ON REACTION-TIMES AND THE VELOCITY OF THE NERVOUS IMPULSE.*

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Our object was to determine the conditions which affect the length of reaction-times on dermal stimuli, and to study the application of the reaction-time to the measurement of the velocity of the nervous impulse in motor and sensory nerves, and in the motor and sensory tracts of the spinal cord.

Sec. 1. *Apparatus and Methods.*—In order to measure a reaction-time at least three instruments are required—one to give the stimulus and record the instant at which it is given, one to record the instant at which a movement is made, and one to measure the intervening time. We used the Hipp electric chronoscope for measuring the time, having made several improvements in its construction and regulation. With our apparatus we could measure the time of a reaction with a variable error of about 1σ (i.e. one thousandth of a sec.), and a constant error of about the same size. The variable error is practically eliminated in the average of 100 measurements, and the constant error is practically eliminated when a difference is taken. We used various methods to apply an electric shock or a blow to the skin. In the case of a blow we were able to measure exactly its force. The greater part of the apparatus was secured through an appropriation from the Bache Fund, and is the property of the National Academy of Sciences.

* Abstract of a paper presented before the meeting of the National Academy of Sciences, Albany, 1893. The paper with description of apparatus, tabulated results, and historical references will be printed in the *Memoirs of the Academy*.

We made 10 reactions in a series and 10 series in a set, each time given in the Tables being the average of 100 reactions. We give the mean variation of the separate reactions and of the separate series and probable errors when it seems needful. The mean variation of the separate reactions is on the average about 10σ, and the probable error of the figures given in the Tables would be about 1σ. Although we omitted no measurements in calculating the averages, the probable errors are much smaller than in previous investigations on reaction-times. In some cases we made 10 reactions in succession at intervals of 2 sec., and only measured the resultant time. By this method more reactions can be made in a given time, but the probable error of the single reactions is not known.

The experiments were begun in 1889 in the psychological laboratory of the University of Pennsylvania and completed in 1893 at Columbia College. The experiments were made by D and C (the writers) and J, all of whom were used to scientific work.

Sec. 2. *Reactions on Electrical Stimuli.*—An electric shock can be applied conveniently to different parts of the body. The shock may be made as strong as desired and the moment of its occurrence registered. We used electrodes of various sorts. The method we found best was to apply one electrode (usually a platinum surface 10 mm in diameter) to the points on the skin which we wished to stimulate, while the other electrode was conducted to a pail of saturated salt water in which the left foot was placed. The stimulus was given 10 times in succession at the same point, and then immediately switched to another point without shifting the electrodes The shock was usually given on the left-hand side of the body, the reaction being made with the right hand or foot.

The sensory effects of electrical stimulation of the skin have not been properly investigated, and this is the more curious as the effects on the organs of sight, hearing, taste, and smell have been thoroughly studied. With a galvanic current from 28 cells in pairs we found a decided difference in sensation according to the pole with which the electrode was connected. Thus when the positive pole was applied to the outside of the upper lip (the other pole being conducted to the foot) there was a prickling sensation, a strong taste and a flash of light, the prickling and taste continued while the current was closed and there was a flash of light on breaking. When the negative pole was applied to the same point there was a slight shock and flash of light and no taste, but sensations of piercing and boring followed which were unendurably painful. The current caused tetanus of the muscle and left blisters. This experiment shows that the current from the negative pole was more intense and from the positive pole more diffused (extending with much energy to the organs of taste and sight), which indicates that the current passes through the body from negative to positive pole.

We used in our experiments the momentary shock following breaking of the primary circuit. The same objective current does not give a shock of the same subjective quality and intensity when applied to different parts of the body. The sensation is more piercing when the electrode is applied close to the nerve, and more massive (as from a blow) when there is muscle intervening. The sensation of a shock from 8 cells on the upper arm might be as intense as that from 28 cells on the wrist. The shock from the same current also varied with the pressure of the electrode and especially with the moisture of the skin. Further as the experiments proceeded the part of the skin to which the shock was applied became continually more sensitive. The shock is more piercing from a small electrode and more massive from a large electrode.

We have made so many experiments (more than twenty-four thousand reactions) and with such numerous variations in the place of applying the stimulus, and in the nature of the stimulus and of the movement, that we fear an abstract of our results will be somewhat confusing. The details could only be properly understood from the Tables, and a study of these will only be undertaken by those especially interested in research in this direction.

In our first experiments we chose four points on the skin for the application of the stimulus. These were permanently fixed by pricking the skin and introducing nitrate of silver.

Two of the points were on the arm over the median nerve, and two on the leg over the posterior tibial nerve. The points on the arm were 30 cm apart and those on the leg 50 cm apart, and the length of intervening nerve would be nearly the same. To stimulation of these points 5360 reactions were made, the movement being made in two thirds of the cases with the hand and in one third with the foot.

The reaction-time was the shortest when the stimulus was applied to the upper arm and the movement made with the hand. The time was 149.6σ for D and 113.1σ for C, about $\frac{1}{7}$ and $\frac{1}{9}$ sec. respectively. Such a personal difference must be due either to differences in the nature of the process or to differences in the sensitiveness of the parts of the nervous system concerned. The variation from time to time is much greater than can be due to chance variations, and the differences must measure secular changes in the nervous system.

When the stimulus was applied to the lower arm or on the leg the reaction-time was longer, the excess of time for the lower arm being 14.2σ for D and 6.9σ for C. The lower point was 30 cm furtner from the brain than the upper point, and if we could assume the difference in time to be due to the difference in length of the nerve travelled we should have a velocity of the impulse in the sensory nerve of 21.1 m per sec. for D and 49.5 m per sec. for C. The velocity in the sensory fibres of the posterior tibial nerve would be 31.1 m per sec. for D and 64.9 m per sec. for C. We are not, however, prepared to accept these velocities as valid. The differences in the time of reaction are undoubtedly correct, the variable error being practically eliminated. But the variation of the two observers and of the same observer at different times are so considerable, that we think these must be attributed to differences in the cerebral processes rather than to differences in the velocity of the impulse in the sensory nerve. The shorter reactions on the upper point might be due to other causes than nearness to the brain, such as to greater intensity.

When the shock was applied to the leg in one case, and to the arm in the other, the impulse in the former case had in addition to travel through the spinal cord from the lumbar to the brachial plexus, and the times are considerably longer. The differences when the movement was made with the hand were 26σ for D and 27.1σ for C. When, however, the movement was made with the foot the differences were 18.4σ for D and 18.7σ for C. The excess of distance in the spinal cord was the same as before, but the times were about 8σ shorter. We thus show that when the stimulus is applied to the left leg the cerebral reflex is relatively shorter to the right foot, and when applied to the left arm is relatively shorter to the right hand. The sensory fibres from one part of the body are most closely connected with the motor fibres to the same part. If we may assume that the cerebral reflex occupied the same time in the cases compared we should have a velocity in the motor tracts of the spinal cord of about 15 m per sec., and we may at least assume that the velocity is not less than this.

When the movement was made with the foot in one case and with the hand in the other, the stimulus being applied to the arm, the excess of time with the foot was 37.7σ for D and 54.4σ for C. When the stimulus was applied to the leg the differences were less (8.5σ for D and 9.4σ for C). We have thus again measured the difference in time of the cerebral reflex when the motor impulse proceeds to the part of the body from which the sensory impulse arrives and when it proceeds to a different part.

The difference in the time when the reaction is made with the hand and foot, respectively, is partly due to the time required to traverse the motor tracts of the spinal cord, but it may also be due to differences in the cerebral processes. The cerebral reflex is undoubtedly less perfect to the foot than to the hand. The difference in the case of the two observers is almost certainly a difference in the cerebral process. C's reaction with the hand is very automatic, with the foot it is more nearly like D's. If the whole excess of time in the case of D were consumed in traversing the motor tracts of the cord between the brachial and lumbar plexus we should have a velocity of about 10 m per sec. In so far as we can accept these results, the velocity in the sensory tracts of the cord would be greater than in the motor tracts, and this could be explained by a partial co-ordination of the movement in the cord.

As the differences found might be due to varying intensity of the shock or differences in the cerebral reflex, we made a large number of reactions (10,400) with a view to studying these factors. After some diverse experiments which will be found in our paper, we chose four points on the arm, and in some of the experiments used three intensities of shock. Two of the points were the same as before, but we chose an additional point on the lower arm near the wrist the stimulation of which was followed by muscular contractions and a massive sensation, and a point on the middle arm the stimulation of which was followed by a prickling or piercing sensation. We had thus two points on the lower arm close together, the stimulation of one giving a strong and massive sensation, the stimulation of the other giving a weaker and more prickling sensation. On the mid-arm the stimulation was followed by a prickling sensation, on the upper arm by a massive sensation. As a result of our experiments we found that the time of reaction was shorter when the intensity of sensation was greater, whether the increase in intensity were due to a stronger objective shock or to greater physiological effect on different points from the same shock. Thus as the final result of 1200 reactions on each point (made by J and C), we found the time on the lower point giving the massive sensation to be 126.6σ, and on the upper point giving a similar sensation to be 126.8σ, almost exactly the same. We must therefore conclude that the time of transmission in the nerve was exactly counterbalanced by a shorter cerebral reflex in the case of the point further from the brain. In the case of C the subjective intensity of the shock was greatest on the upper point and the final time was 2.2σ shorter on this point. In the case of J the subjective sensation was stronger on the lower point and the time was 2.4σ shorter. These differences are so small that the velocity of the impulse was not counterbalanced by any difference in intensity in favor of the lower point, but we conclude that the cerebral reflex is shorter when the stimulus is applied to a point near the hand, the movement being made with the hand on the opposite side of the body. The sensory fibres from one part of the body are most closely connected with the motor fibres to a corresponding part.

When the same stimulus was applied to two points on the arm nearly equidistant from the brain but accompanied by different sensations, the reaction-time was 10.2σ shorter on the point for which the sensation was the stronger. When it was applied to the point on the lower arm and to the point on the mid-arm giving nearly the same sensation, the times differed by only 0.6σ.

When three intensities of shock were used, the time of reaction was on the average 19.6σ shorter for a very strong shock than for a medium shock, and 9.8σ shorter for the medium shock than for the weak shock. But the physiological intensities of the shocks could not be measured. The reaction times were nearly the same for the two observers (J, 127.4σ and C, 128.3σ) when the shock was strong, but were longer for C when the shocks were very weak.

When the size of the electrode was altered the difference in the length of the reaction-time seemed due to the intensity only. The time was also nearly the same when the shock was applied from electrodes 5 cm apart, when the current was sent through the limb, and when it was sent through the entire body.

When the attention was directed alternately to the stimulus and to the movement no difference in reaction-time was found for J and C, but D's reaction-time was longer when the attention was directed to the movement, he being in the habit of attending to the stimulus. When the reaction-time is short and regular the amount and direction of the attention does not materially affect the time of reaction; but when the process is less reflex, it may be lengthened by an unusual direction of attention.

The reaction-time was shorter (J, 18.9σ, C, 14.2σ) when the shock is applied to the hand with which the movement is made than when it is applied to the other hand. This might be expected, as the movement is a natural reflex—a person will without reflection withdraw the hand when it touches a hot object. The fact is of interest in connection with the results already noticed, which show that the cerebral reflex is in general quicker when the sensory fibres stimulated are from the same part of the body as that with which the movement is made.

The reaction-time is longer when the movement is made from the shoulder, and nearly the same when it is made from the fore-arm, wrist, or finger. This shows that when the movement is made with the foot the delay may be partly due to a more difficult co-ordination in the higher centres. The reaction-time is longer with the organs of speech than with the hand, but it is the same for the right and left hands.

Sec. 3. *Reactions on Touch.*—In the case of reaction experiments with dermal stimuli the electric shock has mostly been used, as it is easy to apply the shock to different parts of the body. We have, however, seen that the physiological effects of the shock vary greatly on different parts of the body, and even at the same point they cannot be kept constant. We have found that the same objective force of blow is followed by the same subjective sensation more nearly than in the case of electrical stimulation. On different parts of the body the same blow, indeed, calls forth different sensations, the sensations being more intense when the part is hard, as over a bone. But the difference is not so great as in the case of the electric shock, and at the same point the same sensation can be given time after time and day after day. The probable error is consequently smaller than in the case of the electric shock; indeed, the variable error in our experiments on touch is much smaller than in any reaction-time experiments hitherto published.

We used various methods for applying a touch or blow, but in this abstract we need only describe the method which we find best. We allowed a hammer to fall from a fixed height, the current controlling the chronoscope being closed when the blow was given. The weight of the hammer and the height from which it fell could be altered, as also the area with which the blow was given. A blow of a given force could consequently be given time after time, and the force and area of the blow could be varied when desired. We made reactions in answer to blows on different parts of the body, the hammer weighing 30 g and falling 20 cm. The area which gave the blow was circular, 1 cm across.

The reaction-time with a blow was about 10σ shorter than with an electric shock. It was nearly the same for J and C, and about 30σ longer for D. Thus when the blow was given on the arm the reaction-time was (as the result of 600 experiments with each observer) 113.9σ for C and 114.7σ for J. When the blow was given on the thigh the time was 148.5σ for D and 121.5σ for C.

In some of the experiments we used three intensities of stimulus, the hammer weighing 15, 30, or 60 g and falling 20 cm. The blow from the 60 g weight was nearly painful on a hard part of the body, and the blow from 15 g was quite strong. There was not much difference in intensity of sensation and the decrease in reaction-time was not great. As a result of all the experiments (2400) the time was decreased 1.3σ when the weight was increased from 15 to 30 g, and was decreased 1.7σ when the weight was increased from 30 to 60 g. If, as Fechner's law assumes, the intensity of a sensation increase as the logarithm of the stimulus, the reaction-time would tend to vary inversely as the intensity of sensation.

The shortest reaction-time followed stimulation of the finger or cheek in the case of C (105.8σ for the finger and 103.1σ for the cheek). The reaction-time on stimulation of the finger was thus about 8σ shorter than on stimulation of the arm. As in the case of electrical stimulation we find that the cerebral reflex is shortened when the stimulus is applied to the opposite side of the body to a point corresponding to that with which the movement is made. The time was about 1σ shorter for the toe than for the thigh. As the average of two observers, the times for the neck and cheek were nearly the same.

The time was 7.8σ shorter when the stimulus was applied to the arm than when it was applied to the thigh. If this difference be due to the time of transmission from the lumbar to the brachial plexus, we should have a velocity of the nervous impulse in the sensory tracts of the spinal cord of about 40 m per sec. The times on the upper and lower arm and on the upper and lower thigh, respectively, were the same. In the case of the arm the time for the upper point was 0.2σ shorter for J and 0.6σ longer for C. In the case of the thigh the time for the upper point was 1.1σ longer for D, and 0.1σ shorter for C. The difference in the length of nerve traversed is not counterbalanced by a difference in intensity. Doubling the stimulus shortens the reaction by only 1.5σ, and the differences in sensation were not so great on the different points as on the same point when the stimulus was doubled. When the stimulus is applied to a point further from the brain the time of transmission in the nerve seems to be exactly counterbalanced by a shorter cerebral time, the sensory fibres from a point nearer the extremities discharging more quickly into motor fibres to the extremities.

We do not think that the velocity in the plain nerve can at the present time be determined by differences in the reaction-time. But equal difficulties are present when the motor nerve is stimulated electrically. It would seem that the velocity of the impulse in the nerve can only be measured when we are able to record its progress, perhaps by electrical or chemical changes. But we hope our work has thrown some light on the subject, especially in the case of the motor and sensory tracts of the spinal cord. We think, further, that a general survey of our experiments indicates a rate in the plain nerve much greater than that commonly accepted of 30 m per sec.

We think that the study of the reaction-time is itself important both for physiology and psychology. These sciences cannot rank co-ordinate with the physical sciences until they consist of exact measurements. Experiments on the reaction-time have been of use in the analysis of physiological and mental processes and in studying the relations of these. The reaction-time has also certain practical applications in pedagogy and medicine. Thus experiments such as these indicate important personal differences, or they may be used to locate exactly the place of disease in the nervous system.