation on the paper of the kymograph.

Opening the fourteenth stopcock at the end of the metal pipe sends a current of odourless air to one of the odour tubes of the odour plate.

To secure quiet and exclude light stimulation, the subject was at first placed in a separate and darkened room. I soon found that movements of any part of the body might produce a change in the volume of the inclosed arm. It was necessary, therefore, to bring him into a position where I could observe any movement he might make. A screen was placed so as to prevent him from seeing me or the recording apparatus. The room was of course kept quiet, and visitors excluded except where their presence is noted. All the records discussed here were taken by the improved form of apparatus described above.

Discussion of Results.

To illustrate the character of the records actually obtained, several specimens (reduced in size) of the tracings upon the kymograph are given in Plate III, Figs. 1, 2, 3. Fig. 1 illustrates the vasomotor reaction obtained in a certain instance by the odour of extract of heliotrope, and Fig. 2 shows the effect of formic acid when inhaled into the nose. The lowermost line gives the time record in seconds; above this is the pulse record taken by the tambour; and above this the volume curve of the arm upon which the pulse movements are not perceptible. A fall of this curve indicates a shrinkage of the arm due to vaso-constriction. At the top of the tracing the respiratory movements are recorded; and above, the signal pen marks the time of application of the sensory stimulus—i. e., in these cases heliotrope and formic acid. Fig. 3 is a portion of a tracing in which the effect of isobutyric acid was studied. This tracing may be taken for special description, as it illustrates one of the main difficulties met with in interpreting the curves. The subject's arm was in the cylinder about fifteen minutes when this portion of the record was begun. Curve E gives the time in seconds. Ordinates are drawn at every fifth second. The base line F is drawn parallel to the curve E. The pulse curve, D, shows very little change in the heart rate. There are nineteen heart beats in the first fifteen seconds, and about eighteen in each succeeding fifteen seconds. The respiratory curve, B, shows no very great irregularities. The vasomotor curve, C, shows an increase of 1·2 cubic centimetres in the volume of the arm during the first twelve seconds. Curve A indicates that the odour of isobutyric acid was turned on at the tenth second, but it is evident from the respiratory curve (phase of expiration) that it could not have reached the olfactory membrane much before the twelfth second. At this point, the arm ceases to increase in volume, and three seconds later it begins to decrease. At the twentieth second it shows a diminution of 1·5 cubic centimetres. The curve then slowly returns to the base line, which it almost touches at the thirty-eighth second. It indicates a second diminution of one cubic centimetre at the forty-fifth second. After this the curve rises slowly and crosses the base line at the sixtieth second. This is followed at intervals of about ten seconds by three positive waves and one negative wave, not shown in the figure, of somewhat less than five cubic centimetres. This curve would seem to indicate that the odour of isobutyric acid produces a reflex stimulation of the vasoconstrictor fibres of the arm, but I do not think it furnishes sufficient evidence for such a conclusion. The curve in other places frequently shows just the opposite effect, although the conditions remained the same. To be at all certain of the effect of any particular stimulation we must, at least, know the general movement going on for some time before and after the stimulation. To avoid the inconvenient length of the original records needed for such a study, I have condensed their data into plotted curves, several of which (Plates IV, V, VI, and VII) accompany this article. In these curves the distance between the ordinates marks intervals of ten seconds each. Curve A, at the bottom of the plates, gives the changes in the amplitude of the pulse waves. The absolute value of this amplitude might easily be determined empirically, but this I have not done. Nor can I calculate it exactly, since I failed to keep a record of the magnification due to the leverage of the writing apparatus. But as this leverage was not varied during any of the individual records, its effect could have no influence on the changes which occur during the same record. The vertical distance between the abscissæ represents about two-tenths of a cubic centimetre in volume. Curve D gives the heart rate. For this curve the distance between each two abscissæ represents one beat per minute. Curve C gives the changes in the volume of the arm in cubic centimetres. The vertical distance between the abscissæ represents a change of two-tenths of a cubic centimetre. The pulse amplitude and the volume changes are calculated at every fifth second. The heart rate is reckoned for every ten or fifteen seconds. The time of stimulation by the various odours is indicated in the plates. The respiratory curve was taken in all the original records, and whenever it presented any marked irregularities, this fact is noted on the plates.

In order to study the effects of repetition and of individual variation in response to the same odours, the experiments were arranged in two series. The first series of experiments were all made on the same subject; the second series were made on twelve different individuals.

First Series.

Mr. George Bill, who acted as subject in the first series of experiments, is a mechanic, thirty-three years of age, in good health, of fair muscular development, and not particularly susceptible to odours. His arm was kept in the cylinder about an hour daily from the middle of October to the middle of January. He was trained to keep his mind as blank as possible. The monotony of daily repetition soon removed the disturbances which in untrained subjects arise from the novelty of the surroundings. The odours of heliotrope, wood violet, wintergreen, musk, skatol, and indol were used daily; a few others were used occasionally.

Defects in the earlier forms of apparatus used render the experiments made during October and November unsatisfactory. Plates IV to VI, inclusive, give the results of three experiments of this series, which were made during December and January, when all the conditions were most favourable, and may serve as examples of the general results obtained from this series.

One of the most obvious features of these curves is the general increase in the volume of the arm which they exhibit during the course of the experiment. In one experiment there was an increase of 39 cubic centimetres in the volume of the arm between the 450th and the 2350th seconds; in another, an increase of 30 cubic centimetres between the 1st and the 1360th seconds; a third gave an increase of 35 cubic centimetres between the 20th and the 1300th seconds; and in a fourth the arm increased 37 cubic centimetres in volume between the 1st and the 1900th seconds.

Several facts indicate that this increase in the volume of the arm is due not to the temperature or pressure of the water in the arm cylinder, but to the mental condition of the subject; for in other experiments on the same subject, though the temperature and pressure of the water were the same as in the series just described, no such general increase in volume occurred, nor did it take place in experiments made on the other subjects. Second, the volume of the arm decreased immediately when anything attracted the subject's attention. In Experiment V (Plate IV) the subject was resting quietly with his arm in the cylinder for ten or fifteen minutes before I began to take the record. During this time the arm increased several cubic centimetres in volume. One hundred seconds after the record was begun Dr. K. entered the room quietly, but was perceived by the subject. The volume of his arm decreased 11·5 cubic centimetres in the following 50 seconds. One hundred and fifty seconds later, as Mr. G. entered the room, a further decrease of 4 cubic centimetres in 20 seconds ensued. After both had left the room the arm immediately began to increase and continued to increase to the end of the experiment. In Experiment X, I spoke to him at the 240th second. This occasioned a fall of 5 cubic centimetres in a few seconds. Twice in the course of this experiment I turned on the odour of formic acid for a few seconds; each time it occasioned a sudden diminution in the volume of the arm.

The subject had grown familiar with his surroundings; the chair was very comfortable, the room quiet; there was nothing to attract his attention, and as a consequence his mind quieted down, and he was frequently dozing toward the end of the experiment. In Experiment VII he slept from about the 300th second to the end of the experiment. It was found, too, that in these experiments the heart rate became slower and steadier as the arm increased in volume—an indication that the subject was gradually quieting down or going to sleep. These facts, I think, show pretty clearly that this general increase in the volume of the arm is due to diminished mental activity; but, whatever may be its cause, it must be taken into account in calculating the effect of any particular sensory stimulation. To check an upward movement of the curve is practically the same thing as to cause a downward movement of a curve that is running horizontally. A horizontal line evidently can not be taken as a base line in calculating local changes. The base line must run in the general direction of the curve. It is not an easy matter to determine accurately what this line should be; but in most cases it may be approximated and a line obtained which will be much nearer the truth than a horizontal would be.

The curves also exhibit two species of local variation which do not seem to be connected with sensory stimulation. In most of the curves small oscillations occur, which suggest Traube-Hering waves. Besides these, larger and slower changes occur at irregular intervals, which seem to be due to variations in the mental condition of the subject. These changes are the most annoying factors in the curves. I have been unable to eliminate them ; and it is very difficult, if not impossible, to determine the part they play in the volume changes which take place during sensory stimulation.

Some peculiar features appear in Plate V, which are probably due to the fact that the subject was asleep during most of the experiment. The arm increased rapidly in volume from the beginning of the record to the 1300th second, and gradually decreased from this to the end of the experiment. The subject had been resting quietly with his arm in the cylinder for some time before the record was begun. He seemed to be asleep about the 300th second ; at the 430th second I spoke to him and found that such was really the case. He did not wake, but his arm decreased 3 cubic centimetres in the following 20 seconds, and then increased more rapidly than before ; 75 and 120 seconds later two other falls of about 4 cubic centimetres occurred which did not seem to be connected with any external stimulus. At the 1930th second, 50 seconds after a musk stimulation had ceased, there was a fall of 5·5 cubic centimetres in 30 seconds. At the 2250th second, during an indol stimulation, there was a fall of 6·6 cubic centimetres in 35 seconds, followed by an increase of 9 cubic centimetres in 265 seconds, when, 35 seconds after the indol stimulation had ceased, there followed another fall of 7·6 cubic centimetres in 30 seconds. The odour of wintergreen was now turned on for 150 seconds, during which time the volume of the arm increased 4 cubic centimetres ; 5 seconds later there was a fall of 5 cubic centimetres in 35 seconds. During the following 400 seconds four or five similar falls of less extent occurred. At the 3150th second, during a skatol stimulation, the subject woke with a deep inspiration ; the heart rate changed from 56 to 80 ; the volume of the arm increased 20 cubic centimetres in 70 seconds, and presently decreased almost as rapidly. He spoke to me at the 3250th second, and seemed asleep 100 seconds later. This sudden increase in the volume of the arm upon awaking is noteworthy, as ordinarily the reverse result is obtained, the arm decreasing in size as the subject returns to a conscious condition. The probable explanation of the unusual result in this case will be given presently in speaking of the changes in heart rate.

How are these changes in the volume of the arm to be interpreted? The curve throughout its entire extent exhibits rhythmic changes which suggest Traube-Hering waves. Are the larger changes mentioned above of a similar nature? There is a certain periodicity about them, and, if we except the sudden increase in volume which occurred at the 3150th second, they resemble the small changes in all but extent, and, even in this respect, it will be seen that they gradually shade off into each other. It is possible that they are caused by variation in cerebral activity. This explanation would harmonise with Mosso's observations on the changes in cerebral circulation during sleep.* Changes in mental activity invariably cause changes in the volume of the arm; the play of the sleeper's imagination may account for the changes with which we are here dealing. Some facts in the curve itself point in this direction. The fall at the 430th second was apparently caused by my speaking to the subject. The large increase in the volume of the arm at the 3150th second upon awaking appears to be due chiefly to the very great acceleration in heart rate, which occurred at that moment. This was during a skatol stimulation, but it will be seen from the other records that skatol does not, itself, quicken the heart rate. Did the foul odour occasion an unpleasant dream in which some spasm of emotion caused the sudden increase in heart rate and woke the subject? Speculation concerning the origin of these changes, however, will be of little value until we have more data at our disposal. The question which immediately concerns us here is whether or not, when all due allowances are made for changes produced by other causes, the curve still presents any evidence of sensory reactions. We will be in a better position to answer this question after we have made a comparative study of the other curves. The odour of formic acid was administered once for a few seconds in Experiment IX and twice in Experiments

* Mosso. Kreislauf des Blutes, Leipzig, 1881, S. 74 ff.

VI, VIII (Plate VI), and X. Each time it prevented full respiration, and caused a sudden and quite large decrease in the volume of the arm. The same result was invariably obtained whenever I used formic acid. Lehmann * obtained similar results with ammonia and bisulphide of carbon, which he used as typical unpleasant odours. I think, however, that the reactions in these cases are due in greater measure to the irritating action of these substances on the terminations of branches of the trigeminal nerve in the mucous membrane of the nose than to their odours.

In Experiment VIII, Plate VI, acetic acid was administered at the 1260th and again at the 1410th second. Each time it produced a diminution of 9 cubic centimetres in about 50 seconds. It was also administered in Experiment VI at the 1400th second, in Experiment X at the 1450th second, and at the end of Experiment XI; but in none of these cases did it produce any marked reaction. The cause of this discrepancy in results is not apparent.

Propionic, butyric, isobutyric, and valeric acids were administered on several occasions without any very decisive reactions appearing.

In Experiment VI propionic acid was administered at the 2225th second. A fall of 4 cubic centimetres occurred during the 65 seconds of the stimulation; but it is not at all certain that this fall was due to the acid, since similar falls occur throughout this curve without any apparent dependence on sensory stimulation. In Experiment VIII, Plate VI, at the 2160th second the volume of the arm increased 3 cubic centimetres during the first 40 seconds of a propionic acid stimulation, and decreased 1·8 cubic centimetres during the remaining 20 seconds. But this stimulation followed immediately upon a fall of 11 cubic centimetres produced by formic acid. The curve usually rises in this manner in such cases without any sensory stimulation. The fall during the latter part of the stimulation was possibly due to the acid. Propionic acid was administered again at the 1870th second in Experiment X. There was a rise here of 1·5

* *Op. cit.*, p. 84

cubic centimetres during the 20 seconds of the stimulation; but this rise is in the general direction of the curve, and presents no evidence whatever of a sensory reaction. In Experiment VI butyric acid was administered from the 1710th to the 1890th second, and valeric acid from the 2000th to the 2175th second. Falls occurred in both instances; but from the general movement of the curve it would appear that they are rhythmic contractions, and independent of the stimulations. At the 1920th second in Experiment VIII, Plate VI, the curve was rising rapidly and continued to rise, apparently uninfluenced by the butyric acid which was turned on during the following 50 seconds. At the end of the stimulation the curve took a horizontal direction, which it kept during the following 130 seconds. Valeric acid was administered during 75 seconds of this time without producing any apparent effect. Butyric acid was also administered at the 1715th second in Experiment X. A fall of 2 cubic centimetres occurred during the first 30 seconds, but the curve shows that this also may be a rhythmic contraction. Isobutyric acid was used once in each of the Experiments VI, VIII, IX, X, and XI without any apparent effect.

Besides formic acid and the two instances of acetic acid mentioned above, there are three other causes which, when present, usually produce a marked diminution in the volume of the arm. These are a deep inspiration, muscular movement, and mental activity. A typical effect of a deep inspiration occurred at the 1070th second in Experiment X. This diminution in the volume of the arm seems to be due in part to the increased negative pressure in the pleural cavity, but I think it probable that a factor in the production of this reaction is the change in the mental condition of the subject, which usually accompanies an inspiration of this kind; for on such occasions the subject is usually drowsy, and with the deep inspiration the mind brightens temporarily. It would seem that there is a constriction of the peripheral arteries, causing an increased flow of blood to the brain. When a deep inspiration occurs while the mind is bright there is seldom any very large decrease in the volume of the arm. It is possible that when the change takes place during the odour stimulation, the stimulation also plays a part in its production; but if so, the effect of the odour can not well be isolated. It is better, therefore, for present purposes, to discard such reactions. At the 2940th second in Experiment VI, I requested the subject to move his foot, which he did during the following fifty seconds. The heart beat immediately changed from 72 to 92, and after thirty seconds gradually returned to its former rate. This sudden increase in heart rate caused a transitory increase of 6·5 cubic centimetres in the volume of the arm, followed by a decrease of 13 cubic centimetres in fifty seconds. In this case it is probable that the effect was due in part to the muscular work and in part to increased mental activity. Whenever the subject moved his foot unconsciously, as he sometimes did, as at the 1670th second in this experiment, it produced a slight decrease in the volume of the arm, but of course there was not nearly the same amount of muscular work in these cases as in the instance referred to above.

The curves furnish numerous illustrations of the effect of mental work. This factor always causes a decrease in the volume of the arm. A typical instance of this occurs at the 100th second in Experiment V, Plate IV. Sometimes the fall is preceded by a transitory rise, as at the 1690th and 2940th seconds in Experiment VI; but in all such cases the rise is evidently due to a sudden acceleration of heart rate. Besides these changes, which can be definitely accounted for, the records of this series of experiments show a number of other variations in the volume of the arm. The general movement of the curve has already been discussed. In all the curves small oscillations occur every few seconds which are very much more pronounced in some records than in others, but which remain pretty much the same throughout the entire extent of the same record. These facts indicate that they are influenced by the condition of the subject rather than by any particular stimulation.

When due allowance is made for all these changes, do the records of this series of experiments present any evidence of pure odour reactions?

White heliotrope, wood violet, wintergreen, and musk were chosen as specimens of pleasant odours; skatol and indol as unpleasant odours. The subject enjoyed the first four very much and disliked the latter two.

Heliotrope was administered at the 1365th second in Experiment V, Plate IV; at the 220th and 270th seconds in Experiment VI; at the 210th and 2800th seconds in Experiment VII, Plate V; at the 45th second in Experiment VIII, Plate VI; at the 850th and 1910th seconds in Experiment XI. In none of these instances is there any clear evidence of a reaction. There is not one feature common to these various curves. There is scarcely a resemblance between any two of them. The only approach to a resemblance among them is the upward tendency of the curve, but this is in the general direction of the curve, and evidently is not due to the stimulation.

What has here been said of heliotrope applies with equal force to the other five odours mentioned. Violet was administered at the 430th second in Experiment VI. The volume of the arm increased 2 cubic centimetres in the first thirty seconds and decreased 4·5 cubic centimetres in the following thirty seconds; it then increased to the end of the stimulation. Indol was administered at the 920th second in the same experiment, with very similar results. At first sight these look like odour reactions. But it was found that five other similar falls occur in the first 1,000 seconds of this experiment, at approximately equal intervals of time. The first two falls occurred before any odour was administered; the third, fifth, and sixth in intervals between stimulations. The latter portion of the curve presents a similar series of falls. Besides, if the falls occurring during the violet and indol stimulations were odour reactions, we would expect that they would be repeated with some regularity in numerous experiments on the same subject; but such is not the case. It is altogether probable, therefore, that we are here dealing not with sensory reactions, but with rhythmic contractions of the blood vessels. A comparison of the curves obtained by repeated applications of any one of these six odours will make it clear that, if the stimulation had any effect on the volume of the arm, it is very thoroughly masked by other movements of the curve. If the odours really produced any characteristic effects they would come out in a composite curve made from a large number of experiments. I have not yet a sufficient number of experiments to give any value to such a composite curve.

The experiments presented here are essentially similar to a number of other experiments made on the same subject, all of which were conducted with great care; but the results obtained do not justify any such conclusions as those which Lehmann deduces from his experiments.

"Jeder lusterregende Eindruck erzeugt eine Vergrösserung des Volumens des Armes und der Höhe der einzelnen Pulsschläge nebst einer Vergrösserung der Tiefe des Atemholens." *

"Einfache, unlusterregende Sinneseindrücke rufen, wenn sie schwach sind, sogleich eine Verminderung des Armvolumens und der Höhe der einzelnen Pulsschläge hervor. Das Volumen nimmt bald wieder zu, trotz der Verkleinerung der Pulsschläge, und überschreitet gewöhnlich die Norm, wenn die Pulsschläge ihre vorige Grösse erreicht haben, die übrigens im allgemeinen ebenfalls überschritten wird. Bei stärkeren, aber doch nicht schmerzhaften Eindrücken treten diese Veränderungen mehr hervor und werden zugleich unmittelbar nach Anfang der Reizung von einigen tiefen Atembewegungen begleitet." †

"Einfache lustbetonte Sinnesempfindungen werden von einer Gefässerweiterung begleitet und vielleicht auch zugleich von einer Vergrösserung des Umfanges der Herzkontraktionen in Verbindung mit einer Erhöhung der Innervation der willkürlichen Muskeln, jedenfalls der Atmungsmuskeln." ‡

An inspection of the curves of this series will satisfy any one that none of these statements is true of them. Heliotrope and wood violet are certainly pleasant odours and were enjoyed by the subject; yet the volume of the arm diminished quite as often as it increased during their application. Indol and skatol are unpleasant odours, yet

* *Op. cit.*, p. 82. † *Ibid.*, p. 89. ‡ *Ibid.*

the volume of the arm frequently increased during the first few seconds of their application, and then decreased. It is not certain, however, that any of these changes were pure odour effects. It is but proper to say that the results obtained in this series with the perfected apparatus were all obtained from the subject after he had been repeatedly used in similar experiments involving the same set of odours. There were some indications that the vasomotor effects in the beginning were more pronounced than toward the end, when the odours had lost somewhat of their pleasant or unpleasant effects and the subject endured them in a rather perfunctory manner, but it is not possible to speak definitely as to this point, since the earlier apparatus employed was subject to so many errors that the records then obtained were not trustworthy.

Second Series.

The second series of experiments was made on twelve students, ranging from twenty to thirty years of age. Each experiment lasted about an hour. The same odours and acids were used as in the former experiments. There are some features common to all these experiments.

In the first couple of experiments with each subject the curve exhibited very little of the tendency to rise which constituted such a prominent feature of the series already described; but this tendency became more pronounced in the third and fourth experiments. Where the general tendency of the curve is upward the heart rate also becomes slower and steadier. This supports the view advanced above, that the gradual increase in the volume of the arm and the slowing of the heart rate are due to the diminished mental activity, and is therefore more pronounced when the subject has become accustomed to the plethysmograph and ceases to feel the mental excitement naturally attendant upon a novel experience. The small oscillations in the curves are, as in the former series, characteristic of the experiment. They are much more pronounced in some experiments than in others, but remain pretty constant throughout the whole extent of the same experiment.

The reactions in all the experiments are in the same direction, but they vary in extent with the different subjects, with the same subject at different times, and with the different stimuli.

Plate VII (Experiment XII) will serve as an illustration of the reactions obtained from subjects who are sensitive to odours. This was the third experiment on Mr. D., who is a student twenty-two years of age, of rather slight build, and nervous temperament.

The amplitude of the pulse wave diminishes to about one half at the first odour stimulation,* and does not again return to its original size. The heart rate slows up considerably during the experiment. The general tendency of the volume curve is slightly upward.

The subject was resting quietly with his arm in the cylinder for ten or fifteen minutes before the record was begun. During this time, and for the first 370 seconds of the record itself, the volume of the arm increased slowly, without exhibiting any very marked changes. Heliotrope was administered from the 370th to the 725th second. During the first 50 seconds of this period the volume of the arm decreased 19·5 cubic centimetres. It increased about 1 cubic centimetre during the following 50 seconds, and 14 cubic centimetres during the next 125 seconds. This was followed by a fall of 4·5 cubic centimetres in 25 seconds, and a rise of 7·5 cubic centimetres in 100 seconds. The prompt fall at the beginning of the stimulation, and the fatigue effect after about 100 seconds are pretty good evidence that this is an odour reaction, especially when it is taken in connection with the character of the curve previous to the stimulation. This conclusion is confirmed, I think, by the fact that a similar reaction was obtained every time I used this odour on Mr. D. Two other heliotrope stimulations occur in this record with results very similar in everything but extent; and this difference is at least partially accounted for by the fact that at the 740th second I moved the terminal plate farther from the subject's nose so as to diminish considerably the strength of the stimulation.

The fall of 18 cubic centimetres which occurred between the 740th and the 790th second is a mental reaction caused by my

* The original record of part of this stimulation, reduced in size, is given in Plate III, Fig. 1.

speaking to the subject and readjusting the odour plate. When the volume of the arm had returned to about its former condition and seemed inclined to remain pretty steady I turned on wood violet. It will be seen that the reaction is very similar to the previous heliotrope reaction, only less extensive. There is a fall of 8·4 cubic centimetres in the first 30 seconds. It remains down about 25 seconds, and increases 6·5 cubic centimetres in 70 seconds, when a second fall of 3·7 cubic centimetres occurs. Wintergreen was turned on from the 1265th to the 1440th second; the reaction is very similar to the previous violet reaction in every respect but the extent of the second fall. I had requested the subject before the experiment began to leave his mind as blank as possible, and not even to speculate about the nature of the odours. So great, however, was the down sweep of the curve that I suspected the presence of a mental reaction, and accordingly at the 1500th second I turned on a current of odourless air strong enough to be felt on his face. When the experiment was over I remarked to him that he had not obeyed my instructions, but had been indulging in speculations concerning the odours. He assured me that such was the case on only one occasion for a few seconds, when he felt the air coming from the tube but could perceive no odour. This indicates that the reaction in the other instances are connected in some way with the odours. At the 1650th second heliotrope was again administered. There was a prompt fall of 10 cubic centimetres in 35 seconds, followed by two quite large falls during the course of the stimulation. After an interval of 150 seconds, during which time there was very little change in the volume of the arm, musk was turned on. It occasioned a prompt fall of 8 cubic centimetres in 20 seconds. The two secondary falls were very slight. Skatol was turned on from the 2640th to the 2740th second without any apparent effect. Heliotrope was administered for the third time at the 2760th second. The reaction is essentially similar to the two former instances. I spoke to him at the 3060th second. An acquaintance entered at the 3150th second. When the subject had quieted down I turned on formic acid for 35 seconds. This caused a fall of 18 cubic centimetres in 50 seconds.

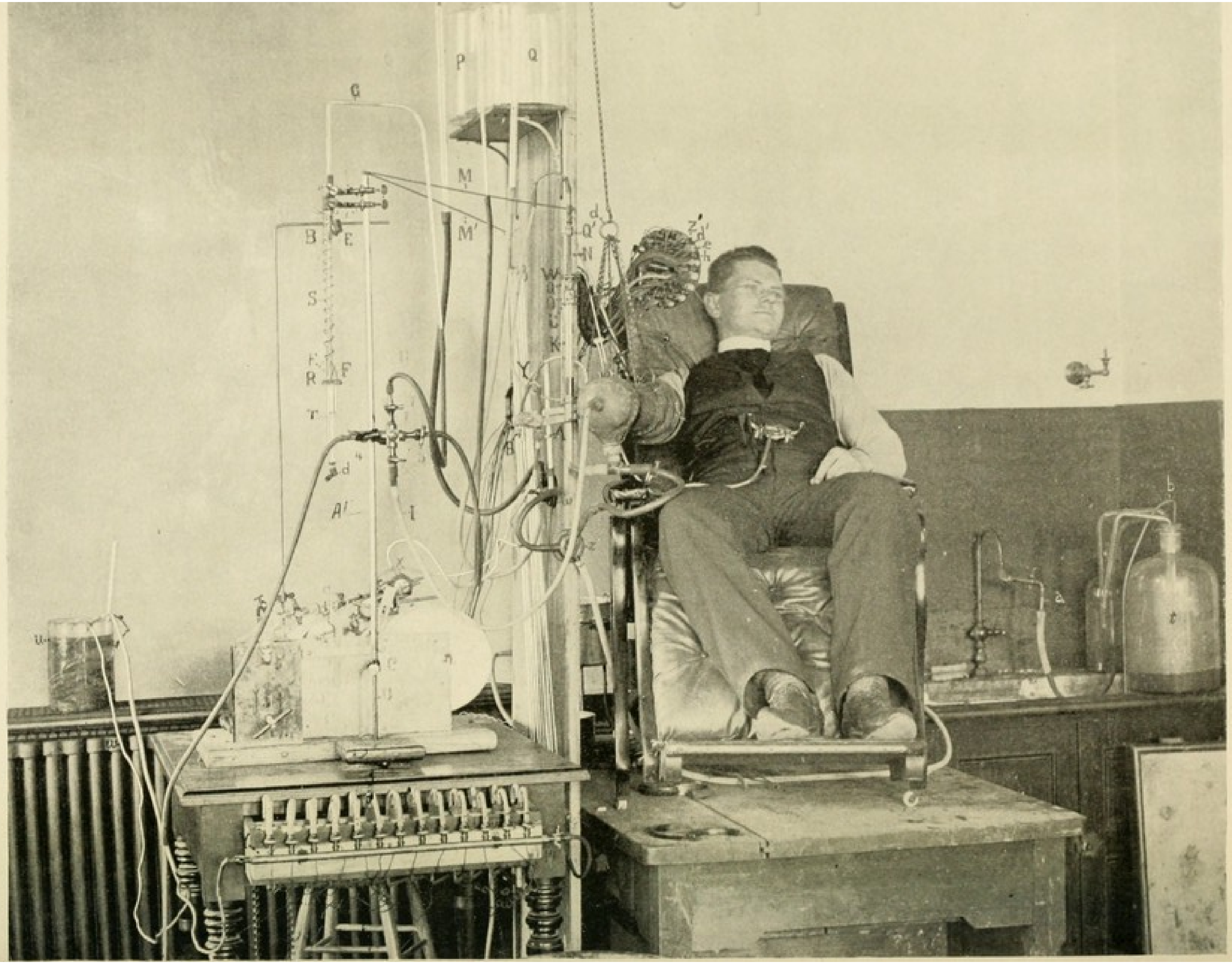
This record, as has already been said, was chosen as a specimen of very pronounced odour reactions, but each of the twelve subjects on whom this series of experiments was made gave unmistakable evidence of reactions to odours and irritant vapours. The reactions were always in the same direction, although seldom as pronounced as in the case of Mr. D. In the mental reactions obtained in this series it was found that the volume of the arm decreased very markedly notwithstanding a simultaneous quickening of the heart rate. This is characteristic of the mental reactions in all my experiments. A second striking peculiarity of the mental reactions is their long continuance. The effect of odours or irritant vapours passed off in three or four minutes at most, whereas mental work frequently kept the heart beating at a high rate and kept the volume of the arm low for many times that period.

The relation existing between the effects of sensory stimulation and of mental work will be discussed in a future paper.

Summary.

The most important outcome of this investigation has been the completion of various improvements in the construction and use of the plethysmograph, by means of which numerous errors attending the use of the instrument have been eliminated.

The results of the work show that all olfactory sensations, so far as they produce any effect through the vasomotor system, tend to diminish the volume of the arm, and therefore presumably cause a congestion of the brain. Whenever the stimulation occasions an increase in the volume of the arm, as sometimes happens, it seems to be due to acceleration of the heart rate, which, of course, tends also to increase the supply of blood to the brain. The effect of odours varies in extent with different individuals, and with the same individual at different times. It was most marked in subjects sensitive to odours. Irritant vapours, such as formic acid, have a marked effect in the same direction—that is, they cause a strong diminution in the volume of the arm. The experiments give no support to the view that pleasant sensations are accompanied by a diminution of the


P
Q
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blood supply to the brain and unpleasant sensations by the reverse effect. In all my experiments mental work caused a marked and prolonged diminution in the volume of the arm. This vasomotor effect was sometimes preceded by a transitory increase in the volume of the arm caused by acceleration of heart rate.

Acknowledgment.

I wish to return my sincere thanks to Prof. Howell, at whose suggestion this work was undertaken, and whose kind supervision and advice was a constant help and encouragement at every step of its progress. I am further indebted to him for his generosity in providing a subject for the first series of experiments. I am also indebted to Prof. E. A. Pace, of the Catholic University, for many valuable suggestions on the psychological aspects of the problem, and to the Rev. C. A. Ramm for suggestions in the constructions of the apparatus, and for the three accompanying drawings.

I must also take this opportunity of thanking the young gentlemen of St. Mary's Seminary, who generously placed their time at my disposal in acting as subjects for the second series of experiments. My thanks are due in a special manner to Messrs. Riedel and Beavan, who acted as subjects in a number of experiments and who assisted me in the laborious task of tabulating the results and plotting the curves.

June 1, 1895.

Explanation of Plates.

Plate I.—General Arrangement of Apparatus.

A, B, support for test tube and siphon; C, D, D′, clamps for same; E, clamp for spiral; F, F′, wires from spiral to rubber ring; H, I, tube connecting siphon with arm cylinder; J, four-way; 1, 2, 3, 4, stopcocks on same; K, piston tube; S, metal cap for same; M, M′, stay rods to upright; N, piston rod; O, O′, rods connecting metal cap with washer; P, Q, supply jars; Q, milled nut for adjusting level of piston; Q′, milled nut for adjusting indicator; R, rubber ring carrying test tube; S, spiral suspending test tube; T, test tube; U, upright; W, washer over milled nut on piston rod; X, tambour; Y, T-way in tube connecting piston tube with tambour; A, B, stopcocks on same; *w*, Z, three-way stopcocks on supply tubes; A, aspirator; *t*, bottle for washing air; U, bath for warming air; *y*, air tube on face of kymograph drawer; *z*′, terminal plate; *e*, electro-magnet; *d*′, armature; *h*, binding screw; *d*, ring suspending arm cylinder.

Plate II.—Arrangement of Cylinder and Method of holding the Arm Rigid.

A, arm ring; B, wristlet band; C, D, rubber rings for making arm holder rigid to arm cylinder; G, H, faces of arm ring; M, M′, rods making arm ring rigid to wristlet; R, ring cemented into rubber sleeve; S, rubber sleeve; *e*, *l*, *m*, orifices in arm cylinder; *h*, thermometer; *t*, stopcock to let air escape from arm cylinder; Y, metal band for supporting cylinder; K, supply tube; *d*, ring from which arm cylinder is suspended.

Plate III.—Specimens of Tracing (reduced one half in size) taken upon the Kymograph.

1. Heliotrope stimulation (subject, Mr. D.). 2. Formic-acid stimulation (very light current of vapour). 3. Isobutyric-acid stimulation (subject, George Bill): A, signal—isobutyric acid turned on from 10th to end of record; B, respiratory curve—expiratory phase from 10th to 12th second shows that the stimulation could not have reached olfactory membrane before the 12th second; C, vasomotor curve; shows increase of 12 cubic centimetres in volume of arm between the 1st and 12th second, a decrease of 15 cubic centimetres at the 20th second, a return to base line at 38th second and a second decrease of 1 cubic centimetre at 45th second, and a return to base line at 60th second; D, heart rate. It shows 19 heart beats in first 15 seconds, and about 18 in each succeeding 15 seconds; E, time in seconds; F, base line; ordinates are drawn at every fifth second.

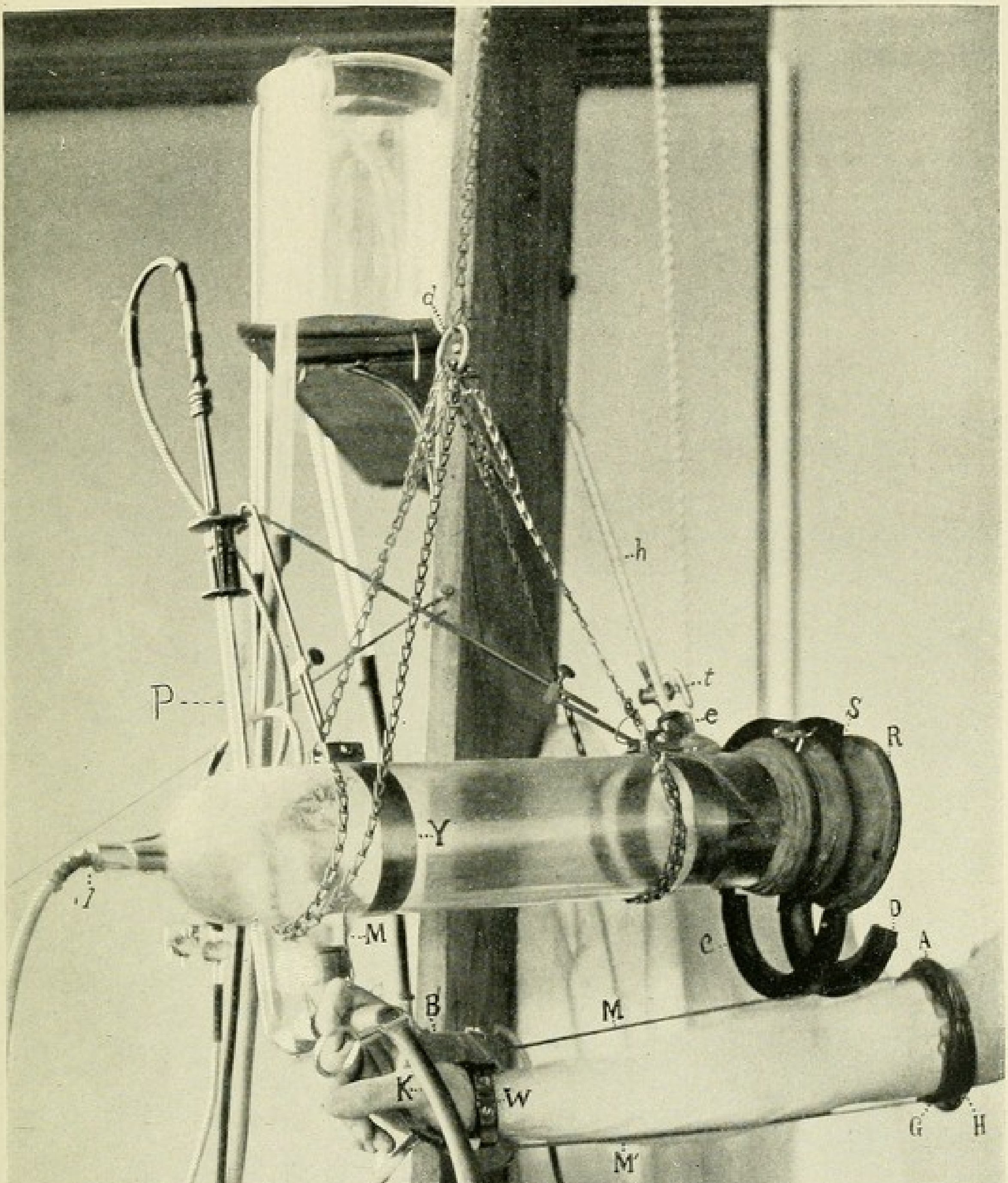
Explanation of Plotted Curves. Plates IV, V, VI, and VII.

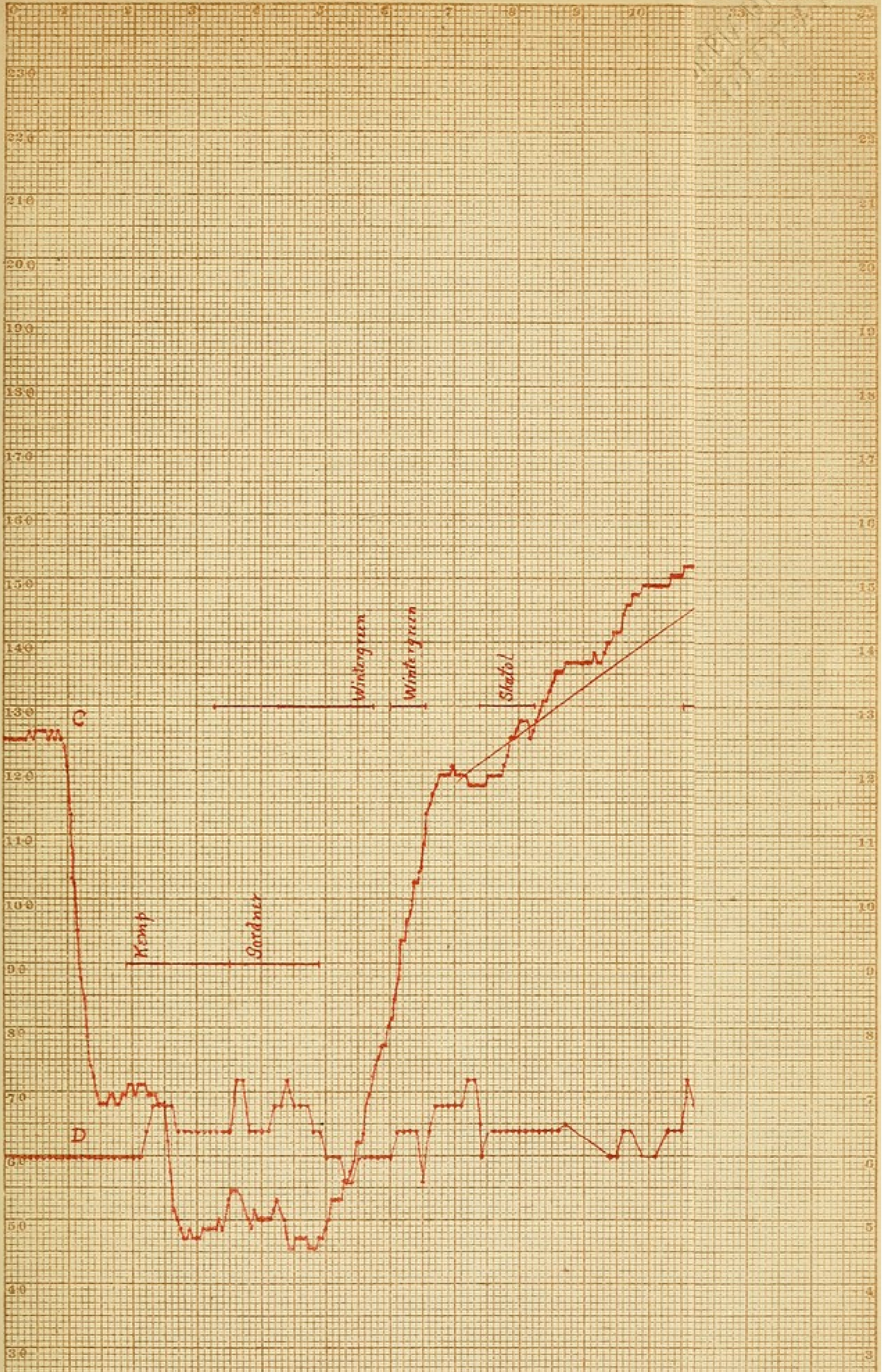
A, changes in amplitude of pulse wave; vertical distance between abscissæ 0·2 cubic centimetre. D, heart rate; vertical distance between each two abscissæ represents one beat per minute. C, changes in volume of arm; vertical distance between each two abscissæ represents 0·2 cubic centimetre. The distance between the ordinates makes intervals of 10 seconds each. The pulse amplitude and volume changes are calculated at every fifth second. The heart rate is reckoned for every 10 or 15 seconds. The respiratory curve was taken in all the original records. Whenever it presents any marked irregularities this fact is noted on the plates. Time of stimulation by the various odours is indicated on the plates.

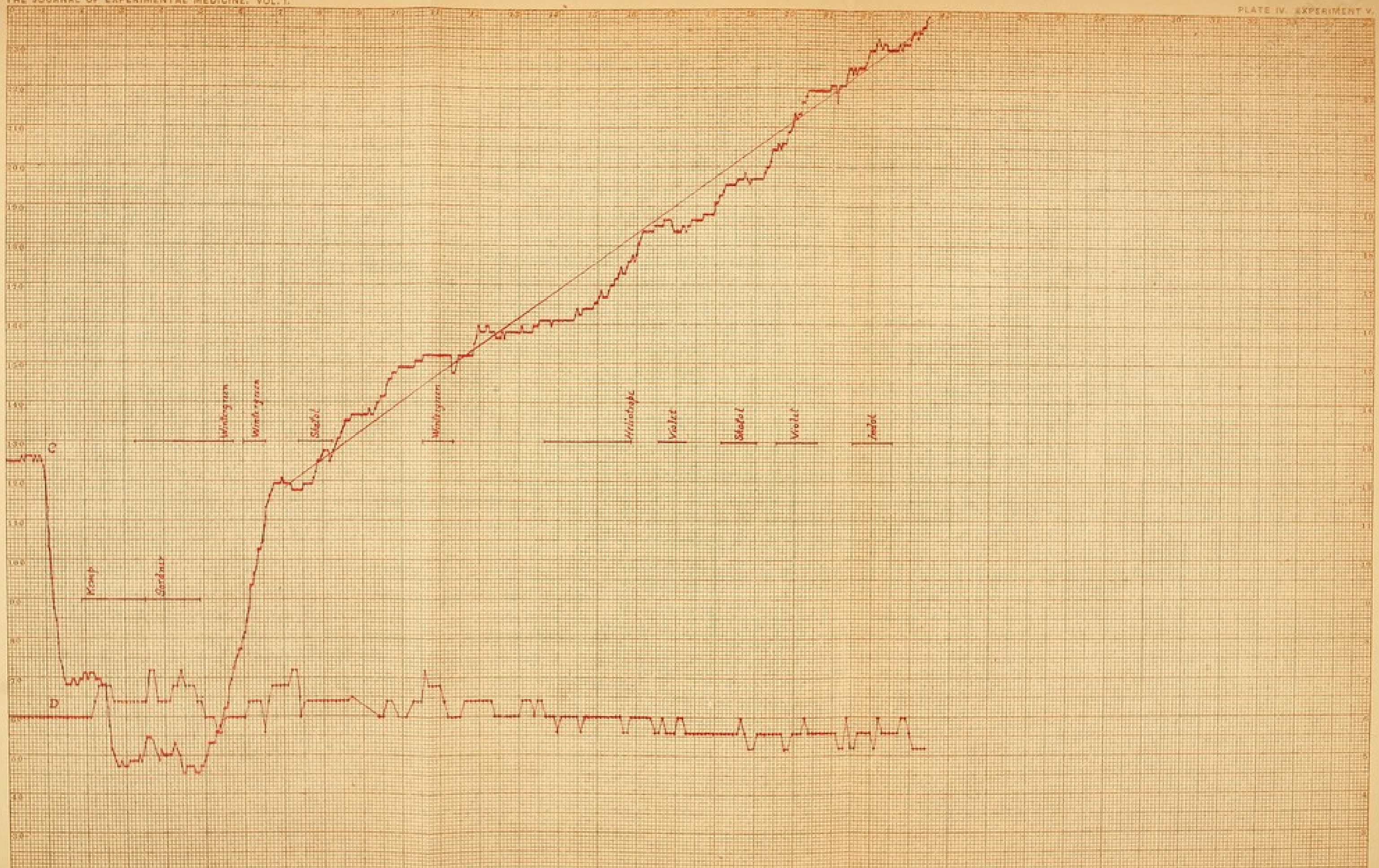
Plate IV.—December 3d (subject, Mr. George Bill). Resting with arm in cylinder 15 minutes before record began. Volume of arm increasing slowly. Heart rate, 60. 100th second, Dr. K. entered. Volume of arm decreased 11·5 cubic centimetres in 50 seconds. 250th second Mr. G. entered. Volume of arm decreased 4 cubic centimetres in 20 seconds. Heart rate changed to 68, 64, 71, 64, 72, 68. 490th second, Dr. K. and Mr. G. leave room. Heart rate, 60. Volume of arm increases rapidly to 700th second, and more slowly to end of record. Subject dozing toward end of experiment. Heart rate gradually sinks to 52 at end of experiment. Total increase of volume of arm between 450th second and end of experiment, 39 cubic centimetres, due to diminished mental activity.

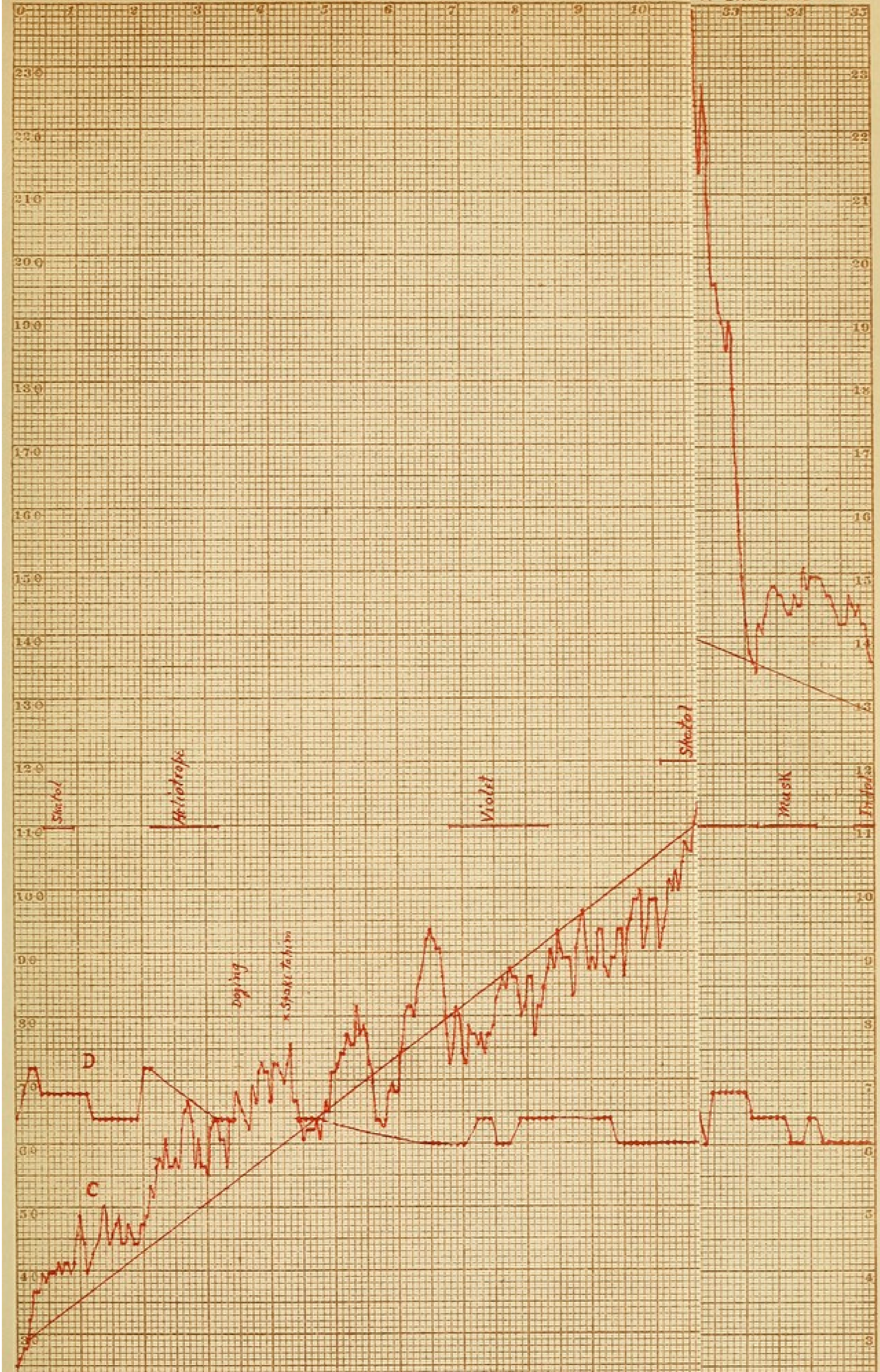
Plate V.—December 12th (subject, Mr. George Bill). Resting quietly with arm in cylinder for some time before record began. Asleep from 300th second to end of experiment. Heart rate 60 during most of the experiment. No odour reaction. Volume of arm increases 30 cubic centimetres between 1st and 1360th seconds. Small rhythmic contractions every 10 or 15 seconds. Spoke to him at the 430th second, which occasioned a fall of 3 cubic centimetres in 20 seconds. 530th second, fall of 4 cubic centimetres. 650th second, fall of 4 cubic centimetres. 1930th second, fall of 5·5 cubic centimetres in 30 seconds. 2250th second, fall of 6·6 cubic centimetres in 35 seconds. 2515th second, fall of 7·6 cubic centimetres in 30 seconds. 2710th second, fall of 5 cubic centimetres in 35 seconds. Four or five similar falls of less extent occur during the following 400 seconds. None of these falls seem to be due to odour stimulation. They are probably rhythmic con-

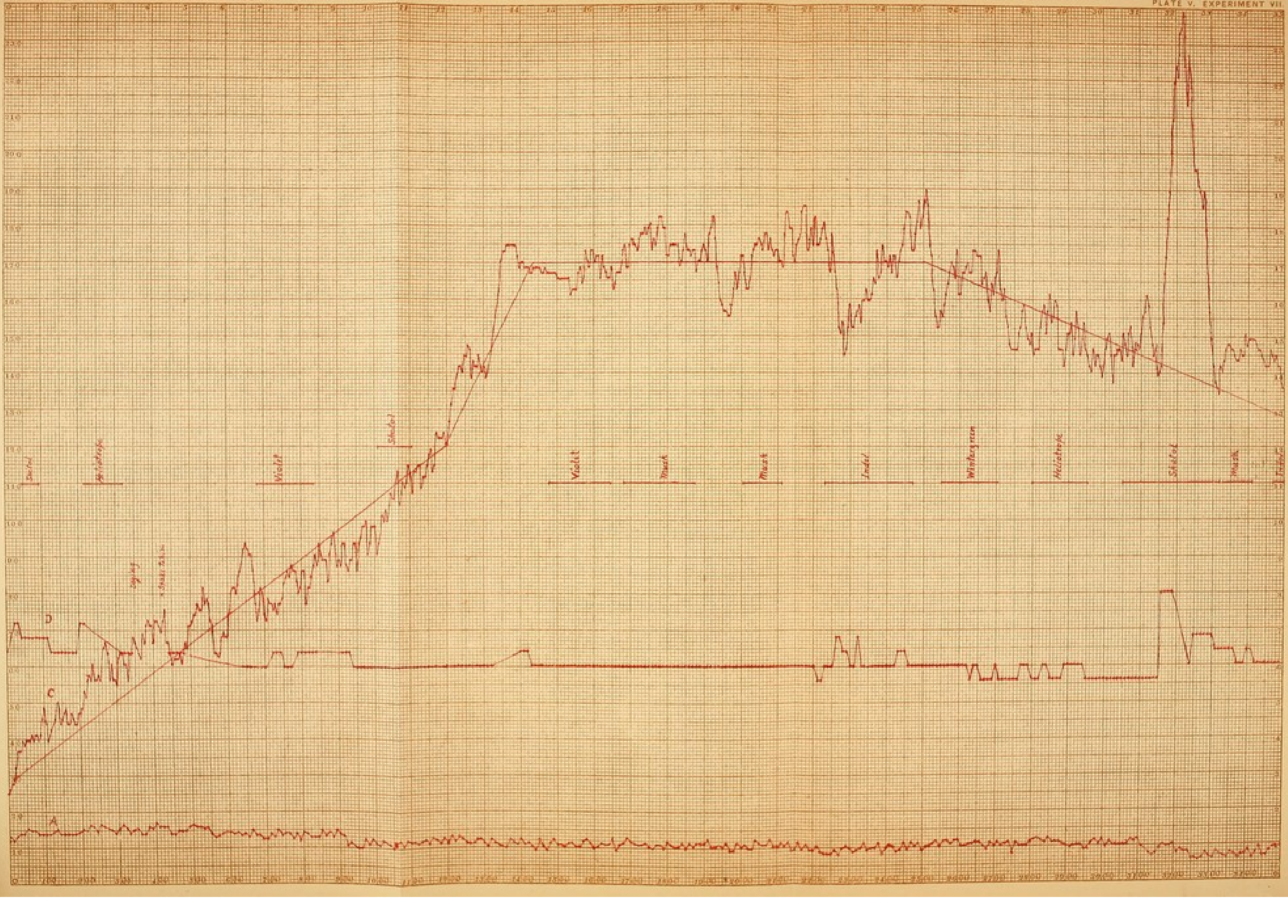
PLATE II.



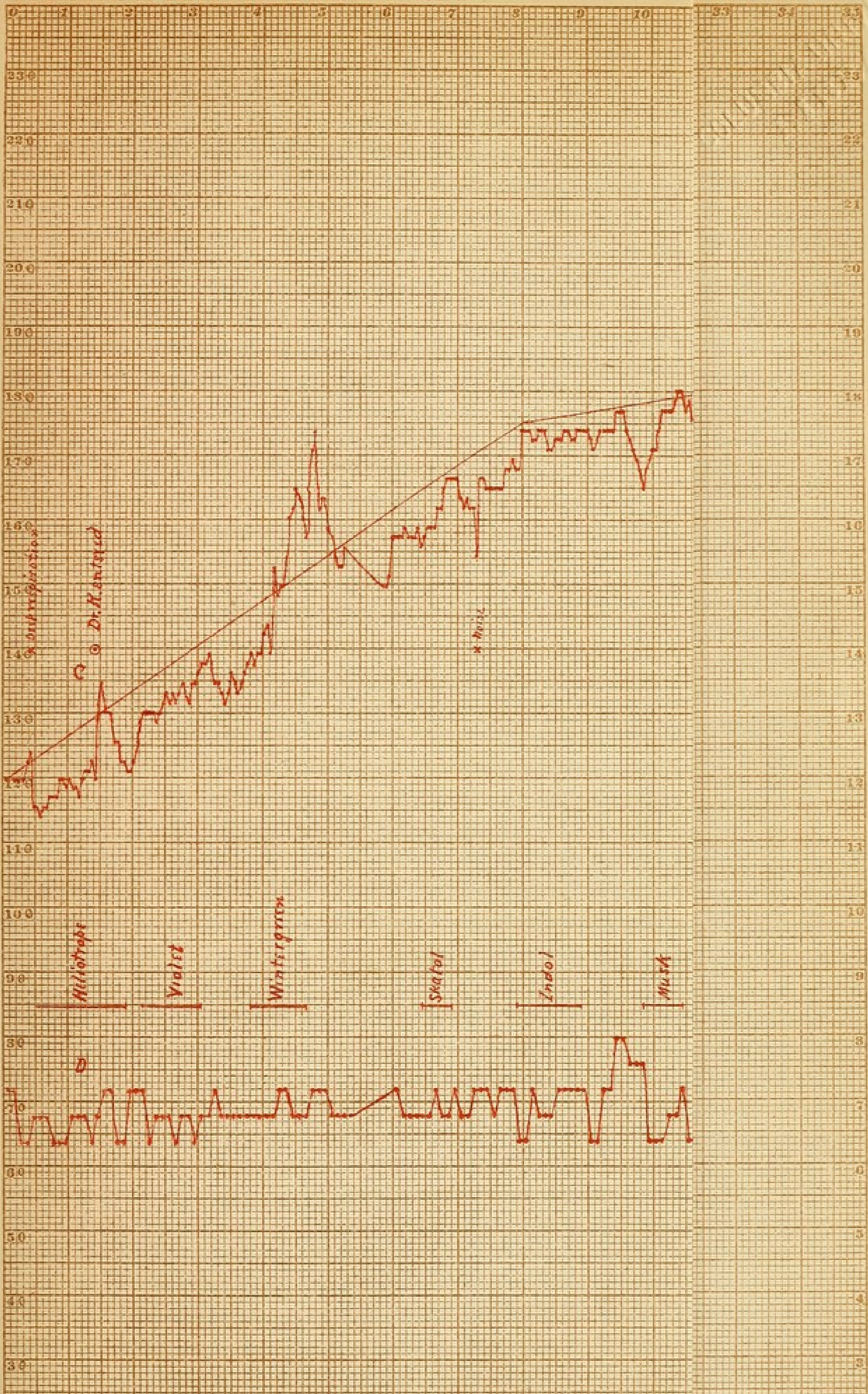

C
D
Kemp
Gardner
Wintergreen
Wintergreen
Skatol

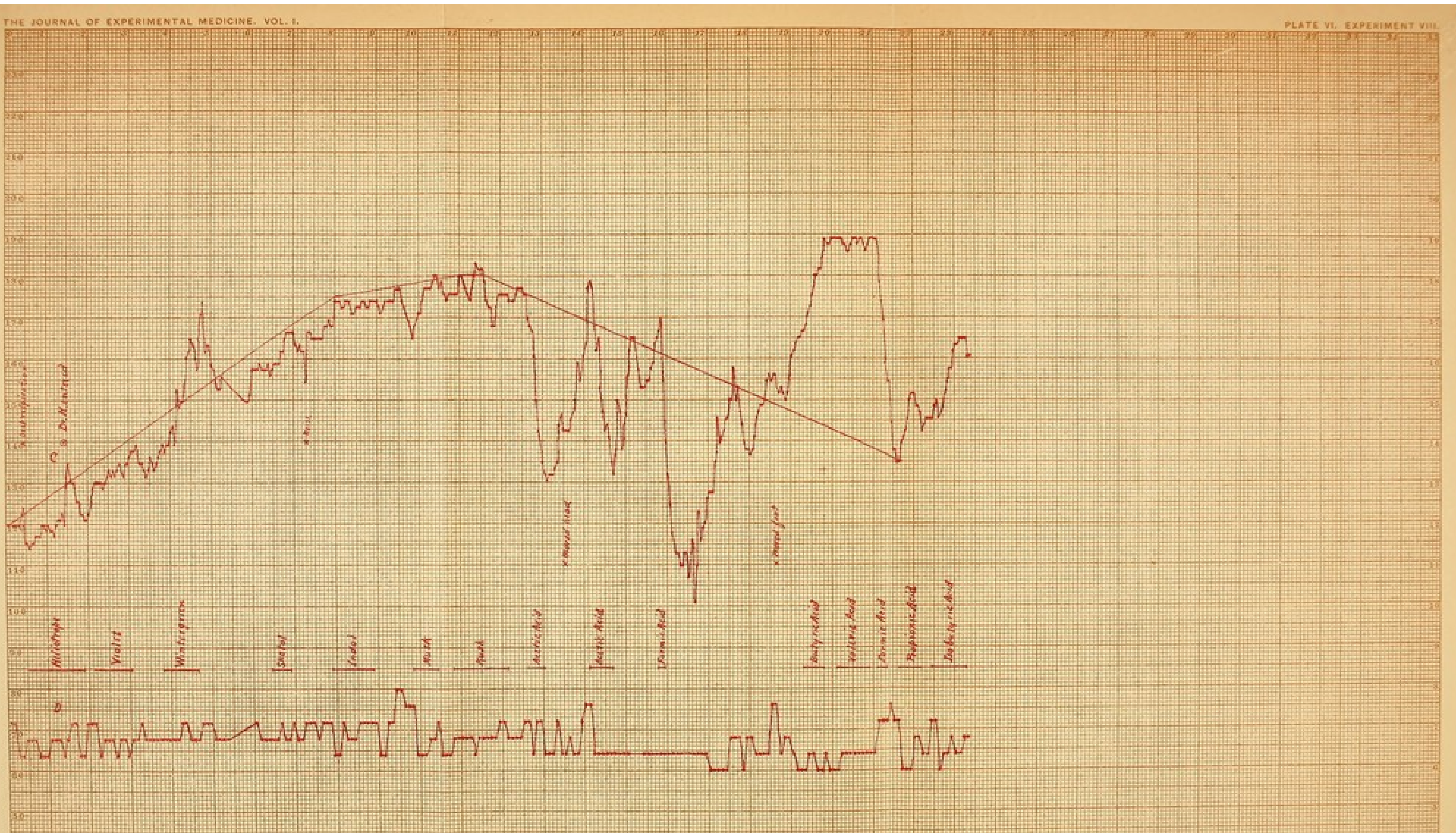

C
D
A
Wintergreen
Wintergreen
Salol
Wintergreen
Heliotrope
Violet
Salol
Violet
Indol


D
C
Skatol
Heliotrope
Dozing
Violet
Skatol
Musk
Indol

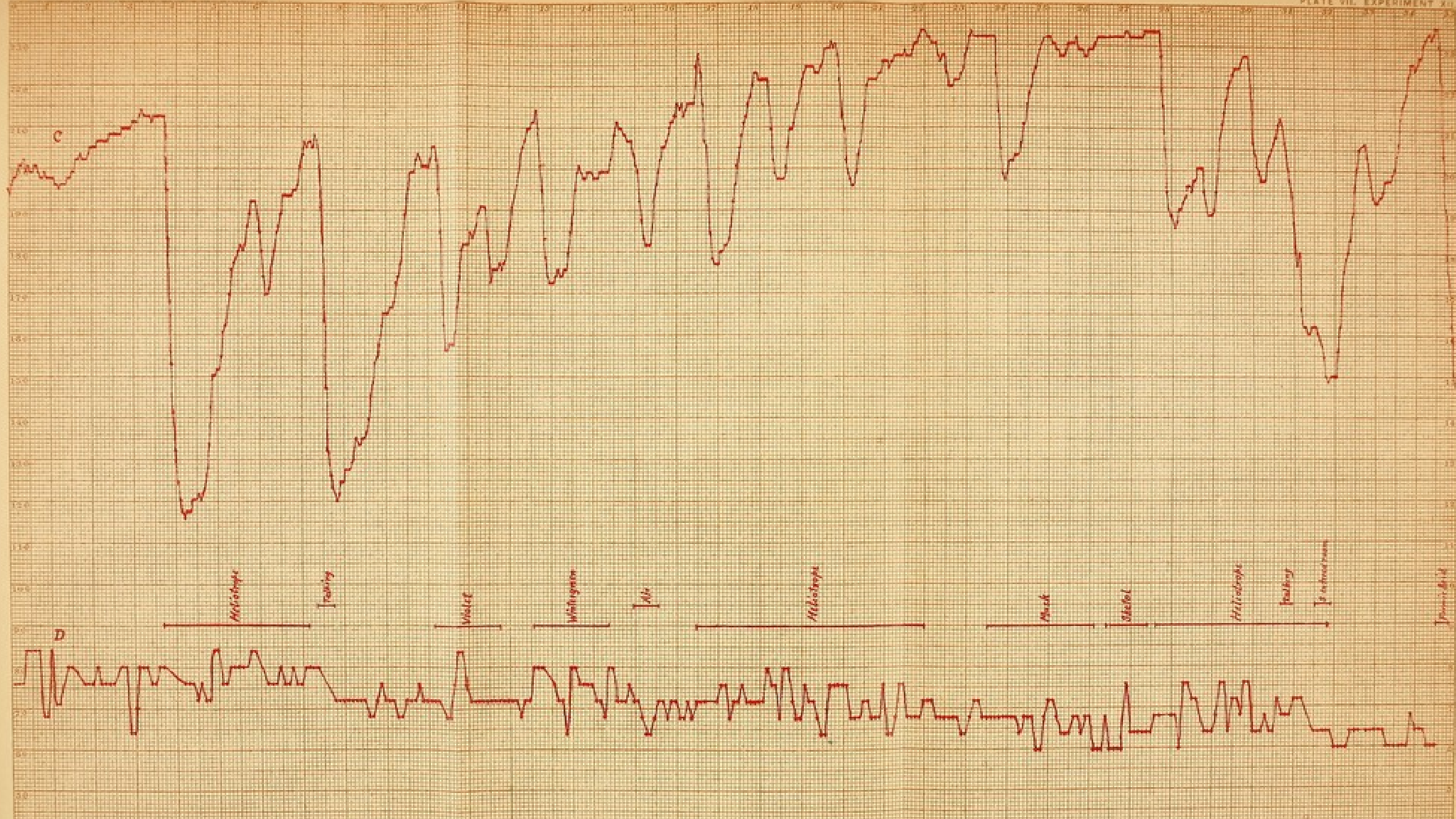

Heliotrope
Violet
Skatol
Violet
Musk
Musk
Indol
Wintergreen
Heliotrope
Skatol
Musk
D
C
A

EXPERIMENT VIII.




Heliotrope
Violet
Wintergreen
Skatol
Indol
Musk


C
D
Heliotrope
Talking
Formic Acid


C
Heliotrope
Talking
Violet
Wintergreen
Air
Heliotrope
Musk
Alcohol
Heliotrope
Talking
D
A

tractions. 3150th second, subject woke with deep inspiration. Heart rate changed from 56 to 80, probably due to a spasm of emotion caused by unpleasant dream. Volume of arm increased 20 cubic centimetres in 70 seconds, apparently due to quickened heart rate. 3250th second, subject spoke and seemed asleep 100 seconds later. Arm returned to its former volume and heart rate to 60. Amplitude of pulse wave diminishes from beginning to end of experiment. 3250th second, about one third its initial amplitude.

Plate VI.—December 14th (subject, Mr. George Bill). Volume of arm increases 12 cubic centimetres during first 1100 seconds. 1260th second, acetic-acid stimulation, diminution 9 cubic centimetres in volume of arm in 30 seconds. 1410th second, acetic acid, with similar result. 1580th second, formic-acid stimulation for 15 seconds, occasioning a fall of 13 cubic centimetres in 80 seconds. 2100th second, formic-acid stimulation for 30 seconds, with a fall of 11 cubic centimetres in 60 seconds. Odour stimulations apparently without effect throughout the curve. Amplitude of pulse wave diminishes gradually throughout the experiment.

Plate VII.—January 31st (subject, Mr. D). Subject resting quietly with arm in cylinder 15 minutes before record began, during which time and for the first 370 seconds of the record itself volume of arm increased slowly without any marked changes. Heart rate gradually slows during experiment. Volume of arm exhibits a slight upward tendency during most of the experiment. Amplitude of pulse wave diminished to about half at the first odour stimulation, and does not return to its original size. 370th second to 725th, heliotrope stimulation. Volume of arm diminishes 19·5 cubic centimetres in first 50 seconds, increases 1 cubic centimetre during the following 50 seconds, and 14 cubic centimetres during the next 125 seconds. 595th second, fall of 4·5 cubic centimetres in 25 seconds. 740th second, spoke to subject; fall of 18 cubic centimetres. 1020th second, wood-violet stimulation, fall of 8·4 cubic centimetres in first 30 seconds; second fall, 3·7 cubic centimetres at 1145th second. 1270th second, wintergreen stimulation, fall of 8·5 cubic centimetres in 30 seconds; a second slight fall at 1370th second. 1500th second, current of air; subject speculates as to its nature; fall of 4·5 cubic centimetres in a few seconds. 1650th second, heliotrope stimulation; fall of 10 cubic centimetres in 35 seconds, followed by two quite large falls in course of the stimulation. 2350th second, musk stimulation; fall of 8 cubic centimetres in 20 seconds, followed by two slight secondary falls. 2640th and 2740th seconds, skatol stimulation, no apparent effect. 2760th second, heliotrope; fall of 10 cubic centimetres in 30 seconds. 2870th second, fall of 2·5 cubic centimetres in 15 seconds. 2985th second, fall of 6 cubic centimetres in 30 seconds. 3060th second, subject spoke; fall of 11 cubic centimetres in 90 seconds. 3150th second, S. entered room; fall of 2·5 cubic centimetres in 30 seconds. 3270th second, fall of 3 cubic centimetres without obvious cause. 3450th second, formic-acid stimulation for 30 seconds; fall of 18 cubic centimetres in 50 seconds.

BIOGRAPHY.

Thomas Edward Shields was born on the 9th of May, in the year 1862, at Mendota, one of the suburbs of St. Paul. Minn. In 1882 he entered the sophomore class of St. Francis College, Milwaukee, and remained there until 1885, completing its classical curriculum. In September, 1885, he began his philosophical studies in the theological seminary of St. Thomas Aquinas at St. Paul. Here he passed six years: two years in the study of mental philosophy, ethics, and the physical sciences, and four years in the study of theology—dogmatic and moral—and the accompanying branches of Holy Scripture, Church history, and canon law. He was ordained priest on March 14, 1891, and in the following June was assigned as curate to the Cathedral of St. Paul. After fourteen months in the active ministry there he came to Baltimore (in September, 1892), received the degree of Master of Arts from St. Mary's University, and began his studies in the Biological Department of the Johns Hopkins University in October of the same year.