V.—RESEARCH.

THE TIME TAKEN UP BY CEREBRAL OPERATIONS.

By JAMES MCKEEN CATTELL,
Assistant in the Psychological Laboratory, University of Leipsic.

Mental states correspond to physical changes in the brain. The object of this paper is to inquire into the time needed to bring about changes in the brain, and thus to determine the rapidity of thought. When waves in the luminiferous ether of a particular length strike the retina a red light is seen, but a certain time passes after the waves have struck the retina before the light is seen:—(1) It takes time for the light waves to work on the retina, and generate in the cells a nervous impulse corresponding to the nature of the light; (2) it takes time for the nervous impulse to be conveyed along the optic nerve to the brain; (3) it takes time for the nervous impulse to be conveyed through the brain to the visual centre; and (4) it takes time for the nervous impulse to bring about changes in the visual centre corresponding to its own nature, and consequently to the nature of the external stimulus. When these changes are brought about a red light is seen. It does not take any time for a sensation or perception to arise after the proper changes in the brain have been brought about. The sensation of a red light is a state of consciousness corresponding to a certain condition of the brain. The chemical changes in a galvanic battery take time, but after they are brought about, no additional time is needed to produce the electric current. The current is the product of chemical changes in the battery, but at the same time the immediate representative of these changes; and the relation is so far analogous between states of consciousness and changes in the brain. Again, as it takes time to see a light, so it takes time to make a motion. Changes in the brain, the origin and nature of which we do not understand (physiologically they are part of the continuous life of the brain, mentally they are often given in consciousness as a will-impulse), excite the centre for the coordination of motions. The impulse there developed is conveyed through the brain (and it may be spinal cord) to a motor nerve, and along the nerve to the muscle, which is contracted in accordance with the will-impulse. We have here in the reverse direction the same four periods as in the case of a stimulus giving rise to a sensation. In each case there is the latent period in the sense-organ or muscle, the centripetal or centrifugal time in the nerve, the centripetal or centrifugal time in the brain, and the time of growing energy in the sensory or motor centre. Besides these two classes of processes, the one centripetal, the other centrifugal, there are centrimanent cerebral operations, some of which are given in consciousness, and make up the mental life of thought and feeling. These cerebral changes all take time, and, as I shall show, the times can in many cases be determined.

I. *Apparatus and Methods.*

The time taken up by cerebral operations cannot be directly measured. It is necessary to determine the time passing between the production of an external stimulus, which excites cerebral operations, and the making of a motion after these operations have taken place. The apparatus needed to determine this time must consist of three parts:—(1) An instrument producing a sense-stimulus to excite cerebral operations and registering the instant of its production; (2) an instrument registering the instant a motion is made, after the cerebral operations have taken place; and (3) an instrument measuring the time passing between these two events. The first two instruments must vary with the sense-stimulus to be produced and the motion to be registered; to measure the times, I have used the Electric Chronoscope made by Hipp in Neuchatel. When properly controlled, this chronoscope measures the time as accurately as any of the chronographic methods which have been proposed, and it is much simpler and more convenient in its application.

The Chronoscope is a clockwork moved by a weight and regulated by a vibrating spring. The spring vibrates a thousand times a second, and at each vibration the tooth of a wheel is allowed to pass, somewhat on the principle of the escapement in a watch. This method of regulating the clockwork is ingenious and accurate, but, especially in the new form of the chronoscope, is apt to get out of order. The value of the chronoscope consists in the application of an electromagnet. The hands recording the time are not in connexion with the clockwork, and consequently do not move when it is set in motion; but, when an electric current is sent through the coil of the electromagnet, the armature is attracted, a system of levers throws the hands into connexion with the clockwork and they are set in motion; and, again, when the current flowing through the coil is broken, a spring draws back the armature and the hands stand still. Thus the time the current flowed through the coil of the electromagnet is measured.[1] The hands record thousandths of a second.[2] The chronoscope works with great accuracy; the only serious difficulty in its application being that the length of the times recorded by the hands varies with the strength of the current passing through the coil of the magnet. Supposing the strength of the spring holding back the armature to remain constant, if the current sent through the coil is very weak, the soft iron is only completely magnetised after a considerable interval, and it takes longer for the magnet to attract the armature after the current has been closed, than for the spring

[1] A second electromagnet makes it possible to reverse this process, and measure the time a current has been broken.

[2] Throughout this paper, both in the text and in the tables ·001 second is taken as the unit of time. I use σ as a symbol to represent this unit: σ is analogous to μ = ·001 mm.

to draw back the armature after the current has been broken; consequently the time recorded by the hands is shorter than the time the current flowed through the coil of the magnet. If, on the other hand, the current used is very strong, the soft iron is rapidly magnetised and the armature attracted. But the magnetism lasts a considerable interval after the current has been broken. Thus, it takes longer for the spring to draw back the armature after the current has been broken than it took the magnet to attract it after the current had been closed, and the time recorded by the hands is longer than the time the current flowed through the coil of the magnet. If the strength of the current is not properly adjusted, the times recorded may be over $\frac{1}{10}$ sec. too long or too short, an error as large as the whole length of the reaction-time. It is, however, possible so to adjust the relation between the strength of the spring and the strength of the current that it takes exactly as long for the magnet to attract the armature after the current has been closed as it takes the spring to draw it back after the current has been broken, and in this case the hands record the exact time the current flowed through the coil of the magnet. This can be done empirically by determining the time the current has been closed, and then so adjusting the strength of the spring and the current that the hands record the correct time. For this purpose (as well as for others later to be described) I have used an instrument, which, with reference to theuse for which it was first devised,[1] I call a Gravity-Chronometer.

It consists (Fig. 1) of two heavy brass columns 30 cm. high and 10 cm. apart, standing perpendicular to the base. The columns can be set exactly perpendicular by means of the three screws on which the apparatus stands. Wedge-shaped grooves are worked in the columns, and in these a heavy soft iron screen slides without appreciable friction. This screen is held up by an electromagnet, which can be adjusted at any height desired. When the current passing through the coil of the magnet is broken, the screen falls, falling through the same distance in an exactly constant time. On one of the columns small keys (Figs. 2 and 3) can be fastened, which respectively close and break a current. They each consist of a hard rubber basin filled with mercury, the mercury being in connexion with a binding screw; a lever with a platinum point, connected by a wire with a binding screw, dips into the mercury. In the one key (Fig. 2) the lever is so adjusted that the point does not touch the mercury, but when the key is fastened to the column of the gravity-chronometer and the lever is struck by the falling screen, the point is thrown into the mercury. In the other key (Fig. 3.) the lever dips into the mercury, but is thrown out (as shown in the figure) when struck by the screen. The keys are fastened to one of the columns, as at x and y (Fig. 1), the key (Fig. 2) at which the current is interrupted being above. The current controlling the chronoscope passes through both of these keys, the connexion, however, being interrupted at the upper key. The screen is now allowed to fall by breaking a current (not the chronoscope current) which through the electromagnet had been holding it up. After the screen has attained a considerable velocity it strikes the lever of the upper key, and throws it into the mercury; thus the current controlling the chronoscope is closed and the hands are set in motion. After the screen

[1] See *Philosophische Studien*, iii. 1; *Brain*, Oct., 1885. The apparatus described in this paper was made under my direction in the workshop of Carl Krille, Leipsic, and he can supply duplicates. The apparatus can be examined in the Psychological Laboratory, Leipsic, or in the Army Medical Museum, Washington.

has fallen the distance between the keys (xy) it strikes the lever of the second key and throws it out of the mercury; the current controlling the chronoscope is consequently broken and the hands stand still. The screen always falls through the distance between the keys in exactly the same time, and the times recorded by the hands of the chronoscope are constant,

FIG. 1.

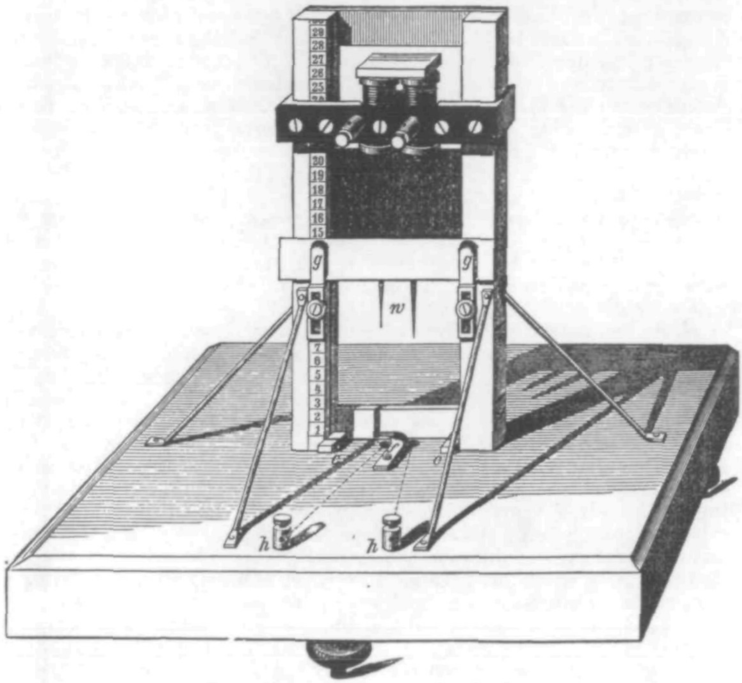


FIG. 2.

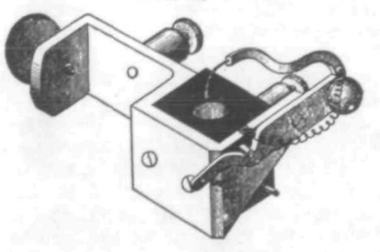
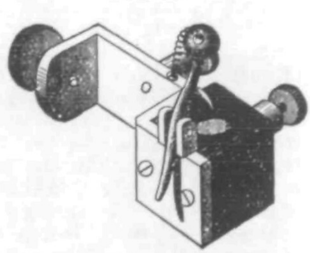


FIG. 3.



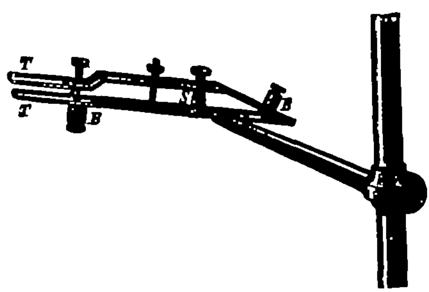
but may be over $\frac{1}{10}$ sec. longer or shorter than the time the current was really closed. The time required for the screen to fall through the distance xy (the time the current has been closed) is determined by means of a tuning-fork which writes on smoked paper covering the screen. The time can also be calculated; the theoretical time for a body falling in a vacuum being but little shorter than the actual time as determined by the tuning-fork. When we know the time between the closing of the current at the upper key, and the breaking at the lower, the strength of the current attracting the armature and of the spring holding it back can be so adjusted that the hands record the correct time. The stronger the current and spring are taken, the shorter is the time required for the armature to be attracted after the current has been closed and drawn back after the current has been broken. The determination with the tuning-fork need only be repeated so often that we are sure no error has been made ; it is well to change the distance between the keys and see that the times given by the chronoscope and the tuning-fork are the same. The chronoscope must, moreover, be controlled every day by the gravity-chronometer (or by a sensitive electrometer ; the apparatus itself is a very sensitive electrometer) to see that the current has remained constant, and to readjust it if it has become stronger or weaker. For this purpose the gravity-apparatus supplied by Hipp can be used if proper precautions are taken. The strength of the current is adjusted by means of a rheostat, (R, R', Fig. 8) and its direction changed (to avoid permanent magnetism) by means of a commutator. It is evident that a battery must be used giving as constant a current as possible. After considerable experiment I have adopted a form of the zinc-copper gravity-battery. I use six large cells, renewing them about once a month.

If the chronoscope is properly controlled it measures the times very accurately. With the same current the mean variation of the chronoscope (including sources of error in the gravity-chronometer) is less than $\frac{1}{500}$ sec. This small variation corrects itself completely in a series of measurements. A second variation about equal to the first is caused by the current not being accurately adjusted, or changing after it has been so adjusted. This error also tends to eliminate itself. A third source of error lies in the chronoscope's running too fast or too slow. This is, however, no greater than in any chronographic method where the time is measured by a vibrating tuning-fork ; the chronoscope can indeed be regulated with great accuracy as it runs a minute (60,000 vibrations).

The gravity-chronometer (Fig. 1) was used in nearly all my experiments to produce the sense-stimulus, and to close at the same instant the current controlling the chronoscope. When the reaction-time for light was to be determined, the space between the columns was filled up with black pasteboard, so that the screen was completely hid from the observer. In the pasteboard (below the screen, the magnet being higher than in the figure) a hole 3 × 2 cm. was cut, and the observer fixated a black surface several mm. back of the hole. The experimenter allowed the white screen to fall by breaking the current which had been flowing through the coil of the magnet. Suddenly and without warning, at the point fixated by the observer a white surface 3 × 2 cm. appeared ; at the same instant (to $\frac{1}{1000}$ sec.) the screen struck the lever of the key (Fig. 2) and closed the current controlling the chronoscope. No noise is made by the falling screen until it is stopped by striking the spring *f* and the rubber cushions *c c*, and this noise comes too long after the light to either shorten or lengthen the time of the reaction. The spring *f* is so adjusted as to partially stop the falling screen and to prevent it from rebounding after it has struck the cushions. If cerebral operations other than those included in the reaction-time were to be investigated, the object exciting these operations, a printed word for example, was pasted on a card 15 × 3 cm. This card is held in position by the springs *g g*, and is hid from the observer by the black screen. The observer fixated a grey spot on the screen, which exactly covered the object on the card (the figure shows of course the back of the apparatus). A bent copper wire *w*, one side longer than the other, is fastened to the screen, as shown in the figure. When the screen falls the amalgamated points run into two holes bored in the base and filled with mercury. These basins are connected with the binding screws *h h*, and these respectively with the battery and chronoscope, so that the current is interrupted at this point. When the screen falls, however, the copper wire connects the two basins of mercury, and the apparatus is so adjusted that the instant (to $\frac{1}{1000}$ sec.) the object on the card is uncovered to the observer, the shorter limb of the wire touches the mercury and the current controlling the chronoscope is closed. This method is in every way better than that hitherto used of illumining the object by an electric light. It avoids altogether the great inconvenience and difficulty of using an induced current, as keeping the light constant, closing simultaneously an induced and galvanic current and other difficulties best known to those who have tried to overcome them. Further, it eliminates the time required to adapt the eye to a light of unexpected intensity, placed by experimenters as quite large. Lastly, it enables the observer to fixate exactly the point at which the object appears, so that words, &c., can be used.

Three instruments were used to break the current controlling the chronoscope at the instant the observer made a motion. The first of these was a telegraphic key, which the observer held closed with his finger or fingers, and let go by a motion of the hand. The key used should be very sensitive ; it should break the current instantaneously, yet should not require much pressure to hold it closed. The other two instruments were devised to break the current when the organs of speech are moved. The first of these (Fig. 4) we can call a lip-key. The binding screws

FIG. 4.



B B are connected respectively with the battery and the chronoscope. The platinum contact at *c* is closed when the observer holds the ivory tips *T T* between his lips ; but as soon as the lips are moved the spring *S* breaks the contact, and, consequently, the current which had been flowing through the chronoscope. The only difficulty in the way of using this lip-key is that it is possible for the observer to move his lips before he makes the motion to be registered. This difficulty is avoided by means of the apparatus shown in Figures 5, 6 and 7, which we can call a sound-key. The current controlling the chronoscope is broken when the observer speaks into the mouth-piece *M* (Fig. 5). An additional galvanic current is needed to work this apparatus. I used four Daniel cells. The current flowed through a commutator (*C''*, Fig. 8), the coil of the electromagnet (Fig. 7), and the instrument shown in Figures 5 and 6. This latter consists of a mouth-piece, a funnel, and a ring (Fig. 6) fitting into the funnel, and covered with kid leather. When the observer speaks into the mouth-piece, the sound waves through the membrane into vibration, and the platinum contact at *c* is broken; the breath accompanying speech also breaks the contact. The current making the electromagnet (Fig. 7)

FIG. 5.

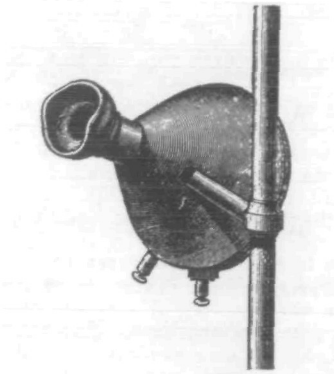


FIG. 6.

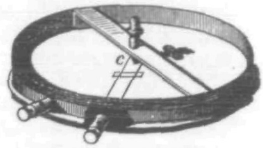
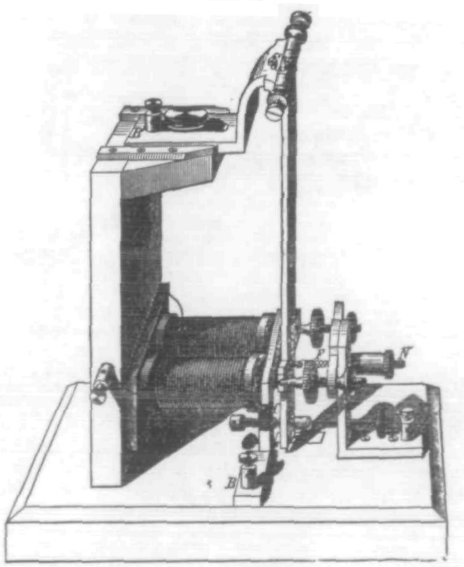
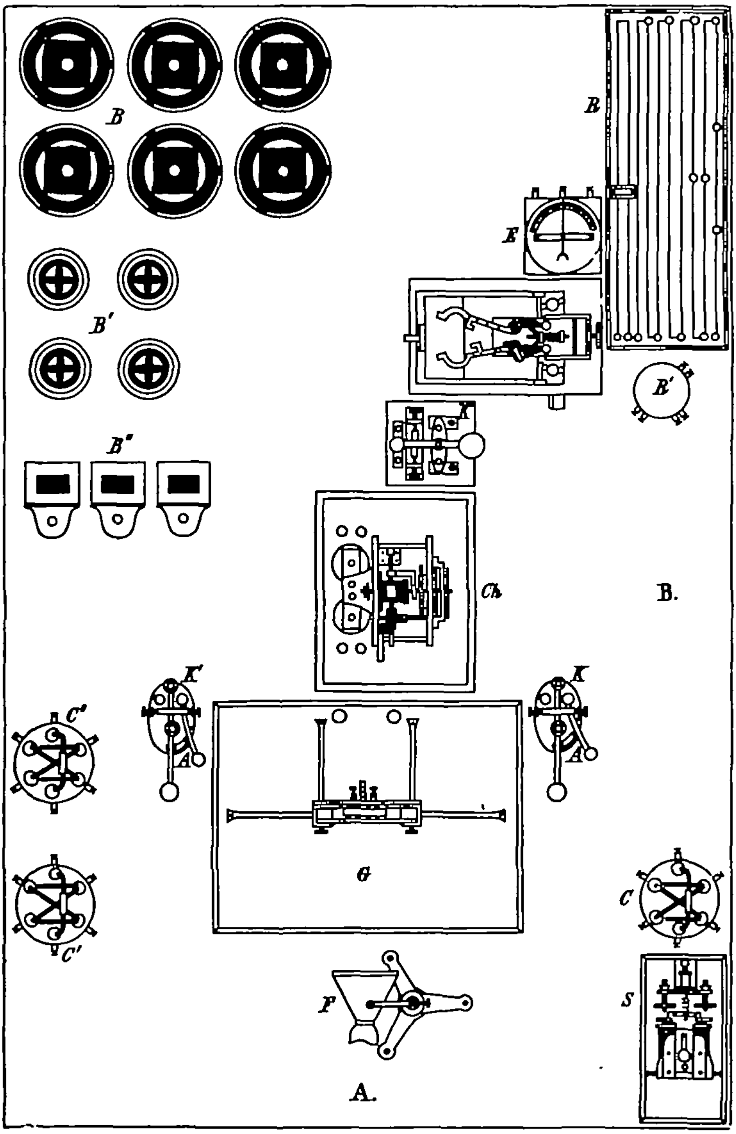


FIG. 7.



flows through this contact; so when it is broken, if only for an instant, the soft iron looses its magnetism, and the armature is drawn back by means of the spring *F*. The strength of this spring can be regulated by means of the screw *N*. The binding screws *B B'* are connected respectively with the chronoscope and its battery, so that the current flows through the contact at *C*. This contact is closed as long as the armature is held by the magnet, but is broken the instant the magnetism in the soft iron disappears or is weakened so that the spring can draw away the armature. The armature is not held against the magnet, the contact being at the point *C*.

FIG. 8.



The pressure is kept constant by regulating the strength of the spring *F*. It will be seen that after the contact in the funnel is broken, no appreciable time elapses before the current controlling the chronoscope is broken ; but the contact in the funnel is broken by the slightest motion of the speech-organs, so the instant of this motion is registered.

In Fig. 8 I give the arrangement of the apparatus when it is wished to determine, for example, the time it takes to see and name a word. It is a matter of no small importance so to arrange the apparatus that it can be conveniently operated on, and the figure will further make clear the connexion of the different instruments and the several batteries. The observer sits at A., the light coming over his left shoulder. His head is held naturally, and at the distance of most distinct vision for the word. He can conveniently speak into the mouth-piece of the sound-key *F*, or hold the telegraphic key at *K* closed. The experimenter[1] sits at B., within easy reach of all the apparatus he has to control. The current belonging to the chronoscope flows from the positive pole of the battery *B* to the commutator *C*, thence through the rheostat *R R'* (if desired, also through the electrometer *E*) and chronoscope *Ch* to the gravity-chronometer *G*, where the connexion is interrupted when the mercury in the two basins is not connected, thence the current flows through the contact of the sound-key at *F* back to the commutator and battery. The current making the electromagnet of the gravity-chronometer flows from the battery *B'* to the commutator *C'*, and thence through the key *K''* and the gravity-chronometer back to the commutator and battery. The third current, controlling the sound-key, flows from the battery *B''* to the commutator *C''*, and thence through the contact of the sound-key at *F* and coil of the magnet at *S*, and back to the commutator and battery. Suppose now we wish to measure the time it takes to see and name a word. The experimenter puts a card on which a word is printed into the springs of the gravity-chronometer ; he then says 'now,' and starts the clockwork of the chronoscope. The observer fixates the point on the screen immediately before the word. Then the experimenter (or the observer himself) allows the screen to fall by breaking the current which, through the electromagnet, had been holding it up. Suddenly the word appears at the point fixated by the observer, and at the same instant the basins of mercury are connected by the copper wire ; thus the current controlling the chronoscope is closed and the hands are set in motion. The observer names the word as quickly as possible. As soon as he begins to speak, the current making the magnet at *S* is broken and the armature is drawn away. The current controlling the chronoscope is thus broken, and the hands stand still. The experimenter then stops the clockwork and reads from the dials the exact time taken to see and name the word.

The special methods and precautions necessary to secure correct results in using the apparatus here described can best be considered when I come to treat of the different cerebral operations, the times of which I have tried to determine. It may, however, be well to mention here two points, which are common to all the experiments I have made. The first of these is the method of deducing a correct average from the separate experiments. Two methods have been employed : either all the re-

[1] I call the person having charge of the apparatus the experimenter ; the person on whom the experiments were made the observer.

actions measured have been averaged together, or those times which the experimenter thought too long or too short have been altogether ignored. There are however serious objections to both of these methods. The former does not give correct results. Through some abnormal circumstance, a reaction may vary so greatly from the average of the others, that the whole series gets a false value. It might be supposed that this error could be eliminated by making the whole number of experiments sufficiently large; this, however, makes necessary a great expenditure of time and labour, without altogether correcting the error. In physical experiments, the measurements varying most from the average are equally likely to be positive or negative; this is not the case in our work. Reactions that are so short as seriously to affect the average can scarcely occur, but through some inner or outer disturbance the reactions are sometimes abnormally long. Thus, even though the average of an indefinitely large number of reactions is taken, the result is not correct, but somewhat larger than the average of the reactions made under normal circumstances. The method introduced by Exner of simply ignoring the reactions which seem to be too long or too short may give correct results, but is undoubtedly unreliable. The experimenter thinks he has found the proper worth, and then almost unconsciously leaves out of his reckoning the reactions which would invalidate it. For example, Merkel[1] gives fifteen averages in which his 'perception time' is between 22 and 25σ, and the times in a hundred and twenty other series, made on eight different persons, correspond exactly with this, varying only between 19 and 26σ. These averages correspond to an altogether impossible extent; we need not therefore be surprised at finding the time quite false. The work of v. Kries and Auerbach[2] loses much of its value from the fact that so many of the determinations have been omitted in calculating the results.

I have used a different and, as far as I am aware, new method. If the apparatus did not work properly, of course no reaction was measured; but the average of all the reactions measured was calculated. Either 13 or 26 reactions were made in a series; the average of these reactions was calculated, and the variation of each reaction from this average. Then the reaction having the largest variation was dropped, the average of the remaining 12 or 25 reactions was calculated, and the reaction varying most from this average was again dropped. This process was continued until the 3 or 6 worst reactions had been dropped, I then having the 10 or 20 best reactions, and the variation of each of these from the average. In practice we need not calculate so many new averages, it being only necessary to drop the 3 or 6 reactions

[1] *Philosophische Studien*, ii. 1.

[2] *Du Bois-Reymond's Archiv*, 1877.

varying most from the corrected average, which can usually be foreseen. In this paper I give the average of all the reactions made, as well as the average corrected by the method I have described. It will be seen that the two values do not differ greatly; this is owing to the fact that the conditions of the experiments were such that really abnormal reactions seldom occurred.

The second point to be mentioned here is the influence of practice, attention and fatigue on the length of the times determined. In a later section of this paper I shall give an account of experiments I have made on this subject. In other cases it was sought to eliminate as far as possible these sources of variation. The two subjects (Dr. G. O. Berger and the writer) on whom the determinations were made had already had much practice in psychological work. They were in good health and lived regularly, not even using coffee. The experiments were made every morning (except Sunday) from eight to one o'clock. After each series of 26 reactions, a considerable and constant interval elapsed before the same subject again reacted. The subject held his attention as constant as possible, and was not disturbed by noise or the presence of others in the room.

These experiments, though begun in America, have been carried out in the psychological laboratory of the University of Leipsic. Professor Wundt, the founder and director of this laboratory, has earned the gratitude of all those interested in the scientific study of the mind. I owe him special thanks for the constant help and encouragement he has given me in my work.

II. *The Reaction-Time.*

The reaction-time can be determined with ease and accuracy, but it is difficult to decide what operations take place when a reaction is made, quite impossible to determine how the time is divided among the several operations. We shall see that under favourable circumstances the reaction-time for light is about 150σ. It seems to me probable that this period is divided about equally between the processes occurring within and without the brain. The latter are: (1) the latent period in the sense-organ; (2) the time of transmission in the afferent nerve; (3) the time of transmission in the spinal cord and efferent nerve; and (4) the latent period in the muscle. Physiologists have attempted to determine these times separately, but they must be far more constant than the discordant results would lead us to suppose. The experiments I am about to describe show that when the reaction-time is measured the mean variation of the separate times from the average is only $\frac{1}{20}$ of the whole time; and we may attribute this small variation chiefly to changing states of the brain. If these times were not constant it is probable that we could not distinguish colours and tones.

The velocity at which a nervous impulse is transmitted has been a favourite subject for physiological research,[1] but the results as yet reached are unsatisfactory. Exner, in Vol. ii. of Hermann's *Handbuch der Physiologie*[2] gives, as result of the "perfectly irreproachable measurements" of Helmholtz and Baxt, the rate of transmission in a motor nerve as 62m. the second; whereas, in the same volume[3] and likewise as the result of experiments by Helmholtz and Baxt, Hermann gives the rate as 33·9005m. the second. The fact seems to be that the rate depends on the temperature and other conditions, chiefly brought about by the method of experiment. Determinations made on the sensory nerve give results still more discordant and unsatisfactory. We can for the present do nothing better than assume the average rate of transmission in both motor and sensory nerve to be 33m. the second. It is probable that the rate is slower in the spinal cord, and that the nervous impulse is delayed in entering and leaving the cord, as also in passing through a ganglion.[4] As a temporary hypothesis we can suppose that when the reaction, lasting 150σ, is made, 50σ is used in transmitting the nervous impulse from the retina to the brain, and from the brain through the spinal cord to the muscle of the hand. The latent period when the muscle of the frog is stimulated by means of an induction-shock, is between 5 and 10σ;[5] and is perhaps the same when the muscle of the hand is innervated by means of a will-impulse. There is also undoubtedly a latent period in the sense-organ while the stimulus is being converted into a nervous impulse. In the so-called mechanical senses this period is very short, but when the retina is stimulated by light a chemical process (as we suppose) takes place, and the time may be quite long.[6] We know that a light must work on the retina for a considerable time in order that the maximum intensity of the sensation may be called forth; from this time, however, we can draw no exact inferences as to the length of the process here under consideration. I have shown[7] that a coloured light of medium intensity must work on the retina ·6 to 2·75σ (varying with the observer and colour) in order that a sensation may be excited; the time becomes however much longer when a white light follows the

[1] See for references Hermann, *Handb. d. Physiol.* II., ii., 14 ff.

[2] ii., 272.

[3] i., 22.

[4] Exner, *Pflüger's Archiv*, viii., *Archiv. f. Anat. u. Phys.*, 1877; François-Franck et Pitres, *Gazette Hebd.*, 1878; Wundt, *Mechanik der Nerven*, ii., 45.

[5] Tigerstedt, *Archiv f. Anat. u. Physiol.*, 1885, and references there given.

[6] V. Wittich (*Zeitschr. f. Rat. Med.*, xxxi.) and Exner (*Pflüger's Archiv*, vii.) found the reaction-time to be shorter when the optic nerve was stimulated by an electric current than when the retina was stimulated by light. This difference may, however, be due to other factors of the reaction-time as well as to the latent period in the sense-organ.

[7] *Philosophische Studien*, iii., 1; *Brain*, Pt. 31.

colour, the second light washing away, as it seems, the impression made on the retina by the first light. Under these circumstances a violet light had to work on the retina 12·5σ, if it were to be distinguished. It seems, therefore, probable that the violet light had not been converted into a nervous impulse within this interval, and if this is the case it would give us a minimum time for this process. The familiar experiment with rotating discs shows that light-impressions of moderate intensity following one another at intervals of 25σ are just fused together. It seems, therefore, that the retina is excited, and begins to resume its normal condition in about 25σ. If this assumption is correct we have the maximum time for the period under consideration. We may be tolerably sure that the time passing before a light is converted into a nervous impulse varies with the intensity of the light, and may perhaps assume the time to be 15-20σ for daylight reflected from a white surface.

These considerations lead us to suppose that, when a reaction is made on light, only about half the time, that is 75σ, is taken up by the cerebral operations. We naturally ask what happens in the brain after the nervous impulse reaches it. It has generally been assumed that the largest factors of the reaction-time are taken up by the processes of perception and willing. I think however that if these processes are present at all they are very rudimentary. Perception and volition are due, we may assume, to changes in the cortex of the cerebrum, but reflex motions in answer to sense-stimuli, as in contraction of the pupil and in winking, can be made after the cortex has been removed, and an animal in this condition can carry out motions adapted to the nature of the stimulus. If a pigeon from which the cerebral hemispheres have been removed is thrown into the air, it will not only fly, but also avoid obstacles and alight naturally on the ground. It seems to have consequently sensations of light, but apparently no perceptions, either because it does not see colour and form, or because it lacks the intelligence needed to understand their meaning. In the same way a reaction such as we are considering can probably be made without need of the cortex, that is, without perception or willing. When a subject has had no practice in making reactions (in which case the reaction-time is usually longer than 150σ) I think the will-time precedes the occurrence of the stimulus. That is, the subject by a voluntary effort, the time taken up by which could be determined, puts the lines of communication between the centre for simple light sensations (in the optic thalami probably), and the centre for the co-ordination of motions (in the corpora striata, perhaps, connected with the cerebellum), as well as the latter centre, in a state of unstable equilibrium. When therefore a nervous impulse reaches the thalami, it causes brain-changes in two directions; an impulse moves along to the cortex, and calls forth there a perception corresponding to the stimulus, while at the same time an impulse follows a line of small resistance to the centre for the coordination of motions, and the proper nervous impulse, already prepared and waiting for the signal, is sent from the centre to the muscle of the hand. When the reaction has often been made the entire cerebral process becomes automatic, the impulse of itself takes the well-travelled way to the motor centre, and releases the motor impulse.[1]

I now go on to give the results of my experiments. I only give the determinations made on B (Dr. G. O. Berger) and C (the writer); I have made similar determinations on other subjects of different age, sex, occupation, etc., but these can be better considered after we know the results of careful and thorough experiments on practised observers. We have first to consider the simple reaction-time for light. When this was to be measured, all being in readiness, as described in the foregoing section, the experimenter said 'Jetzt,' and the observer fixated the point at which the light was to appear, and put himself in readiness to make the reaction. The experimenter then set the clock-work of the chronoscope in motion, and about one second afterwards caused the light to appear by means of the apparatus described. The observer lifted his hand as soon as possible after the appearance of the light, and the interval that had elapsed between the occurrence of the light and the commencement of the muscular contraction was read by the experimenter directly from the chronoscope. In no single case, as far as I can remember, did the observer make a premature reaction, that is, lift his hand before the necessary physiological operations had had time to occur. The only disturbance was caused by the clock-work of the chronoscope sometimes not being properly controlled by the vibrating spring. If the experimenter noticed this in time he did not produce the light. This occasional failure of the chronoscope was always noticed, so does not interefere with the accuracy of the times here given, but the observer was sometimes disturbed so that his reactions may have been made less regular. Throughout this paper I give every series and every reaction made; I give, however, in addition to each series, a corrected value reached by the method above described. This correction simply excludes all abnormal values. In the Tables I give the average of the variation of each reaction from the average of the series to which it belongs (V); that is, if A is the average of the *n* reactions

[1] This theory concerning the nature of the reaction would be none the less probable, though we suppose the centres for sensation and perception not to be distinct, or indeed that in the reaction the brain, in some mysterious way, 'acts as a whole'. In this paper I take it for granted throughout that mental states are due to changes in the brain. We know, however, but little as to the functions of the brain. I therefore make as few assumptions as possible, and these must be kept apart from the positive results, which it is the object of this paper to make known.

making up the series, and $a_1, a_2, a_3, \ldots a_n$ are the values of the several reactions, then

$$V = \frac{(A - a_1) + (A - a_2) + (A - a_3) + \ldots + (A - a_n)}{n}$$

all the differences being taken as positive. The averages under R in the Tables (except when expressly stated) are taken from the 26 observations which made up the series, the averages under R′ from the 20 reactions of the corrected series. Table I. gives the results of twenty series, made at intervals during a period of six months.

TABLE I.

1885.	B				C			
	R	V	R′	V′	R	V	R′	V′
12. I.	140	10	141	8	144	12	143	8
	145	10	143	6	136	9	138	5
16..............	137	16	139	11	133	16	128	11
	156	10·	155	7	147	15	150	11
30..............	131	13	131	9	149	9	151	6
	152	13	149	9	143	11	143	9
27. II.	148	14	147	8	146	10	144	7
	160	13	162	8	144	9	144	6
28..............	139	13	142	11	149	9	149	6
	161	15	163	9	146	9	146	5
	152	13	149	7	144	9	143	6
31. III.........	164	14	164	8	163	9	163	6
	151	10	153	6	150	8	151	5
3. IV.	133	16	132	11	143	8	144	5
	157	9	159	6	138	11	136	7
4.	165	13	170	9	161	9	163	5
5.	144	13	147	9	147	9	148	6
7.	168	9	170	5	148	17	148	9
2. VII..........	137	16	140	11	158	12	158	8
4.	152	13	155	9	140	14	145	9
A...............	150	13	151	8	146	11	147	7

The Table shows that the average of 520 reactions on daylight reflected from a white surface was, for B 150, for C 146σ; or, if the series are corrected by the method explained, the averages for both B and C become 1σ longer. The average of the mean-variation of the reactions from the series to which they belong was for B 13, for C 11σ; in the corrected series it becomes respectively 8 and 7σ. It will be seen from the Table that the series made at different times do not differ greatly from each other; the mean-variation of the twenty series is B 9, C 5. The reaction-time for practised observers is consequently quite a constant quantity; when a reaction is made it will only differ about $\frac{1}{100}$s. from those preceding and following it, and less than $\frac{2}{100}$s. from reactions made on different days and under changed circumstances. I do not however lay much weight on the third decimal; if this investigation were to be repeated it is not likely that we should obtain the same results to $\frac{1}{1000}$s. When B's reaction-time for light is given as 150σ, I only mean that this was the result of these 520 reactions; in comparing this with other determinations where we wish to know the absolute length of B's reaction-time, we can best limit ourselves to saying that it is ·15s., or perhaps better still, between ·14 and ·16s.

In these experiments the reaction was made with the right hand. The time is the same with the left hand.[1] I give in Table II. the average of five series (130 reactions) made with the left hand on light and also on sound.[2]

TABLE II.

		B				C			
		R	V	R′	V′	R	V	R′	V′
Light....	3-7. IV.......	153	12	156	8	147	11	148	6
Sound...	3-7. IV.......	126	8	126	6	122	11	122	7

It is a matter which the later sections of this paper will show to be of special interest to us that the time is longer when the reaction is made with the speech-organs. To determine this time I used both the lip-key and the sound-key above described. In either case the observer said 'Jetzt' as soon as possible after the appearance of the light, and the motion of the speech-organs stopped the hands of the chronoscope in the way I have explained. The results of these experiments are given in Table III.

We thus find that it takes about 30σ longer to make the reaction with the speech-organs than with the hand.

I used an additional method of determining the reaction-time with the speech-organs. The observer as quickly as possible after the appearance of the light simply said 'Jetzt'; a second observer as soon as he heard the sound let go the telegraph-key, and this stopped the hands of the chronoscope. The hands recorded the time of a double reaction, that of the first observer on the light with his speech-organs, and that of the second observer on the sound with his hand. But we can determine

[1] Tischer, *Phil. Studien*, i., 534; Merkel, *Ib.*, ii., 88. Prof. G. S. Hall and Dr. Hartwell (MIND, ix. 93) do not seem to have known of the work published by Tischer and Merkel.

[2] The sound (as in all cases where the reaction-time for sound was measured) was made by a stone ball 22 gr. in weight, falling from a height of 33 cm. on the wooden base of the Hipp gravity-apparatus.

TABLE III.[1]

	Sound-key.				Lip-key.			
	B		C		B		C	
	R	R′	R	R′	R	R′	R	R′
3. IV.	164	167	177	176	199	199	172	171
	161	159	165	165	185	187	173	173
5.	175	176	175	176	199	201	172	173
	170	168	175	172	189	186	177	177
7.	168	168	157	159	166	165	185	176
A.	168	168	170	170	188	188	176	174
AV.	19	10	16	10	11	6	13	8

the time of the second observer's reaction on the sound, and by subtracting this from the entire time, we have the reaction-time of the first observer with his speech-organs. When the average of several series is taken the error becomes very small. A further application of this method will be found below. For our present purposes it was to a large extent superseded by the use of the lip-key and sound-key. There are however certain difficulties in the way of using these instruments, especially in the case of inexperienced persons, children or the insane, for example. The method could further be applied to determining the reaction-time, etc., of the lower animals, and also the length of certain reflex processes where the motion can with difficulty be registered. I give in Table IV. the results of four series of reactions made in this way, Mr. H. Wolfe making reactions on the sound.

TABLE IV.

	B				C			
	R	V	R′	V′	R	V	R′	V′
7. 1	349	30	346	20	328	32	321	17
	330	37	332	23	327	24	326	14
30.	380	30	372	20	392	27	392	18
	357	32	349	19	393	25	393	16
A.	354	32	350	20	360	27	358	16

Mr. Wolfe's reaction-time on sound was about 150σ. The series made on 30 I. seem to have given rather long times, the

[1] To save space in this and some other Tables, I only give the average of the mean-variation for the several series (AV).

others correspond to those where the motion of the speech-organs was directly registered.

The length of the reaction-time depends on conditions which can be classified as belonging, partly to the sense-stimulus, partly to the reacting subject. It was my object in the experiments here under consideration rather to eliminate these sources of variation than to investigate them. I used therefore the same sense-stimuli and the same subjects. The only varying conditions were the changing states of the subject due chiefly to different degrees of attention, fatigue and practice. It seemed desirable thoroughly to investigate these owing (1) to the light they throw on the nature of the cerebral operation, and (2) to the necessity of knowing what influence they exert on the lengths of the processes investigated, before we can judge of the accuracy of our results. I can best postpone the full consideration of this subject until the end of the paper, but it will be of advantage before going further to consider the relation of attention to the length of the reaction-time. It has always been assumed that the length of the reaction varies greatly with different degrees of attention, and this is a natural supposition, when it is believed that the time is mostly taken up by the processes of perceiving and willing. If however the reaction is automatic, the changes not penetrating into the cortex of the cerebrum, then the time would not be greatly dependent on the concentration of the attention during the reaction. The reaction would however be delayed if the conditions were such as to make it difficult for the subject to hold the path of communication and motor centre in a state of readiness. The simplest way of distracting the attention is to cause a noise while the reactions are being made. I let three metronomes beat and ring rapidly. The results of these experiments are given in Table V. for both light and sound.

TABLE V.

	LIGHT.				SOUND.			
	B		C		B		C	
	R	R′	R	R′	R	R′	R	R′
2. IV.	149	150	162	159	122	120	121	118
3.	159	159	146	147	124	127	120	119
	152	152	144	142	126	124	128	127
4.	146	148	162	161	132	131	137	138
5.	155	155	168	170	119	119	125	124
A.	152	153	156	156	125	124	126	125
AV.	8	5	10	6	10	6	10	6

If these results are compared with those given in Table I. it will be seen that B's reaction-time for light was lengthened 2, C's 10σ. These increments are very small, falling in the case of B within the limits of the natural variation. The reaction time for sound was the same as when no distracting noise was present. Wundt[1] found the reaction-time to be considerably lengthened by a distracting noise. This was probably because the subjects had not learned to make the reaction as automatically as B and C. The experiments by Obersteiner[2] are scarcely such as to give accurate results.

The attention can be more thoroughly distracted if the brain is busied with some other operation while the reactions are being made. A good way to accomplish this is to let the subject beginning with any number add as rapidly as possible 17 after 17 to it. The attention can on the other hand be concentrated to a maximum degree by a voluntary effort of the subject. Many experimenters seem to have attempted this in all their reactions; Exner, for example, says[3] that although sitting quietly on his seat he would sweat with the exertion. In my experiments the attention was held in a state which I shall describe as normal; the subject expected the stimulus and reacted at once, but did not strain his attention or make special haste. We have thus three grades of attention: concentrated, normal and distracted.

TABLE VI.

CONCENTRATED.				NORMAL.				DISTRACTED.			
R	V	R′	V′	R	V	R′	V′	R	V	R′	V′
12.—25. II. 1884.				B				LIGHT.			
189	15	187	8	201	17	197	9	245	28	242	13
				C							
158	17	156	10	132	16	133	9	153	19	151	10
27. II.—6. III. 1884.				B				ELECTRIC SHOCK.			
160	13	161	7	165	12	164	7	190	16	189	9
				C							
147	14	147	8	150	15	150	9	184	21	184	11

[1] *Physiol. Psych.*, ii., 243.

[2] *Brain*, 1879.

[3] Herman's *Handb. d. Physiol.*, II., ii., 287.

The first experiments on this subject were made in the winter of 1883-4, before the chronoscope was properly controlled; the absolute times may be as much as 10σ wrong, but the relative times are correct. As a stimulus I used the electric light produced in a Puluj's tube, and an induction-shock of moderate intensity on the left forearm. In these experiments 15 reactions were

TABLE VII.

	CONCENTRATED.				NORMAL.				DISTRACTED.			
	R	V	R′	V′	R	V	R′	V′	R	V	R′	V′
					B LIGHT.							
27. II.	144	16	147	7	148	14	147	8	196	26	185	12
	131	11	130	8	160	13	162	8	186	26	183	19
28.	141	10	143	7	139	13	142	11	178	15	180	11
	137	8	139	4	161	15	163	9	179	16	179	10
	143	8	144	6	152	13	149	7	194	14	190	9
A.	139	11	141	6	152	14	153	9	187	19	183	12
					C							
27. II.	149	13	150	9	146	10	144	7	166	12	167	7
	149	7	150	4	144	9	144	6	154	16	156	11
28.	146	8	144	5	149	9	149	6	157	13	159	8
	146	12	144	8	146	9	146	5	154	9	155	6
	140	8	139	5	144	9	143	6	163	14	160	9
A.	146	10	145	6	146	9	145	6	159	13	159	8
					B SOUND.							
2. II.	132	7	132	5	157	11	157	8	193	26	189	13
	129	6	129	5	158	19	149	8	188	28	191	19
3.	127	14	129	4	155	14	152	7	174	12	173	8
	123	9	122	6	147	10	145	6	169	24	163	17
4.	127	7	126	5	138	9	139	6	188	24	183	17
A.	128	9	128	5	151	12	148	7	182	23	180	15
					C							
2. II.	129	12	126	8	145	10	140	6	166	18	162	12
	135	11	135	8	133	12	132	9	156	19	148	14
3.	125	12	127	6	141	11	140	8	158	15	161	9
	123	12	123	8	142	11	139	6	155	17	155	12
4.	131	11	126	8	136	10	133	5	157	15	153	9
A.	129	11	128	8	139	11	137	7	159	17	156	11

made in a series, 5 being dropped in the corrected series. The numbers in Table VI. give the average from 10 series.

Similar experiments were made in 1885, daylight and sound being used as stimuli. The averages given in Table VII. are as usual taken from 26 reactions.

I put together the results of these experiments in Table VIII., the time when the attention was normal being taken as 0.

TABLE VIII.

	B		C	
	Concen.	Distr.	Concen.	Distr.
Electric light	— 12	+ 44	+ 26	+ 21
" shock	— 5	+ 25	— 3	+ 34
Daylight	— 13	+ 35	0	+ 13
Sound	— 23	+ 31	— 10	+ 20
A	— 13	+ 34	+ 3	+ 22

It will be noticed that when the brain is otherwise occupied the reaction is lengthened, though not to a great extent. The time is however but little shorter when the subject makes a great exertion to react quickly than when he makes the reaction easily and naturally. These experiments support the hypothesis that a reaction is an automatic act, only needing the activities seated in the cortex to prepare its way. A noise did not in the case of B and C so disturb the subject as especially to interfere with the placing in readiness of the parts of the brain concerned in making the reaction. If the brain was busied by adding 17 after 17, it could not so well put the lower centres in readiness, and the time of the reaction was lengthened. On the other hand a great effort of the will could only slightly shorten the reaction by holding the path of communication and motor centre in a state of more unstable equilibrium.

There is still another way of distracting the attention. When the time of normal reactions was measured the stimulus came about a second after the signal (*i.e.*, the starting of the chronoscope), so the brain parts could be put in a state of complete readiness. It might be expected that we could not hold these parts very long in a state of unstable equilibrium, and experiments show this to be the case. Instead of always letting the stimulus occur from $\frac{3}{4}$ to $1\frac{1}{4}$ sec. after the signal, I let the maximum interval be about 2 secs., and obtained the results given in Table IX.

The averages show that the attention can be held strained, that is, the centres kept in a state of unstable equilibrium for 1 sec. B's time is slightly shorter than normal; this is probably

TABLE IX.

	B				C			
	R	V	R′	V′	R	V	R′	V′
27. II.	148	10	149	7	155	9	155	5
	136	9	139	6	147	11	148	6
28.	139	9	139	6	143	12	142	6
	156	10	154	6	157	11	158	7
4. IV.	146	16	145	10	162	12	159	8
A.	145	11	145	7	153	11	152	6

because he strained his attention more, and thus held the centres in more unstable equilibrium than usual in spite of the longer interval. C's time, on the other hand, is slightly lengthened, concentrated attention not shortening his times, and the delay interfering with the maximum of readiness. In like manner the interval between signal and stimulus was varied at the pleasure of the experimenter between normal and fifteen seconds. The experiments recorded in Table X. were made with both light and sound.

TABLE X.

	LIGHT.				SOUND.			
	B		C		B		C	
	R	R′	R	R′	R	R′	R	R′
27. II.	200	198	170	168	184	173	174	169
28.	204	196	164	164	176	173	167	166
	168	161	wanting.		168	164	154	147
4. IV.	159	158	184	181	171	171	173	166
5.	178	174	174	176	158	159	170	166
A.	182	177	173	172	171	168	168	163
AV.	22	14	16	11	23	13	22	13

It will be seen that the times are considerably longer than normal; the mean variation is also large.[1] The first series made

[1] On two occasions with B, I varied the series on sound with results worth noting. I let towards the end of the series the interval between signal and stimulus become regular and normal. B did not notice that any change in method had taken place, but his reaction-time after the first two trials became 40σ shorter. That is, without any conscious effort, the brain-parts concerned were put in the usual maximum state of unstable equilibrium.

on B gave especially long times; afterwards he learned to accommodate himself better to the conditions. All these experiments show that in the case of C the reaction is more thoroughly reflex than in the case of B. Contrary to my expectation the reaction on sound seems to be more lengthened by distracting the attention than the reaction on light; it requires less effort to react on the sound, the reaction seeming to take place quite of itself, and we know that it is easy to make motions in time to sound-rhythms.

I made further series of experiments in which 'Jetzt' was said and the chronoscope was set in motion as usual, but the light was produced only half the time. My thought was that the subject could not put his brain-centres in the maximum state of unstable equilibrium, lest the motor impulse should be discharged in the case where no stimulus was forthcoming. The averages in Table XI. are from 13 and 10 reactions, as measurements were only made in half the experiments of the series.

TABLE XI.

	B				C			
	R	V	R′	V′	R	V	R′	V′
27. II.	153	18	147	10	174	22	165	8
	148	10	148	6	166	18	160	8
28.	154	23	148	15	142	6	143	5
	165	20	157	10	154	12	156	6
	157	9	156	7	153	12	150	8
A.	155	16	151	10	158	14	155	7

The delay here caused is related to the will-time to be considered later on.

From these experiments we see that ordinary degrees of attention do not greatly affect the length of the reaction time. We find, further, grounds for assuming that the cortex is not concerned and that perception and willing are not factors of the reaction-time. It is not necessary to perceive the stimulus before the motor centre can be excited; and the willing—not of necessity given in consciousness—is done before the stimulus occurs, and consists in setting the brain-parts concerned in a state of readiness.

(To be continued.)