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Editorial communications should be addressed to PROFESSOR R. S. WOODWORTH, Columbia University, New York City.

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REACTION TIME TO RETINAL STIMULATION

WITH SPECIAL REFERENCE TO THE TIME LOST IN CONDUCTION THROUGH NERVE CENTERS

BY

A. T. POFFENBERGER, JR., PH.D.

Assistant in Psychology, Columbia University.

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EDITED BY

R. S. WOODWORTH

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INTRODUCTION

SINCE the introduction of the neurone theory in 1891, and the recognition of the cell-body as nutritive in function, attention has turned from the cell-body to the synapse, or the surface of separation between neurones, for an explanation of the processes peculiar to the nerve centers. It is not the physiologist alone who seeks in the synapse the cause of the peculiarities of central function, but the psychologist also is beginning to search for an explanation of the mental processes in the modification of conductivity in the synapses. Of the physiologists, Sherrington[1] may be mentioned, the originator of the most generally accepted theory of the process taking place at the synapse. In the field of psychology probably the most notable example of the appropriation of the synapse theory as the physiological basis of the central processes, is Pillsbury's "Essentials of Psychology." In it changes in the synapse form the physiological concomitant of learning in general, of instinctive movements, habit formation, attention, association and retention. To quote from Pillsbury:

> At present the tendency is to explain all learning as due to a change at the point where two neurones come together, where the end-brush of one comes into contact with the dendrites of another. This point, as was said, has been called the synapse (p. 49). Evidently then, the most important question of nervous physiology for the psychologist is what is the nature of the synapse and its action (p. 50)? Learning, whether of new movements or of new ideas, is a process of making easier the passage of an impulse from neurone to neurone, and is fundamentally the same everywhere (p. 52).

Concerning instinctive movements he says:

> The part of the nervous system to which we must look for an explanation is the synapse, the point of connection between nerve cells (p. 240). The formation of habits is thus a process of decreasing resistance in the synapses in the different possible paths of transmission (p. 55). The change in the synapse as a result of use is the explanation of association as of habit (p. 138).

In regard to retention and recall he says:

> It is probable that the point of connection between the nervous elements involved is where the change that predisposes for return occurs (p. 133).

The changes at the synapse are expressed by physiologists and psychologists alike as modifications of conductivity, lowered resist-

[1] See Sherrington, "Integrative Action of the Nervous System," 1906.

ance, openness of paths, etc., changes which may be detected by a variation in the speed of conduction or the time lost in conduction over synapses. An eminent physiologist[2] considers it quite probable that in the same individual, under the same conditions, the time lost by the block at each synapse is about the same, and that a careful study of the differences in reaction time and of the time lost in the passage through nerve centers may help to form a conception of the amount of delay for which each synapse is responsible.

The experiment to be described is an attempt to develop a method of measuring the time lost in the transmission of an impulse through a synapse within the human nervous system, and to obtain an approximate measure of this lost time under controlled conditions. When such an estimate of the synapse time has been obtained, those theories which associate the various mental processes with a modification of synapse conduction may be put to an experimental test.

Chapters I. and II. of this study give a history of the inquiry into the speed of conduction through nerves and nerve centers, for the purpose of showing the methods used, the great variations in the results and the difficulties that have been encountered; Chapters III. and IV. outline the method and describe the apparatus used; Chapters V. and VI. consider the several preliminary problems which arise in connection with the methods adopted, but which have also a certain intrinsic interest; and Chapter VII. discusses the main problem of synapse time.

I gratefully acknowledge the help received from Professors J. McK. Cattell and R. S. Woodworth, under whose guidance the experimental work was conducted, and from Dr. E. K. Strong, Jr., research fellow in advertising, and John W. Todd, assistant in psychology, who have rendered very valuable assistance in numerous ways.

[2] See Schäfer, "Textbook of Physiol.," 609, 1900.

CHAPTER I

HISTORY OF THE INQUIRY INTO THE SPEED OF NERVE CONDUCTION

THE history of the inquiry into the speed of transmission of the nerve impulse seems to date from the very discovery of a nerve principle. The early idea of the nerve impulse as some vague and mysterious force gave rise to the conception that its speed must be comparable to that of light, or infinitely fast. Haller[1] in his "Elementa Physiologiæ," gives an account of some of these ideas and the methods of calculating the speed of nerve conduction. One reasoned that since the aorta is 2,880 million times the size of the most delicate nerve fibrils in the heart, the speed of the nerve fluid must be that many times the speed of the blood traveling through the aorta, or 57,600 million feet per second. Haller himself based his conclusions on the assumption that the speed of rhythmic movements was limited by the time required for an impulse to travel from the muscle to the brain and return. The total distance traversed and the time being known, he obtained a speed of 9,000 feet per minute.

The first real evidence against the supposed tremendous speed of nerve conduction came in 1795, from the astronomer Maskelyne, who noticed differences in the reports by different men of the same celestial occurrence. Bessel[2] found this difference to be a constant and called it the "personal equation." Nicolai[3] was probably the first to explain the personal equation by differences in the speed of the nervous process. Johannes Müller,[4] however, opposed this explanation of the personal equation as due to the differences in the speed of the nerve impulse and attributed it to purely psychological factors such as attention. In 1848 he stated that the speed of nerve conduction could never be calculated, since the speed was so great and the distances to be traversed in the human body were so short.

[1] Haller, "Elementa Physiologiæ," 4, 372, 1762.

[2] For a general review of the work on the personal equation, see E. C. Sanford, "The Personal Equation," *Am. Jour. Psych.*, 2, pp. 2, 271, 403 ff., 1888–1889.

[3] See Hermann, "Handbuch der Physiol.," 2, 16, 1879.

[4] "Handbuch der Physiol.," 1, 581, 1844.

I. Speed of Conduction in the Motor Nerves of Animals

Only about six years after this statement by Müller, Helmholtz[5] measured the speed of conduction in the sciatic nerve of the frog. He applied an electrical stimulus to the nerve at different distances from its connection with the muscle and compared the resulting differences in the time of the muscular response, with the length of nerve between the points stimulated.[6] He found an average time of 28 meters per second, with slight variations according to changes of temperature. During the next few years, other investigators confirmed these results, using the same general methods, although varying the means of recording the results. For instance, Fick,[7] in 1862 found similar results. Harless,[8] in the same year, used an adaptation of the Atwood machine, in which the falling body consisted of a smoked plate, on which the moment of stimulation and muscular contraction were directly recorded. Thiry,[9] in 1864, employed about the same methods as Helmholtz with a different means of regulating

[5] "Messungen über den zeitlichen Verlauf der Zuckung animalischer Muskeln und die Fortpflanzungsgeschwindigkeit der Reizung in den Nerven," *Archiv f. Anat. u. Physiol.*, 276–364, 1850.

[6] Helmholtz used two methods of measuring the speed of nerve conduction. The first method was an adaptation of the Pouillet'sche method of time measurement. The principle on which this method is based is that a magnet acting upon a needle will divert it a distance proportional to the time during which the current acts. The time is thus calculated from the distance the needle moves. One end of the muscle was attached to a permanent bracket, while the other was fastened to a lever in such a way that the slightest contraction of the muscle would move the lever and break the contact. The electric circuits were so arranged that when the electric stimulus was applied to the nerve, the current was sent through the magnet. As soon as the muscle contracted, this time circuit was broken and the time read off from the position of the compass needle. See Hermann, "Handb. der Physiol.," 1, 31–33, 1879.

The second method made use of Helmholtz's myograph, a detailed description of which may be found in Hermann, "Handb. der Physiol.," 1, 23 ff., 1879. The muscle was attached to a writing lever which wrote upon a revolving glass cylinder. The stimulus was given by an induction shock. A curve was recorded upon the glass cylinder when the stimulus was applied near to the muscle. It was then applied at a distance from the muscle and the second curve superposed upon the first. The distance between the beginning of each curve was then turned into a time value, from the known speed of the revolving drum. This measured the time of conduction over the stretch of nerve between the two points of stimulation. The shock was applied through a contact upon the edge of the drum, an arrangement which enabled the stimulus to be given at the same point in each revolution of the drum.

[7] "Vierteljahrschrift der Naturforschenden Gesellschaft in Zürich," 1862.

[8] *Abhand. der Bayer. Akademia der Wissenschaft*, Bd. 9, Abth. 2, 316.

[9] *Zeitschr. f. rat. Med.*, Bd. 21, 300, 1864.

the speed of his registering apparatus. According to Munk,[10] the excitation does not travel over the nerve at a constant speed. If one takes three points on a nerve fiber equally distant from each other, the speed of transmission between these points would not be the same, although the lengths of nerve would be equal. According to him, the excitation seems to take less time to travel from the upper extremity to the middle of the nerve than from the middle to the lower extremity.

Marey,[11] in 1868, by his own adaptation of the graphic method in which a revolving disc was used instead of a drum, found a speed of transmission of 11 meters per second upon electrical stimulation of the motor nerves of the frog. Lamansky,[12] by a slightly different method, found a speed of 31 meters per second. Bernstein[13] deviated from the previous methods in that he made use of the action current of nerve to register the time of reaction, instead of the contraction of muscle itself. He obtained a speed of 25 to 33 meters per second. Valentin[14] in 1870 published an experiment on frogs, in which he found a speed of nerve conduction in the gastrocnemius muscle of 14 to 20 meters per second. This result was valid only for a nerve-muscle preparation kept in very cold water. When a warmed preparation was used the speed increased to 25 to 30 meters per second. Chauveau,[15] in order to show that the results of experiments made on frogs' nerves are not applicable to mammals, made a comparative study upon the motor nerves of frogs and horses. The nerves in both cases were left in their normal position in the body. To prevent any disturbance of the results through voluntary movement, chloral was administered, or else the cord was severed at the bulb and the animal kept alive by artificial respiration. In the horse he worked upon the pneumogastric and recurrent nerves and in the frog upon the sciatic nerve. Unipolar electric stimulation was used and the results were graphically recorded. In the frog Chauveau obtained a speed of 21 meters per second, and the same method gave a speed of 65 meters in the horse. He also found individual differences in the speed of conduction varying from 40

[10] "Untersuchungen über die Leitung der Erregung im Nerven," *Archiv f. Anat. u. Physiol.*, Physiol. Abth., 798, 1860.

[11] "Du Mouvement dans les Fonctions de la Vie," 410–444, 1868.

[12] See Richet, "Physiol. des Muscles et des Nerfs," 376, 1882.

[13] See Hermann, "Handb. der Physiol.," 2, 18, 1879.

[14] "Fortpflanzungsgeschwindigkeit der Nervenerregung," *Moleschott's Untersuch.*, 10, 526 ff., 1870.

[15] "Vitesse de Propagation des Excitations dans le moteurs Nerfs des Muscles de la Vie animale, chez les Animaux mammiferes," *Compt. rend. Acad. de Sc. Par.*, 87, 95–99, 138–142, 1878.

to 75 meters per second. Two further conclusions were drawn from his work: (1) If one increases the distance which separates the muscle from the point stimulated, the time taken for the conduction of the excitation increases less rapidly than the length of fiber traversed. (2) The excitations travel less rapidly as they approach the terminations of the nerve, that is, the conductivity decreases from the origin toward the termination of the nerve.

In 1880, Fredericq and Vandevelde[16] experimented upon the motor nerves of the lobster, using the graphic method of Helmholtz, and found an average speed of 6 to 12 meters per second. Ott,[17] in a study upon the "Rapidity of Transmission of Nerve Force in Normal and Stretched Nerves," obtained in the motor nerves of the frog, a speed ranging from 20 to 30 meters per second. His results showed that stretching a nerve lowered the speed at which it conducts impulses. Englemann[18] reported the speed of conduction in the nerves of the frog, upon mechanical stimulation at different points, to be 22.5 meters per second. He considers the differences found by other experimenters to be due to the condition of the nerve rather than to external conditions such as temperature and the like. By adopting certain refinements in method he was able to apply an electrical stimulus to points on a nerve only a short distance apart without spreading of the current. He concludes that the speed of conduction is the same in all parts of the nerve, except perhaps very near to its central and peripheral connections, and that the speed does not change upon a continued maximal stimulation.[19]

II. Speed of Conduction in the Motor Nerves of Man

Helmholtz and Baxt[20] applied the methods used by Helmholtz on frogs, to determine the speed of conduction in the motor nerves of man. By stimulating the median nerve near the wrist and in the upper arm, and recording the resulting contractions of the muscles of the thumb, they obtained an average speed of 34 meters per second. From their experiments they concluded that the speed of conduction varies in different parts of the same nerve. Thus the speed in the nerve in the upper arm was thought to be slower than that in the nerve in the forearm. Place,[21] by the same methods as those used by Helmholtz and Baxt, found very definite differences in different parts of the median nerve. For the forearm he obtained a speed of 62 meters per second and for the upper arm 17 to 24 meters per second. Later experiments by Helmholtz and Baxt gave higher values for the speed of nerve conduction, 65 meters per second, and contrary to their earlier conclusions and those of Place, showed that conduction was slower in the lower part of the median nerve than in the upper part. Oehl,[22] somewhat after the manner of Helmholtz, stimulated the radial nerve in the armpit and on the inner side of the index finger. He measured the resulting contractions of the finger and found the average time of conduction for the normal body temperature[23] to be about 30 meters per second. Alcock,[24] in 1895, performed an experiment on "The Rapidity of the Nervous Impulse in Tall and Short Individuals." By means of a writing lever pneumatically controlled, he measured the time between the twitches of the finger when the median nerve was stimulated at the shoulder and near the elbow. He obtained an average speed of 66.8 meters per second. He found that the size of the body had no influence on the speed of the nerve impulse. Since, therefore, the rate of transmission of an impulse is the same in all individuals, the time required for an impulse to traverse the limbs of a tall man is appreciably longer than in the case of a short man. Hermann[25] gives an average speed of 40 meters per second for the motor nerves of man.

Von Wittich[26] applied the reaction time method to the study of conduction in the motor nerves of man, and although his method differed greatly from that employed by the other experimenters, the results were about the same. He stimulated a certain point on the surface of the body and required a reaction by muscles located at different distances from the brain. He assumed that the sensory and central processes would remain the same, and that the resulting

[16] "Vitesse de Transmission de L'excitation motrice dans les Nerfs du Homard," *Compt. rend. Acad. d. Sc. Par.*, **91**, 239, 1880.

[17] *J. Nervous and Mental Disease*, **5**, 94–98, 1878.

[18] "Graphische Untersuchungen über die Fortpflanzungsgeschwindigkeit der Nervenerregung," *Archiv f. Anat. u. Physiol.*, s. 1, 1901.

[19] For the relation of the speed of nerve conduction to the intensity of the stimulus, and for references to work on the subject, see Von Wittich, *Pflüger's Archiv*, **2**, 329, 1869. Hermann, "Handbuch der Physiol.," **2**, 24, 1879. Nicolai, *Arch. f. Anat. u. Physiol.*, Suppl., 367, 1905.

[20] *Monatsber. der Berliner Acad.*, 228, 1867; 184, 1870.

[21] "Uber die Fortpflanzungsgeschwindigkeit des Reizes in den motorischen Nerven des Menschen," *Pflüger's Archiv*, **3**, 424 ff., 1870.

[22] "Nouvelles experiences touchant l'Influence de la Chaleur sur la Velocite de Transmission du Mouvement nerveux chez l'Homme," *Arch. ital. de Biologie*, t. **24**, 231, 1895.

[23] For the influence of temperature on the speed of nerve conduction and a bibliography, see Hermann, "Handbuch der Physiol.," **2**, 23 ff., 1879; and Oehl, *Arch. ital. de Biologie*, t. **24**, 231 ff., 1895.

[24] *Proceedings of the Royal Society of London*, **72**, 414–418, 1903.

[25] "Lehrbuch der Physiol.," s. 218.

[26] *Zeitschr. f. rat. Med.*, **31**, 106, 1868.

differences in time would be due to the differences in length of motor nerve traversed. He thus found an average speed of 30 meters per second.

III. Speed of Conduction in Sensory Nerves

Helmholtz[27] was the first to calculate the speed of conduction in the sensory nerves of man, by means of what was later called the "reaction time" method. Points on the skin at different distances from the brain were stimulated and as soon as the stimulus was felt, the subject reacted by breaking an electric circuit. The total reaction time included the latent time of the sensory end organ, the time required for the excitation to reach the brain, to pass through the brain centers, to travel over the motor nerve, and the latent time of the contracting muscle. Helmholtz assumed that all the factors except the length of the sensory nerve remained the same, hence the difference in time resulting from the stimulation at different points must be the time required for the stimulus to pass over the additional length of sensory nerve, included between these two points. By this means he found a speed of 60 meters per second.

Upon this same assumption and with methods varying only in the recording apparatus, the experiment has been repeated by many investigators with widely divergent results. Hirsch,[28] in 1861 using the Hipp chronoscope and applying his stimuli to the hand and foot, found a speed of about 34 meters per second. To the objection that the two paths could not be compared on account of the different lengths of spinal cord traversed, he replied that the speed of conduction was the same for white matter wherever found, and that the amount of gray matter was the same in both cases. Schelski[29] used the graphic method of recording his results and stimulated electrically the groin and the foot, thereby making the length of cord traversed equal in both cases. In this way he obtained an average speed of 94 meters per second. De Jaager,[30] using the same graphic method and the same points of stimulation as Schelski, found an average speed of 26 meters per second. Von Wittich[31] employed the graphic method and stimulated a great many points on

[27] See Hermann, "Handbuch der Physiol.," **2**, 18, 1879.

[28] "Chronoscopische Versuche über die Geschwindigkeit der verschiedenen Sinneseindrücke und der Nerven-Leitung," *Moleschotts Untersuch.*, **9**, 183, 1865.

[29] "Neue Messungen der Fortpflanzungsgeschwindigkeit des Reizes in den menschlichen Nerven," *Archiv f. Anat. u. Physiol.*, 151, 1864.

[30] See Hermann, "Handbuch der Physiol.," **2**, 20, 1879.

[31] "Uber die Fortleitungsgeschwindigkeit in menschlichen Nerven," *Zeitschr. f. rat. Med.*, **31**, 87 ff., 1868.

the skin at different distances from the brain, requiring a reaction by the hand. He found an average speed of 39 meters per second.

Marey[32] calculated the speed of conduction in the sensory nerves of the frog by means of reflex action. He cut the cord above the sciatic center and then stimulated the sensory nerve at different points and observed the differences in the latent time of the contraction of the opposite leg. In every case he obtained a speed greater than 30 meters per second. He injected strychnin into the frog and took his observations before tetanus set in, in order that the heightened irritability would bring about contractions of the opposite leg, that is, reflex contractions. The leg stimulated was bound so as to be immovable. Marey attributed the high speed obtained to the injection of the strychnin. In certain experiments[33] performed on himself according to the method of Helmholtz, he obtained a speed of 30 meters per second. Richet[34] criticized all the methods of finding the speed of conduction in the sensory nerves, which included in the paths used, various lengths of spinal cord. He selected for his own work two points on the arm, one at the shoulder and the other at the finger tips. From stimulation of these points he calculated a speed of 50 meters per second.

Bloch[35] devised an experiment by which the speed in the sensory nerves could be calculated independently of the motor nerves. He first showed that the method used by Schelski and others, of stimulating points at different distances from the brain and observing the resulting voluntary reactions, was invalid. He found that stimulating the finger brought forth a quicker reaction than stimulating the cheek, also that the general position of the body has an influence upon the speed of reaction. He attributed these differences not only to variation in the sensibility of the part stimulated, but also to differences in the speed of the volitional process. Thus an impulse from the hand could be more quickly transformed into a motor response than one from any other part of the body. His conclusion was that the speed of the sensory nerve current can not be studied when volition is a part of the process employed; also that when the sensibility of the parts is the same and the strength of the stimulus is uniform, the persistence of the sensation in consciousness is the same. By stimulating points at different distances from the brain, he found that the greater the distance between the points stimulated,

[32] "Du Mouvement dans les Fonctions de la Vie," 410–444, 1868.

[33] "La Machine animale," 43, 1873.

[34] "Physiologie des Muscles et des Nerfs," 583, 1882.

[35] "Experiences sur la Vitesse du Courant nerveux sensitif chez L'Homme," *Archiv de Physiol., norm. et path.*, 588–623, 1875.

the greater was the difference in the time of the appearance of the sensation in consciousness. He then timed the application of his stimuli in such a way that the two stimuli should be perceived at the same time, that is, that the two sensations should fuse. In order that this might take place, the point farther from the brain would have to be stimulated earlier than the nearer point. This time interval he considered to be due to the difference in the length of sensory nerve traversed. His results thus obtained were 192 meters per second in the nerves and 194 meters per second in the spinal cord. His method was based on the assumption that the fusion of two sensations in consciousness depends only upon the time of their arrival in the center and not at all upon their points of origin. His figures, however, suggest that the time of the appearance of a sensation in consciousness may vary according to the part of the body stimulated.

Hall and Kries,[36] in 1879, published an experiment on the "Dependence of Reaction Time upon the Place of Stimulation," and concluded that the central or reduced reaction time varies with the place stimulated, and that such variation is due not to a difference in the sensitivity of the parts (as shown by the fact that the reaction to a stimulus on the tongue is slower than to one on the forehead, although the former is about 20 times more sensitive), but it is due rather to the relative use or exercise of the parts. For instance, the reaction to a stimulus on the finger tips is faster than to one on the upper arm, although the distance traversed by the impulse is greater in the former case. Also the reaction to a light stimulus falling on the fovea centralis or the point of clearest vision, is more rapid than to one falling on the periphery of the retina. These differences in time the authors believed to be the result of differences in the speed of the central processes, which are faster for the finger and the center of vision. The speed of sensory conduction was for one subject found to be 214 meters per second, and for the other a negative value was obtained, that is, the point farther from the brain gave the quicker reaction. They concluded from their experiments that the speed of the central processes controlling movement increases with use, so that the speed of conduction in motor nerves calculated from the reaction by different members of the body is invalid. The speed of transmission in the cord, therefore, based on these erroneous figures, would be unreliable.

Hermann[37] concludes from the physiological identity of motor and sensory nerves, that the speed of conduction is the same in both

[36] *Archiv f. Anat. u. Physiol.*, Suppl., 1–10, 1879.

[37] "Handbuch der Physiol.," 2, 23, 1879.

and that the apparent difference is due to the difference in the intensity of the stimuli used. Oehl, Fasola and Predigeri[38] used the reaction time experiment and stimulated points at different distances from the brain. They obtained an average speed for sensory nerves of 32 meters per second.

IV. More Recent Methods and Results

Reichert,[39] in 1888, experimented upon the nerves of rabbits in order to determine whether the nerve impulses travel at a rate directly proportional to the length of the fiber. This law holds for the nerve muscle preparation but it has been suggested that a different condition exists in the intact nerve and cord. Reichert experimented upon living animals, and in order to prevent volitional movements, the spinal cord was cut in the lower dorsal region. The stimulus was an induction shock applied to the nerve near its entrance into the muscle and at the pelvis. An independent electric circuit was so arranged that contraction of the muscle broke a metal contact, and this break in the circuit was recorded on a kymograph along with the stimulus and time record. An average of all his experiments gives a rate of transmission of 185 meters per second. In ten out of nineteen experiments the time required for the transmission of the impulse was longer by about 6.5 sigma when the point nearer the muscle was stimulated, than when a farther point was stimulated. These results are in accord with those of Munk and Chauveau, who found that the speed of conduction was reduced as the nerve termination is approached.

In 1893 Cattell and Dolley[40] made an extended research to determine the conditions which affect the length of reactions to dermal stimuli and to study the application of the reaction time experiment to the measurement of the velocity of the nervous impulse in motor and sensory nerves and in motor and sensory tracts of the cord. They employed electrical and tactile stimuli at points on the arm and leg over the median and posterior tibial nerve respectively. With electrical stimulation, the speed of conduction in the median nerve was for one subject 21 meters per second, and for the other 49 meters per second; in the tibial nerve 31 meters per second for the one subject and 65 meters per second for the other.

[38] "Sur la Velocité de Transmission de L'excitation dans les Fibres sensitive de L'homme," *Arch. ital. de Biologie*, 17, 400, 1892.

[39] "The Velocity of Nerve Impulses in Cut and Intact Nerves," *Jour. of Nervous and Mental Disease*, May, 1889.

[40] "On Reaction Times and the Velocity of the Nervous Impulse," *Memoirs of the Nat. Acad. of Sciences*, 7, 393 ff., 1893; *Psych. Rev.*, 1, 159, 1894.

When the stimulus was applied to the arm, the reaction by the foot was for *A*, 37.7 sigma, and for *B* 54.4 sigma slower than by the hand. When the stimulus was applied to the lower leg, reaction by the foot was for *A* only 29.7 and for *B* 45.0 sigma slower than by the hand. This means that when the stimulus is applied to the reacting member the time is shorter by 8.0 sigma for *A* and by 9.4 sigma for *B*, than when another member reacts. This difference may be attributed to the delay of coordination in the brain centers. The following figures give these results in tabular form:

Subject	Reaction	Stim. on Arm	Stim. on Leg	Diff.
A	By hand	163.8	190.7	
	By foot	201.5	220.4	
	Difference	37.7	29.7	*8.0*
B	By hand	119.2	147.3	
	By foot	173.6	192.3	
	Difference	54.4	45.0	*9.4*

On account of certain difficulties in the use of the electrical stimulus, a tactual stimulus was employed in later experiments. By this means the times for the upper and lower arm and upper and lower leg were practically the same. In one subject the reaction time upon stimulation of the finger was shorter than when the arm was stimulated, and somewhat shorter for the toe than for the thigh. These differences must clearly be due to the differences in the time of the cerebral reflex. The conclusions of Cattell and Dolley were as follows:

1. It does not follow that electrical stimulation of the excised and dying nerve of the frog produces the same effects as the cerebral discharge in the living animal, nor that these effects would hold for man.

2. The velocity of the normal nerve impulse can never be determined by electrical stimulation, owing to the great variety of results, which must be due to the methods of stimulation and not to the velocity of the normal impulse.

3. The chief difficulty in measuring the velocity of the sensory impulse is not the variable error of the cerebral reflex, but the fact that the same physical stimulus applied to different parts of the body produces physiological effects varying in intensity and cerebral discharges varying in facility.

4. The differences in the reaction time which occur in different individuals and in the same individual at different times are due, not to the differences in the length of nerve traversed, but to differences in the speed of the cerebral process. The reaction times for points nearer to the brain than others may be shorter because the physical effects of the shock may be greater or because the fibers from the upper points may lead to a more rapid transference in the brain.

5. The velocity of the nerve impulse is greater than that commonly supposed, 30 meters per second, and probably one half of the total time is taken up in the cerebral processes.[41]

DuBois Reymond[42] in 1900 published a paper on the speed of transmission of the nerve impulse in different parts of the nerve. He used the most approved and careful methods of stimulation and of recording the results. All of his work was done on the nerve muscle preparation of the frog. Three different parts of the nerve were selected and an average of seven series of experiments upon each region gave the following differences for stimulation of the limiting points of each region, 9.2, 9.4, and 9.2 sigma. He found that the greater the number of experiments the nearer the averages for the different parts of the nerve approached each other. He therefore concluded that the differences found in previous researches were due to irregularities in the methods and to insufficient data.

Kiesow[43] in 1903 devised a method of stimulating various points on the skin to avoid the possible influence of a difference of intensity upon the time of reaction. He marked out different touch spots on the arm and leg and tested these for their sensitivity. He then stimulated them by an electrically controlled touch hair, thereby making the physical stimulus uniform. The spots used in each experiment were on the same member and were of the same degree of sensitivity. He assumed that the cerebral processes would be equally rapid in such cases, and that the differences in reaction time would be due to the difference in the length of the sensory nerve traversed. His results showed a speed in the arm of 31 meters per second, and in the leg, 33 meters per second. He compared these figures with those of Helmholtz and Baxt and concluded that no distinction can be claimed between the speed in motor and sensory nerves of man

[41] "The Time taken up by the Cerebral Operations," *Mind*, London, **11**, 220–242, 1886.

[42] "Über die Geschwindigkeit des Nervenprincips," *Archiv f. Anat. u. Physiol.*, Physiol. Abth., Suppl., 68, 1900.

[43] "Zur Frage nach der Fortpflanzungsgeschwindigkeit der Erregung im sensiblen Nerven des Menschen," *Ztschr. f. Psychol. u. Physiol. des Sinnesorgane*, **33**, 444 ff., 1903.

Nicolai[44] experimented on the olfactory nerve of the pike and found no difference in the rate of transmission in different parts of the nerve. He also found that within the nerve trunk conduction was equally rapid in either direction.

The most recent work on nerve conduction is that on the motor nerves of man, by Piper[45] in 1908, who followed the method used by Helmholtz except in the manner of recording the results. Two points were selected for stimulation, one in the armpit and the other near the elbow, both being directly over the median nerve, and about 16 centimeters apart. An induced current was used for stimulation and the indifferent electrode was placed on the back of the subject. The time of the muscular response was not measured by its contraction, but by the production of the action current in the muscle. The muscle was connected to an Edelmann string galvanometer by means of electrodes placed upon the skin over the muscle. The movements of the galvanometer, together with a time record, were reflected upon a screen and photographed.[46] The galvanometer curve showed not only the beginning of the action current, but also the moment of stimulation, since a part of the stimulating current was conducted into the galvanometer circuit and caused a break in the curve, quite different from that produced by the action current. By these measurements he found the time interval greater, the nearer to its central end the nerve was stimulated. The average time lost in conduction over the 16 centimeters of nerve fiber was 1.36 sigma, giving a speed of 117 to 125 meters per second. By calculating the time of transmission from the lowest point stimulated to the muscle, a distance of 10 centimeters, according to these figures and subtracting the result from the measured time, he found the latent time of the muscle and the nerve end organs to be 3.6 sigma. Piper considers it proved that the speed of conduction is the same in all parts of the nerve, in agreement with the previously cited experiments of DuBois Reymond and Englemann on the sciatic nerve of the frog and of Nicolai on the olfactory nerve of the pike.

This review shows, in general, the methods employed in the study of the speed of nerve conduction, their defects and the discordant results obtained by the different experimenters; it shows that natural stimuli should be used on nerves normally situated in the body, and that the great drawback in the determination of the speed of sensory conduction is the lack of knowledge of the cerebral processes involved, where such a large proportion of the time is consumed; it shows also that the early attempts to find the time consumed in the cerebral processes, or the reduced reaction time, by eliminating from the total time, the other factors such as the motor and sensory time, the latent time of the sense organs, etc., are invalid, since these very factors have not been reliably determined.

[44] "Über Ungleichförmigkeiten in der Fortpflanzungsgeschwindigkeit des Nervenprincips nach Untersuchungen am marklosen Riechnerven des Hechtes," *Archiv f. Anat. u. Physiol.*, Suppl., 341 ff., 1905.

[45] "Über die Leitungsgeschwindigkeit in den markhaltigen, menschlichen Nerven," *Pflüger's Archiv*, 124, 591 ff., 1908.

[46] For a detailed description of his method, see Piper, "Über den willkürlichen Muskeltetanus," *Pflüger's Archiv*, 119, 317 ff., 1907.

CHAPTER II

SPEED OF CONDUCTION THROUGH NERVE CENTERS

NUMEROUS attempts have been made to estimate the speed of conduction through nerve centers, especially those in the brain, by subtracting, from the total reaction time, the time spent in peripheral conduction, and by comparing the simple reaction time with the time for a more complicated reaction, *e. g.*, that involving choice or association. Thus the time spent in a choice reaction in addition to that of the simple reaction was assumed to be the time necessary for the particular mental process involved in choice. Only those experiments are of interest here, which attempt to calculate the speed of conduction through some definite center in the brain or cord. However a case worked out by Exner[1] may be mentioned, in which he found the reduced reaction time for a simple psychic process to be 8 sigma. Donders also found the central time for a choice reaction to be from 30 to 140 sigma. The conduction paths involved in such complex psychic processes are unknown and therefore the time lost can not be attributed to a particular center. In this study the conscious factors of a reaction will not be taken into account, for it is no longer considered necessary to analyze reaction times into the perception of the impression, its apperception, and the volitional release of the motor response. The process is probably an acquired cerebral reflex, which may be accompanied or followed by consciousness. The perception and apperception probably take place after the discharge of the motor impulse. The volitional process consists in preparing the motor impulse, which is reflexly discharged.[2]

I. ANATOMICAL CHARACTERISTICS OF NERVE CENTERS

Anatomically, the brain is made up of the same elements as the peripheral system of nerves, but it is infinitely more complex. It consists of centers or collections of nerve cells and bundles of fibers coursing in various directions and connecting different centers. The bundles of fibers make up the white matter of the brain and are quite similar to the peripheral nerves, the difference being that in

[1] See Schäfer, "Textbook of Physiol.," **2**, 612, 1900.

[2] See Cattell and Dolley, "On Reaction Times and the Velocity of the Nervous Impulse," *Memoirs of the Nat. Acad. of Sciences*, **7**, 394, 1893.

the former the sheets of connective tissue and the primitive sheath are absent. The centers, or the gray matter, consists of nerve cells, their dendrites, terminations of axons and the neuroglia. The last is not considered as nerve tissue and its function is to support and form a framework for the more delicate nerve structure.[3]

Before the introduction of the neurone theory, the cell body was considered the nerve unit and the probable seat of the psychic processes. Gerlach in 1870 formulated the "nerve net" theory, that the dendrites and other cell branches are connected into a dense and continuous mass in the gray matter. But during the next 20 years the use of stains and additional microscopical work laid the foundation for the neurone theory, according to which the cell, with dendrites and axon, forming one neurone, is the unit. The cell, treated with the Nissl stain, showed a multitude of small granules of various shapes, in addition to the nucleus. Certain conditions such as extreme fatigue, poisoning and the like, changed the appearance of these granules or caused them to disappear entirely. The stain used by Bethe and others shows numerous fibrils passing through the cell, and in the case of the vertebrate brain and cord, these fibrils pass from axon to dendrites (of the same cell) without interruption. These facts, along with the evidence from the Golgi stain and from degeneration of the axone after its section from the cell-body, suggest that the cell-body is merely the store-house from which the neurone receives its nourishment and that conduction is independent of it. In certain of the invertebrates the motor neurones are unipolar, the dendrites and axons being continuous, and connected to the cell-body by only a single thread. Bethe,[4] in an experiment on the crab, destroyed the cell-bodies collected at the outside of each ganglion and found that conduction over the neurone was not disturbed, until the nerves degenerated through lack of nourishment. He thus found positive proof that the normal activity of a ganglion can occur without the presence of the cell-body. He is supported in his conclusion by the experiments of Steinach[5] and Langley[6] on the spinal root ganglia, and by those of Exner,[7] and

[3] For a discussion of the neuroglia and references to works on the subject, see Ladd and Woodworth, "Physiol. Psych.," 144 ff., 1911.

[4] "Das Centralnervensystem von Carcinus Maenas," *Archiv f. Mikroscop. Anat.*, L., 629 ff., 1897.

[5] "Über die centripetale Erregungsleitung im Bereiche des Spinalganglions," *Pflüger's Archiv*, **78**, 291–314, 1899.

[6] "On the Stimulation and Paralysis of Nerve Cells and of Nerve Endings," *Journ. of Physiol.*, **27**, 224–236, 1901.

[7] "In welches Weise tritt die negative Schwankung durch das Spinal Ganglion?" *Archiv f. Anat. u. Physiol.*, 567–570, 1877.

Moore and Reynolds,[8] who found no delay in transmission through the spinal root ganglia, a delay which is characteristic of central conduction.

The nerve-cell branches in the centers are continuous with the nerve trunks in the periphery and differ from them only in size. It does not seem likely that conduction over them should be so different from that in nerve trunks as to account for the peculiarities of central conduction.

Therefore the only anatomical structures which exist in a center in addition to those found in a nerve fiber, are the surfaces of separation between neurones. Since no "reflex arc" is composed of less than two neurones, there must be at least one surface of separation in every center. Thus from a histological point of view, the "synapse,"[9] or surface of separation between neurones, becomes the critical point in the study of the cerebral processes.

II. Physiological Characteristics of Nerve Centers

Functionally, the cerebral process is essentially one of conduction, and certain definite differences[10] obtain between conduction in the centers and in the peripheral nerves, while many other differences seem to apply only to special cases. Those most generally recognized are: (1) Slower Speed of Conduction, (2) Irreversibility of Direction of Conduction, (3) Fatiguability of Centers, (4) Resistance to the Passage of a Single Impulse, Lessened by a Succession of Stimuli, (5) Great Variability of the Threshold Value of Stimuli, (6) Refractory Period, (7) Slight Dependence of Effect upon the Strength of the Stimulus, (8) Greater Susceptibility to Changes of Chemical Environment. These differences can be best accounted for by the existence of synapses in the nerve paths. Whatever the nature of the nerve process may be, these surfaces of separation would produce just such changes in conductivity as have been found.

[8] "The Rate of Transmission of Nerve Impulses through the Spinal Ganglia," *Physiol. Centralb.*, 12, 501, 1898.

[9] This term was first applied to the surfaces of separation by Foster, "Textbook of Physiol.," Pt. 3, 929, 1897.

[10] For a detailed description of these differences between central and peripheral conduction and their relation to the properties of the synapse, see Sherrington, "Integrative Action of the Nervous System," 14 ff., 1906. See also Bethe, "Die Theorie der Centrenfunktion," *Ergebnisse der Physiol.*, 5, 250 ff., 1905.

III. Theories of the Process Occurring at the Synapse

Two general theories have been advanced in explanation of the process occurring at the synapse, the mechanical theory and the physico-chemical theory. Of the first may be mentioned the contact theory proposed by Duval[11] and Rabl-Ruckhard.[12] This theory supposes a certain motility in the nerve fibrils, which may by retraction interfere with conduction and produce sleep, narcosis and the like, and by protraction, facilitate conduction and cause states of excitement, etc. Grounds for the theory were found in the similarity of nerve cells with their dendrites to amœba with their pseudopods; and in the appearance of neurones stained by the Golgi method. The nerve centers of animals killed while asleep were compared with those of animals killed while awake, and in certain cases, the synapses, or breaks between the neurones, of the former were larger than those of the latter. Closer study, however, showed these differences to be the result of defective staining.

This mechanical theory has been succeeded by the physico-chemical theory of Sherrington. Instead of explaining the peculiarities of centers by motility of the nerve fibrils, he assumes surfaces of separation which must exist between two cells not in actual physical continuity. Sherrington says:[13]

> Even should a membrane visible to the microscope not appear, the mere fact of the non-confluence of the one with the other implies the existence of a surface of separation. Such a surface might restrain diffusion, bank up osmotic pressure, restrict the movement of ions, accumulate electric changes, support a double electric layer, alter in shape and surface tension with changes in difference of potential, alter in difference of potential with changes in surface tension or in shape, or intervene as a membrane between dilute solutions of electrolytes of different concentration or colloidal suspensions with different sign of charge. It would be a mechanism where nervous conduction, especially if predominantly physical in nature, might have grafted upon it characters just such as those differentiating reflex arc conduction from nerve trunk conduction. For instance, change from reversibility of direction of conduction to irreversibility might be referable to the membrane possessing irreciprocal permeability. It would be natural to find in the arc, each time it passed through gray matter, the additive introduction of features of reaction such as characterize a neurone threshold.

Schäfer,[14] in speaking of reaction time, says:

> There is every reason to believe that the additional delay which is characteristic of the passage of nervous impulses through nerve centers, is due to a block

[11] "Hypotheses sur la Physiol. des Centres nerveux," *Compt. rend. de la Soc. de Biologie*, 74, 1895.

[12] "Sind die Ganglionzellen Amoeboid?" *Neurolog. Zentralbl.*, 199, 1890.

[13] "Integrative Action of the Nervous System," 17 ff., 1906.

[14] "Textbook of Physiol.," 2, 607, 1900.

at each synapse; that in fact the nervous impulses are momentarily arrested at these places of contact of the nerve cells with one another. And it is not improbable that the relative number of these blocks will furnish a key to the differences which are found to obtain in the reaction for different reflexes and psychic processes. The differences of reaction time are too great to be accounted for simply by the fact that the nervous impulses are sent along paths of different length in the various cases; it is more probable that they pass through an increasing number of nerve units, according to the increased complexity of the processes involved. And this, according to the theory of isolated units, would mean the passage across as many synapses, which are the parts of the nerve chain where relative blocks occur.

He considers it quite probable that in the same individual, under the same conditions, the time lost by the block at each synapse is about the same; and further, that, "a careful study of the differences in reaction time and of the lost time in the passage through nerve centers may help to form a conception of the amount of delay which each synapse is responsible for."[15]

IV. Experiments on the Speed of Conduction through Centers

Certain attempts have been made to determine the time consumed in crossing one synapse. Wundt[16] found the time lost in the lower part of the frog's cord, when the stimulation of the posterior root caused a contraction of the gastrocnemius muscle of the same side, to be 8 sigma. For a crossed reflex, that is, the reaction by the leg on the side opposite to where the stimulus is applied, the lost time was 12 sigma. Assuming that the crossed reflex involves one additional synapse, its lost time would be 4 sigma, and if there were two, the time would be only 2 sigma for each synapse. In the same way, the simple reflex, having a lost time of 8 sigma, would involve either two or four synapses. The time lost between the excitation of the cortex of the frog and the response of the gastrocnemius muscle, in addition to the time required for the impulse to travel over the motor nerve, was found by Exner[17] to be 50 sigma. The difference in lost time between the stimulation of the cortex of the frog and stimulation of the medulla, and the muscular response to each, was found by Langendorff and Krawsoff[18] to be 20 sigma. Comparing

[15] *Loc. cit.*, 609.

[16] "Untersuchungen zur Mechanik der Nerven und Nervencentren," 1876, Abth. 2, Stuttgart. See also "Physiol. Psychol.," **1**, 266, 1893.

[17] "Experimental Untersuchungen der einfachsten psychischen Processe," *Pflüger's Archiv*, **8**, 532, 1874.

[18] The difference in time between the stimulation of the cortex and stimulation of the nerve was 36 sigma; the difference in time betwen stimulation of the medulla and stimulation of the nerve was 17 sigma. The difference between the two, about 20 sigma, was taken as the time lost in the cerebrum. "Zur elektrischen Reizung des Froschgehirns," *Archiv f. Anat. u. Physiol.*, 90–93, 1879.

this with the result of Exner, the time lost in the cerebrum proper would be 20 sigma and the time lost in the medulla would be 30 sigma. Other investigators[19] have obtained practically the same results on the frog. The response of the electrical organ of the *Malapterurus* to stimulation of its afferent nerve was studied in the living specimen by Gotch and Burch,[20] who found it to have a lost central time of 8 sigma. This would be the time required for the impulse to pass over the one synapse involved. Wilson[21] found a lost time in the optic lobes of the frog of 15 to 20 sigma. Sherrington[22] calculated the lost time in the flexion reflex of the spinal dog. Assuming the reflex arc to be two thirds of a meter in length, and allowing 5 sigma for the latent time of the muscle, if there were no retardation in the nerve center, the latent time should be 27 sigma. But he found the actual time with weak stimuli to be about twice that amount, or nearly 60 sigma. This would give a lost time in the center of about 30 sigma. But with strong stimuli this time is considerably reduced, so that a total latent time of 30 sigma has been obtained for the flexion reflex. This would give a lost time of about 3 sigma in the center, when the speed of conduction in plain nerve is taken at 30 meters per second. Assuming that there is one synapse in the arc, its time would then be 3 sigma. Sherrington concluded that the stronger the stimulus, the more nearly conduction along a reflex arc resembles conduction over a simple nerve trunk.

Much work has been done on the latent time of the knee jerk, but there is no agreement as to whether it is a true reflex or a direct reaction to mechanical stimulation of the muscles. The latent times found have varied from 25 to 75 sigma in man, which would average about the same as the winking reflex, or 50 sigma. Howell[23] quotes figures for the knee jerk in the dog with its spinal cord severed, 14 to 20 sigma, and in the case of the rabbit of 5 to 8 sigma. These latter figures seem to him too low for reflex time, as just about that much time would be required for conduction over the nerve fiber included in the reflex arc.

According to Wundt,[24] the reflex time increases as the cord de-

[19] Bubnoff and Haidenhain, *Pflüger's Archiv*, **26**, 1881. Novi and Grandi, "Rivi sper. di freniat.," Reggio-Emilia, 13, 1888.

[20] See Schäfer, "Textbook of Physiol.," **2**, 589, 1900.

[21] "Note on the Time Relations of Stimulation of the Optic Lobes of the Frog," *Journ. of Physiol.*, **11**, 504, 1890.

[22] "Integrative Action of the Nervous System," 19, 1906.

[23] "Textbook of Physiol.," 149 ff., 1908.

[24] *Physiol. Psychol.*, **2**, 314 f., 1893.

velops in complexity. Thus in man a simple reflex with the response on the same side of the cord as the stimulus, requires an average time of 35 sigma. From this he concludes that the processes in the brain consume a much greater time than the spinal reflexes. The results of Exner[25] on the winking reflex are generally quoted as the reflex time for man. He stimulated one eyelid electrically and recorded the reaction of the other eye. The total reaction time was 57.8 to 66.2 sigma. He calculated that the time consumed in sensory and motor conduction and in the latent time of the muscles was 10.7 sigma. Thus the central time would be 47.1 to 55.5 sigma. The time of the winking reflex has been more elaborately determined by Mayhew[26] to be 42.0 sigma. Deducting the peripheral time as given by Exner, the central time would be 31.3 sigma.

Schäfer[27] considers as unsatisfactory, the explanation of the difference between the reaction time of the eye and ear, as being due to the chemical processes in the retina. This process should not be longer than that occurring in the muscles, also a chemical process, and requiring about 2.5 sigma. The remaining difference of about 40 sigma he believes to be due to the greater number of synapses in the nerve chain connecting the retina with the cortex. There are at least two synapses in the retina, while in the cochlea there are none. The first synapse in the auditory path occurs in the medulla oblongata.

To draw a general conclusion from the work done on the question of the time consumed in the passage of an impulse through a synapse, it may be said that such a loss is generally recognized, that the time is highly variable, influenced by the intensity of the stimulus, by practise and by many drugs and stimulants; but under normal circumstances with moderate stimuli, the time may vary in the neighborhood of from 4 to 10 sigma. Schäfer and others consider it quite possible to obtain some idea of this time by careful reaction time experiments applied to appropriate conduction paths.

It is the purpose of the present experiment to compare the reaction time over two conduction paths, identical except that the one path must cross from one side of the brain or cord to the other. Such a crossing would involve one additional neurone, and that is equivalent to saying that one additional synapse, at least, must be traversed. After the elimination of all other disturbing factors, any difference in time may be attributed to the delay in the passage of the impulse through the synapse.

[25] "Über Reflexzeit und Rückenmarksleitung," *Pflüger's Archiv*, 8, 531, 1874.

[26] "On the Time of Reflex Winking," *Journ. of Exp. Medicine*, 2, 35–48, 1897.

[27] "Textbook of Physiol.," 2, 611, 1900.

CHAPTER III

ANALYSIS OF CONDUCTION PATHS

THE extreme complexity of the nervous system, and especially of the nerve centers in the higher animals, makes a study of the time lost in conduction through a synapse seem rather hypothetical. The histological investigation of the human cortex has been only recently undertaken and the results are few and uncertain. Some centers and the association paths connecting them have been definitely traced by the various experimental methods. But the complex structure of a center, or to speak in terms of the neurone, the number of neurones interposed in any center, is yet unknown. Every center contains at least one synapse, and it is quite probable that, in some centers at least, a single synapse becomes a whole system of synapses. But even under these uncertain conditions, it seems worth while to attempt to find a normal time value for the process occurring at the synapses in human beings.

I. CONDUCTION PATHS

The present experiment consists of the reaction, by either the right or the left hand, to visual stimuli upon the center of vision and at various distances toward the periphery of the retina. The conduction paths which are involved in such a reaction probably are:

1. The optic nerves and the optic tracts connecting the retina with the thalamus and the lateral geniculate body; the optic radiations connecting the thalamus and the lateral geniculate body with the visual centers in the occipital lobes.

2. A visual-motor association tract between the occipital lobes and the motor area in the pre-Rolandic region.

3. The descending fibers from the motor area of the cortex, which are included in the direct and crossed pyramidal tracts of the cord; and the motor nerves leading from the cord to the muscles used in finger movements.

The only assumption necessary concerning the centers included in these paths is that their complexity is equal in the two halves of the nervous system, or that there are no differences in the time of conduction through them.

The optic fibers are so distributed in passing through the optic

chiasm,[1] that one half of each retina is represented in each visual area of the cortex, that is, that the right half of each retina sends its fibers to the visual area in the right occipital cortex, and the left half of each retina sends its fibers to the visual area in the left occipital cortex.[2] Thus a lesion in the right occipital cortex causes blindness of the right half of each eye or right-sided hemiopia, and lesion in the left hemisphere causes blindness in the left half of each eye, or left-sided hemiopia. No cases have been recorded in which a lesion of one occipital cortex has affected only one fourth of the retina, or only circumscribed the visual field. Foveal or central vision is not lost in cases of hemiopia, and in the majority of cases of double hemiopia, it is only weakened. Two explanations have been offered for this immunity of the fovea. First, the fibers from the area of clearest vision enter a limited area of the cortex which remains unaffected by the lesions; second, the fibers from the foveal region of each eye are distributed in such a way that each fovea is equally represented in each hemisphere, and that only complete destruction of the two occipital lobes could destroy central vision. The latter view is considered by Monakow as the most probable, in opposition to Munk and Henschen who support the former explanation.[3]

Fig. 1 is a schematic representation of these conduction paths, and is intended to show the connections between the hands and any part of the retina of either eye. In order to make the diagram as simple as possible, intermediate centers such as the thalamus, lateral geniculate body and the medulla oblongata are not shown. Rays of light striking the retina are represented by the lines marked AA', BB', and CC'. All lines which lead to or from the right occipital cortex are broken lines, those leading to or from the left occipital cortex are solid lines. Thus rays B and B' react upon the right occipital cortex and rays A and A' react upon the left occipital cortex. Since the fovea is equally represented in each visual area, two lines are drawn from each fovea, one leading to each visual area. The line joining the two motor areas represents the commissural fibers which traverse the corpus callosum and by which these two regions are associated.

The visual-motor fibers, connecting the frontal and the occipital

[1] For a detailed discussion of the distribution of the optic fibers in the optic chiasm, see Barker, "Nervous System," 785–796, 1901.

[2] For a discussion of the localization of vision in the cortex, see Monakow, "Localisation des Gesichtssinnes im Cortex," *Ergebnisse der Physiol.*, 1, Pt. 2, 642–645, 1902.

[3] Monakow, *loc. cit.*, 657.

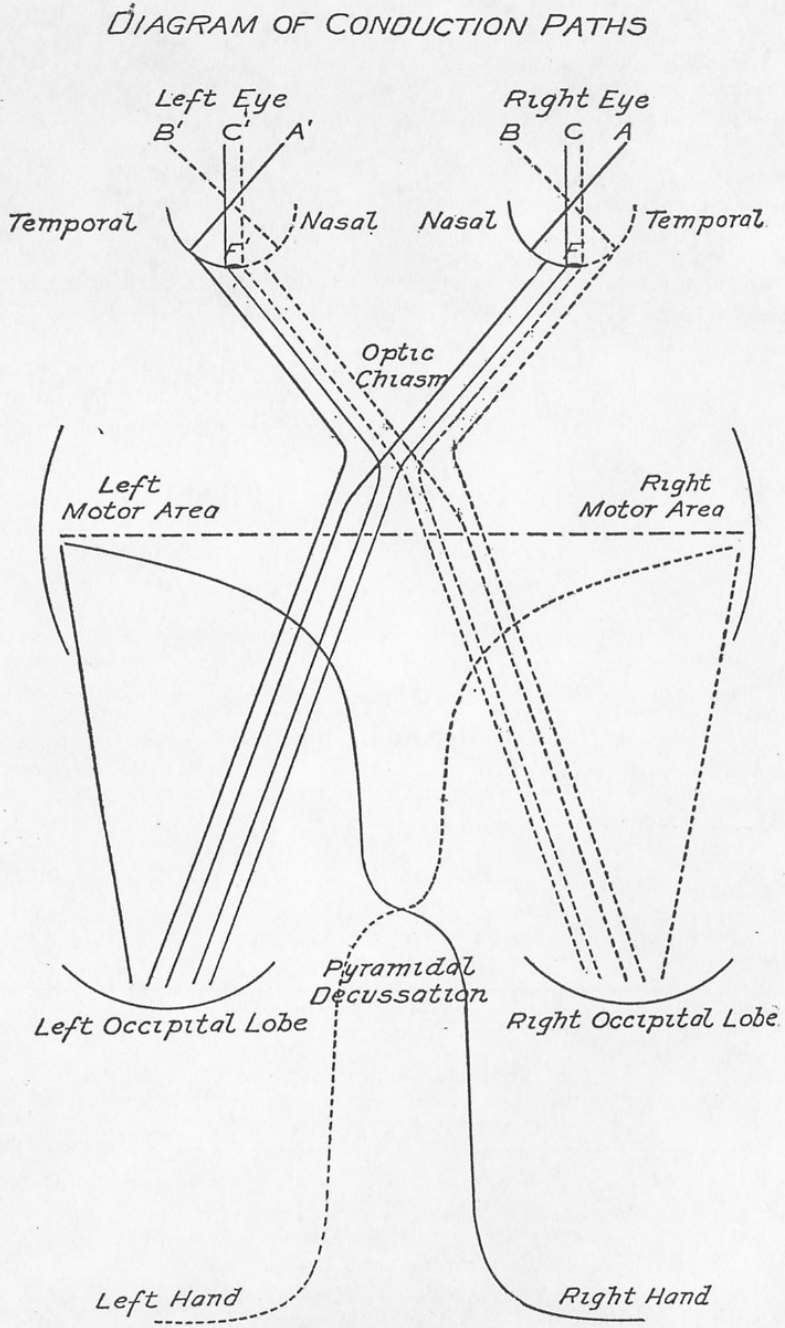

FIG. 1. Schematic Representation of the Conduction Paths.

lobes in the same hemisphere, make up one of the most distinctly marked association tracts in the brain,[4] which is called the superior association bundle.[5] These fibers connect the two regions without passing through any intervening centers.

The fibers from the motor area descend through the internal capsule into the medulla oblongata. There a portion of the fibers decussate and descend into the cord on the opposite side, forming the crossed pyramidal or the crossed cortico-spinal tract. The remaining fibers descend on the same side of the cord and form the direct pyramidal or the direct cortico-spinal tract. All of these latter fibers,[6] however, cross at different lower levels in the cord.[7] From the anterior horn of gray matter in the cord, the motor fibers pass out to the muscles of the hands and fingers.

According to the conduction paths as they have been outlined in the preceding paragraphs, if a light stimulus strikes the retina of the right eye on its temporal side (*B*, Fig. 1), the impulse will be conducted through the optic chiasm to the occipital lobe on the right side. If the hand is to react to this stimulus, the impulse will reach the motor area on the same side, through the visual-motor association tract. From there an impulse generated in the cells of the motor area will be conducted over the descending motor tract to the opposite side of the cord and thence to the left hand. This may be considered as the most direct path over which the impulse can travel.[8] If a stimulus strikes the retina of the right eye on its nasal side (*A*, Fig. 1) the impulse will cross in the chiasm to the left occipital lobe. By way of an association tract to the motor area and the descending motor tracts, the impulses, crossing in the cord, will finally reach the right hand. As may be seen from the diagram, the relations of the retinal areas of the left eye to the hands are reversed, so that the most direct path from the temporal side of the right eye and from the nasal side of the left eye would lead to the left hand, while that from the nasal side of the right eye and the temporal side of the left eye would lead to the right hand.

Since the center of vision of each eye is represented in each visual area of the cortex, a light stimulus striking the fovea of either eye (*C C'*, Fig. 1) would have paths equally direct and open to each hand.

[4] See Ladd and Woodworth, "Physiol. Psych.," 223, 1911.

[5] See Schäfer, "Quain's Anat.," 3, Pt. 1, 165, 1893.

[6] Certain exceptions to this statement will be made later (p. 29).

[7] Howell, "Textbook of Physiol.," 168 ff., 1908.

[8] With reference to the retina, the relation between eye and hand is crossed, but when the visual field is considered, it is evident that the left hand is most directly associated with the left half of the visual field.

II. Possible Contralateral Connections

If the hand not most directly connected with the part of the retina stimulated is to react, then at some point in its course the impulse must cross to the path leading to that hand. This, in terms of the neurone theory, would mean that one synapse or a system of synapses must be interpolated in order that connections may be established between the two sides of the body. This indirect association between hand and eye might be accounted for in several ways:

1. The impulse might pass over the association path connecting the motor areas in the two hemispheres, a definite tract of fibers occupying the central portion of the corpus callosum.

> Studies of secondary degeneration indicate that through the corpus callosum the activities of a given center in the cerebral cortex of one side are associated with the activities of a precisely similarly located cortical area in the opposite cerebral hemisphere.[9]

Howell,[10] in speaking of the corpus callosum, says:

> So far as the motor regions are concerned, there is some evidence that the connection thus established is between symmetrical parts of the cortex—that is, between parts having similar functions—and we may perhaps regard the corpus as a means by which the functional activities of the two sides of the cerebrum are associated.

Bechterew[11] concludes from a study of the degeneration method, that the corpus callosum connects symmetrical parts of the two hemispheres. (He found, however, that the degeneration may involve convolutions adjacent to the symmetrical parts.) According to Schäfer, if one hemisphere be cut away and electrodes applied to the cut surface of the corpus callosum, the motor centers in the remaining hemisphere may be excited through the fibers of this commissure as readily as if the electrodes were applied directly to the gray matter of the motor area, and the effects produced are similar, though not so easily isolated. That the movements which are produced by excitation of the callosal fibers are brought about through the cortex and not through the fibers which have been described as passing from the cortex of the one side across the corpus callosum directly to the internal capsule of the opposite side, is shown by the fact that they are not obtained if the Rolandic area is destroyed, although the connection between the corpus callosum and internal capsule may not be disturbed. Thus there is direct experimental proof that the same motor impulse may be generated, either directly

[9] Barker, "Nervous System," 1055, 1901.

[10] "Textbook of Physiol.," 216, 1908.

[11] "Leitungsbahnen im Gehirn u. Rückenmark," 558 ff., 1899.

in the motor center, or by impulses coming from the opposite motor center, over an association path.

2. If there were an association tract connecting the occipital lobe of one hemisphere with the motor area of the other hemisphere, an impulse could pass directly to the opposite motor area without involving additional neurones, and with only a very slight increase in the length of path traversed. However, evidence of the existence of such a path is wanting. Wundt[12] says that to some extent the corpus callosum connects cortical regions asymmetrically situated, but he does not state any definite tracts. Schäfer[13] mentions an association tract connecting the occipital lobe of one hemisphere with the temporal lobe of the other. He also says that the Rolandic area receives fibers from numerous other regions than the occipital, but he does not mention any connection between the visual area of one side and the motor area of the other, through the corpus callosum.[14]

3. Some evidence has been adduced, especially by Liepmann and Pick,[15] for the existence of a special coordinating center located in one of the hemispheres, probably in the frontal region, analogous to the speech center, and controlling the more complicated and skilled movements. For instance, in some localized diseases of the brain, there is a loss of the ability to perform very familiar and apparently simple acts, such as lighting a candle or picking a flower. In right-handed persons this center would probably be located in the left hemisphere, similar to the speech center. If a single center controlled such movements as are required for a simple reaction experiment, it would probably be directly connected with each motor area, and impulses could be transmitted from the coordinating center to either motor area over similar nerve paths. But coordinated movements such as are required in the present reaction can be obtained directly by stimulation of the motor area or the cut surface of the corpus callosum. Thus Ladd and Woodworth[16] say:

> The movements obtained by stimulating the motor area are coordinated movements, in much the same way as reflexes are coordinated. That is to say: Neither isolated contractions of single muscles nor general contractions of all the muscles in a limb are usually obtained by exciting the motor area. The movements are such as, for example, flexion and extension of the limbs, clenching or opening the fist, pricking up the ear, mastication, turning both eyes to the side, etc. In higher apes, movements of separate fingers can be obtained; but even these are to be regarded as coordinated movements.

[12] "Physiol. Psych." (trans. by E. B. Titchener), 214, 1904.

[13] "Textbook of Physiol.," 2, 780, 1900.

[14] In Räuber's "Lehrbuch der Anatomie des Menschen," 185, 1909, he quotes the statement from Cajal, that the callosal fibers do not appear to connect two symmetrical points of the hemispheres; the callosum is rather a complex system, through which the nerve fibers arising in any point of the cortex, influence not only symmetrical cells of the other hemisphere, but through their collaterals, influence many other cells of different convolutions.

[15] See Ladd and Woodworth, "Physiol. Psych.," 254, 1911.

[16] "Physiol. Psych.," 241, 1911.

In a subject trained in reaction time work, the movements of the reacting finger become virtually reflex. Thus experiment seems to demonstrate that such movements as are required for the reaction of a finger to a stimulus may be obtained without the control of a coordinating center.

4. There is some evidence,[17] both anatomical and physiological, that the motor area of one hemisphere, though principally connected with the opposite side of the cord, is connected to a much slighter degree with its own side. And the presence of such poorly developed paths has been suggested to explain the puzzling cases of return of function after injury to the motor area. Howell,[18] in attempting to explain bilateral control of certain muscles and organs, such as the muscles of the chest and diaphragm, says:

> The motor area on each side may send down a double set of pyramidal fibers, one of which crosses and the other remains on the same side, or the fibers may bifurcate. . . . Some evidence in favor of this view is found in the undoubted histological fact brought out by Mellus and others, that small unilateral lesions in the motor area—the center of the great toe in the monkey, for instance—are followed by degeneration in the lateral pyramidal tracts on both sides, showing that some portions of the motor area send fibers to both sides of the body.

Bechterew[19] mentions the fact that lesions of the motor zone are not followed by degeneration of the crossed and direct pyramidal tracts alone, but also by a slight degeneration in the lateral pyramid on the same side. He opposes the view of Charcot, that the fibers cross back to their original side in the ventral commissure of the cord, and also that of Marchi, that there is a partial crossing of the pyramidal fibers in the region of the corpus callosum. Bechterew cites the more recent work of Dejerine and Thomas and concludes that there are some uncrossed fibers in the lateral pyramids. However the condition of hemiplegia, or the paralysis of voluntary muscles on one side of the body, as a result of injury to the opposite hemisphere of the brain, has long been known, and gives sufficient evidence of the crossed control of the muscles producing the movements of the limbs.

[17] See Ladd and Woodworth, "Physiol. Psych.," 242, 1911.

[18] "Textbook of Physiol.," 188, 1908.

[19] "Leitungsbahnen im Gehirn u. Rückenmark," 496 ff., 1899.

III. Advantages of Retinal Stimulation for Experiment

Experimental evidence, therefore, seems to point to the association path between the two motor areas, as the path over which an impulse from a given part of the eye must travel in order to innervate the muscles of the hand not directly associated with this part. The possible existence of connecting neurones in the lower centers, which might also perform the function attributed to the corpus callosum, can not be denied, although experiment offers no affirmative evidence. Associations between other parts of the body and the hands probably take place through the corpus callosum, with a resulting difference in the character of the conduction paths similar to the ones described. But the plan chosen in the present experiment seems to be particularly free from the difficulties brought out in the historical sketch of the study of nerve conduction by the reaction time method. These are the differences in reaction time, due to:

1. *Differences in the Sensitivity of the Parts Stimulated.*—As the history showed, this has always been a disturbing factor where either electrical or tactual stimuli are used. But the difference in the sensitivity of the two eyes and of the nasal and temporal sides of each eye, as far as it affects the speed of reaction, may be determined and eliminated by averaging in the final result the reaction for the temporal side of one eye with that of the nasal side of the other eye and *vice versa*. The discussion of this difference will make up Chapter V., and the method of eliminating it will be considered in Chapter VII.

2. *Different Distances of the Parts Stimulated from the Brain.*—When stimulation of different parts of the body, *e. g.*, hand and upper arm, is used in determining the speed of conduction in nerves or nerve centers, the distance of the parts from the brain is a factor to be taken into account. The use of the eyes, and especially of different sides of the same eye, makes all points of stimulation equidistant from the brain center.

3. *Differences in the Speed of Reaction of the Two Hands as a Result of Training or Use.*—Any difference in the time of reaction of the right and left hands, may be found by comparing the reaction time to stimulation of both eyes, in which case the paths to each hand are equal; and it may be eliminated by averaging the reactions of one hand to stimulation of one position of the eye with that of the other hand upon the same position of the other eye. The difference in the reaction times of the two hands will be discussed in Chapter VI., and the elimination of this difference will be considered in Chapter VII.

We may conclude from this discussion that the conduction paths as they are schematically shown in Fig. 1, including the commissural fibers between the two motor centers, are the means of association between the hands and the different retinal areas. We may conclude further that these paths supply the conditions called for in Chapter II., that there shall be two conduction paths identical except that the one path must cross from one side of the brain or cord to the other and that the difference in the reaction time over these two paths will give the time consumed in traversing the synapse or synapses involved.

CHAPTER IV

THE EXPERIMENT

I. The Apparatus

The conditions of the experiment require that the subject and the experimenter shall be in the same room. Although this arrangement has the advantage when frequent changes in the position of the subject necessitate the presence of the experimenter, as in the present case, it has a disadvantage in that the contact devices of the apparatus must be noiseless. This qualification excludes the pendulum contact apparatus and the ordinary exposure screen methods. The apparatus adopted for this experiment, and shown schematically in Fig. 2, is a modification of that used by Froeberg, and described in his study on "The Relation between the Magnitude of Stimulus and the Time of Reaction."[1] It consists of a heavy iron wheel 92 cm. in diameter, with a wide rim, and with its axis in a vertical position. An electric motor drives the wheel by means of a belt around its circumference. The belt drive gives greater satisfaction than the worm gear previously used, because it is less complicated and practically noiseless. The motor is supplied with current from the University light circuit, through rheostat[1] (see diagram). If there are any irregularities in the current, they are counteracted by the momentum of the heavy wheel, which preserves a uniform speed of one revolution in 1.25 seconds.

The light stimulus, a two-candle-power electric lamp, mounted in a small metal box, with an aperture one centimeter in diameter, is fastened to the rim of the wheel. The metal box extends 4 centimeters beyond the circumference of the wheel, and thus makes the diameter of the path traversed by the light stimulus 100 cm. Traveling at the rate of one revolution in 1.25 seconds, the light would have an exposure through a one centimeter opening, of about 4 sigma. The current for the light is obtained from the university circuit, and passes through rheostat[2]. The fluctuations in this current are too slight to produce a noticeable change in the brightness of the stimulus. The artificial light as a stimulus is less convenient than daylight reflected from white paper, but we chose the former so that a

[1] Archives of Psychology, No. 8, 1907.

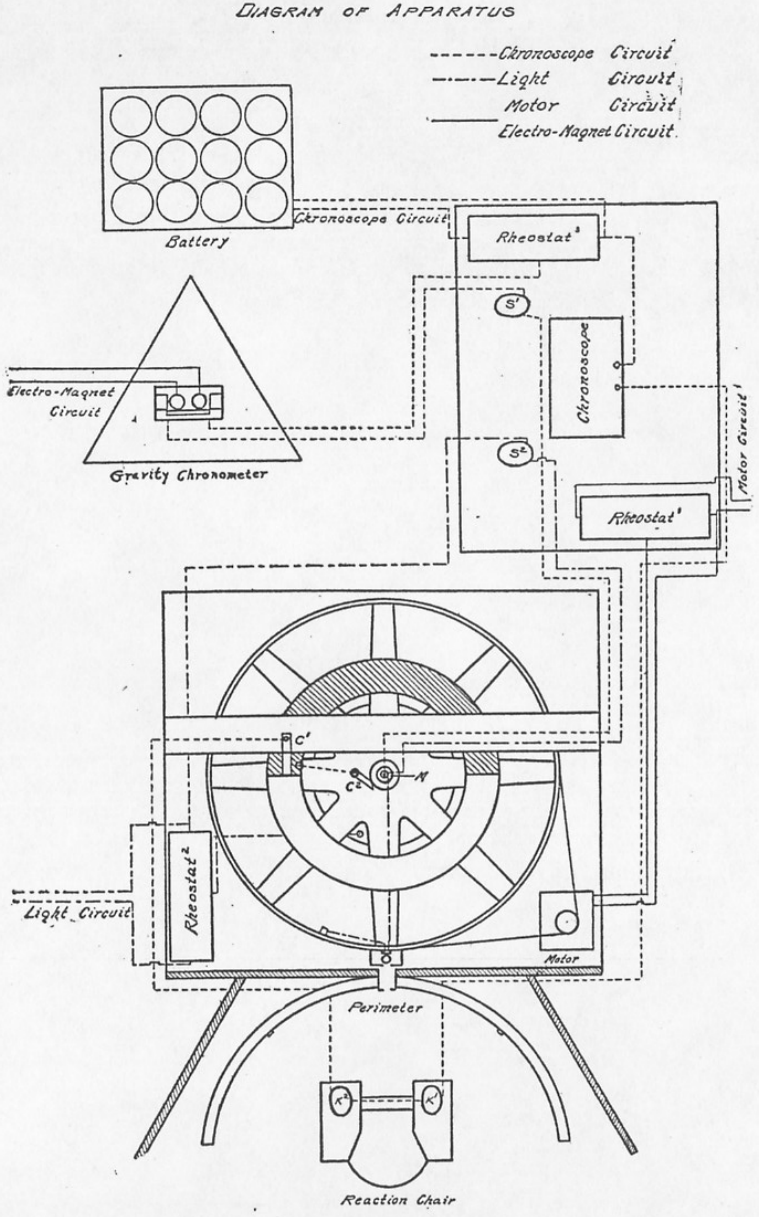

Fig. 2. Diagram of the Apparatus.

comparative set of experiments could be conducted at night with the same stimulus. The light passes through a double screen of ground glass and pale blue glass. The latter counteracts the excessive yellow rays of the carbon filament, so that examination with the spectroscope showed the result to be a pure white light. We took this precaution so that the reactions might serve as a standard with which to compare reactions to colored stimuli of the same size. The stimulus was made strong enough to reduce the mean variation of the reactions as much as possible, without producing troublesome after-images. The light current, after passing through rheostat,[2] goes through a switch S^2, shown at the right of the chronoscope in the diagram, then by means of the mercury cup M, fastened to the stationary shaft of the wheel, the current is carried to the lamp on the rim of the wheel. From the lamp the circuit is completed through the wheel, and from its base, the current returns to the rheostat.[2]

To record the reaction times, we were fortunate in being able to use the Hipp chronoscope modified by Cattell and Dolley.[2] The arrangement of the chronoscope circuit is a modification of that used by Froeberg. The upper side of the wheel carries a circular track, half of which is brass and half a non-conducting fiber. A copper brush C^1, fastened to a bridge above the wheel, rests upon the moving track and closes the chronoscope circuit, when it touches the brass half of the track. As the brush passed from brass to fiber, the quality of the sound changed so much that there was danger of a false reaction to the sound. But a slight change in the form of the brush contact made it practically noiseless.

The lamp is adjusted on the rim of the wheel so that the instant it is exposed to the subject, the chronoscope circuit through the brush C^1 is closed. The lamp occupies this position in the diagram. The current for the chronoscope is supplied by 12 gravity cells. We first tried the university light circuit, and later a 6-volt current from a motor dynamo receiving its power from the university circuit. But in both these cases the mean variation of the chronoscope readings was too high, showing a fluctuation in the current. The chronoscope circuit contains the Cattell gravity chronometer,[3] which is set

[2] The description of the changes made in this chronoscope is contained in "On Reaction Times and the Velocity of the Nervous Impulse," *Memoirs of the Nat. Acad. Sci.*, 7, 1893. The principal one of the changes consisted in rewinding the electro-magnets with coarser wire, which reduced the time of magnetization and demagnetization.

[3] This chronometer is described in detail and illustrated in *Memoirs of the Nat. Acad. of Sciences*, 7, 1893.

to give a standard time of 200 sigma, since the reactions to the light vary about that time. The electro-magnet of the chronometer receives its current from an independent circuit, as shown in the diagram. Ten chronometric readings were taken at the beginning of each experiment and the current so adjusted that the mean variation of the readings per 100 sigma should be less than one sigma. After the current passes through rheostat[3], it traverses the chronometer circuit, then the switch S^1 at the left of the chronoscope. From this switch it is carried to the stationary shaft of the wheel, where it passes down through the center of the mercury cup M, and insulated from it, into a collar upon the shaft. The brush C^2, upon the moving wheel, carries the current from the shaft to the semicircular brass track. By means of the brush C^1, the circuit is completed through the track, then passes through the two reaction keys, K^2 and K^1, and finally through the chronoscope into rheostat[3].

The light stimulus appears to the subject at the middle point of a perimeter 92 cm. in diameter. Black screens are arranged above, behind and at the sides of the perimeter, so that the subject sees none of the mechanism and when in position, always faces a black background. There is a diaphragm at the aperture in the perimeter, a distance of 12 cm. in front of the light. While the stimulus is being observed with both eyes, the diaphragm is thrown wide open. When only one eye is being stimulated, it is adjusted so that the light can be just completely seen through it. The value of this arrangement is that the subject can see the light as a complete circle only when the eye is in its proper position, and any variation from this position can be detected at once. A guide marks the center of the circle, of which the perimeter is an arc. It consists of a hinged metal strip suspended from above, with a one cm. hole in its lower end. This marks the proper position for the subject's eye, and is raised out of the way during the test. However after some practise the subject can assume the correct position with the aid of the diaphragm alone, and in that case the guide serves only to maintain the proper distance of the eye from the stimulus. The perimeter is marked off in degrees and carries two white movable fixation points, one centimeter in diameter, one on each side of the diaphragm. The total distance of the eye from the stimulus is 58 cm. According to Howell,[4] the average diameter of the fovea is usually given as lying between .3 and .4 mm. Lines drawn from the ends of its diameter

[4] "Textbook of Physiol.," 322, 1908.

to the nodal point[5] of the eye would subtend an angle of one degree, and therefore an object in the external world whose visual angle would fall within one degree would be imaged on the fovea. An object subtending an arc of one degree at a distance of .58 cm. must be 1.01 cm. in diameter. According to these measurements then, an image of the present stimulus which is one centimeter in diameter, must fall within the limits of the fovea.

The reaction chair consists of an ordinary swivel chair, adjustable in height. On each of its two broad arms, is a reaction key of the Morse type. Between these arms a sliding frame supports the head rest (not shown in the diagram), which is put in place after the subject is seated, and is firmly fastened to the chair by means of a thumb screw. The head rest gives a firm support for the forehead and chin, the height of the chin rest being adjustable. Additional supports for the head proved a disturbance rather than an aid in preserving a fixed position. Lateral supports upon the temples and a cast for supporting the jaws were tried and discarded. The work which has been done on visual fixation shows that, even when the head is firmly fixed, eye movements still occur. McAllister[6] found that the eye, when fixating, unconsciously wanders over an area somewhat less than one degree. Dodge[7] distinguishes three classes of head movements, a pulse movement occurring somewhat rhythmically, movements corresponding roughly to the breathing, and other miscellaneous, irregular movements. But when the head is pressed against a support, the movements occurring in five minutes are not greater than about one half of a degree. Such slight variations in the position, both of the eyes and of the head, can be disregarded in the present experiment, where the fixation required at one time is never longer than a few seconds. The subjects seemed to experience no difficulty in holding their fixation, as far as they could judge from introspection. The fixation points are white upon a black background and the aperture through which the stimulus appears also shows black, so that the only bright spots in the visual field are the fixation points. Dodge[8] studied the reaction time of

[5] The nodal point of the eye lies in the crystalline lens, 7.3 mm. from the anterior surface of the cornea. It is the center of an ideal refracting surface, equivalent to the sum of all the refracting mediums of the human eye. See Howell, *loc. cit.*, 289 ff.

[6] "The Fixation of Points in the Visual Field," *Psych. Rev.*, Mon. Suppl., 7, 17–53, 1905.

[7] "Eine experimentelle Studie der visuellen Fixation," *Zeitschr. f. Psych. u. Physiol. des Sinnesorgane*, 52, 321–422, 1909. "Study of Visual Fixation," *Psych. Rev.*, Mon. Suppl., 8, 1907.

[8] "Study of Visual Fixation," *Psych. Rev.*, Mon. Suppl., 8, 13 ff., 1907.

eye movements to peripheral stimulation and found an average time of about 165 sigma, that is, when a stimulus strikes the periphery of the retina, the movement to bring the center of vision to that point requires 165[9] sigma. The duration of the stimulus in the present experiment is only about 4 sigma, and the long reaction time of the eye would preclude any change of fixation between the appearance of the stimulus and its disappearance.

II. Methods

The experiments were conducted during the day between the hours of nine and four. Although experimentation with visual stimuli in daylight has certain disadvantages, it is free from the complication of dark adaptation and can be conducted under more nearly natural conditions. The apparatus is situated in a large room, midway between two windows, in such a way that the only light falling within the hood covering the perimeter, is that reflected from the white wall behind the subject. At the suggestion of Professor Cattell, the intensity of the light in the room is regulated as follows: Under the hood and directly above the middle point of the perimeter, a small photometer was fastened. This consists of a white screen, an adjustable rod and a two-candle-power electric lamp (not shown in the diagram). At the beginning of the experimental work, a day of average brightness was selected and the adjustable rod so placed that its shadow cast on the screen by the lamp would be just perceptible. During all the following tests, the light in the room was regulated by two sets of curtains, so that this shadow would again be just perceptible. No experiments were made on cloudy days, which were too dark to allow such adjustment. Although this device is not extremely accurate, it is considerably more so than ordinary observation. The work of Froeberg[10] shows that a change of 50 per cent. in the light will make a difference of only a few sigma in the reaction time, so that all variations in the reaction time due to great changes in the light intensity have been eliminated.

Three methods of applying the stimulus to different parts of the retina suggest themselves. Probably the best method would be to provide a permanent fixation point for the eye in the center of the perimeter and to move the stimulus to the different eccentric posi-

[9] This time was found by a method devised by Erdmann and Dodge in 1899. Later results obtained by the photographic method, although not the same, confirm the belief that the reaction time of the eye is relatively long.

[10] "The Relation between the Magnitude of Stimulus and the Time of Reaction," Archives of Psychology, No. 8, 1907.

tions. But the nature of the apparatus controlling the stimulus made this method impossible in the present case. The method adopted at first and used for the stimulation of points 45 degrees from the fovea, consisted in keeping the head fixed in such a position that when the eyes looked straight to the front, the stimulus should strike the fovea. Then when an eccentric position was to be stimulated, the head remained in its original position, and the eye was turned in its socket 45 degrees in that direction. When one attempts to hold this position for a time, the strain on the muscles of the eye can be distinctly felt. But during the experiment the subject looked straight ahead until the "ready" signal warned him to assume the peripheral position. Thus each fixation lasted only two or three seconds. A certain amount of attention had to be directed to the fixation process by this method, a factor which it seemed best to eliminate. The third and most satisfactory method was then adopted, that is, the use of the revolving reaction chair described on page 36. The stimulus appears at the middle point of the perimeter and the whole body is turned, so that the eye can fixate any point and still keep a normal position in its socket. All of the subjects considered reaction to peripheral stimuli much easier with this arrangement.

During the study of the reaction to peripheral stimuli, one eye was stimulated at a time. The other was closed by a black screen so fitted that it would allow the eye to remain open and move about freely, and yet not cut off the rays of light directed toward the temporal side of the other eye. No form of screen proved perfectly satisfactory, and since the smallest ray of light entering the covered eye disturbed the subject, it was necessary in some cases to apply a strip of adhesive plaster on the nasal side across the nose. It was this difficulty which prevented our testing points more peripheral than 45 degrees. In every case, after a short time the subject became so adapted to the screen that he was unable to say which eye was covered and which was being stimulated.

At the beginning of each experiment, the chronoscope was tested and the light conditions regulated. The subject seated himself in the reaction chair and the head rest was fastened in position. Two warning signals, "Get Ready" and "Now," were given about a second apart. Two signals were used rather than one mainly because subject *T*, trained in reaction work, was accustomed to this method, and only one proved confusing to him. Between the "Now" and the application of the stimulus, the interval ranged from one to two seconds. The chronoscope was started and when running properly, the "Ready" signal was given, which was the sign for the

subject to press the reaction key, preparatory to its release. Immediately after the lamp had passed the aperture, the experimenter turned on the light by closing switch S^2. This gave nearly one revolution of the wheel for the light to reach its maximum brightness. About the same time, the "Now" signal was given. The switch S^1 in the chronoscope circuit is closed after the brass track has passed beyond the brush contact C^1. At the instant the stimulus is given the circuit through the brush and track is closed and the chronoscope begins to record, and continues until it is stopped by the release of the reaction key.

One *series* consists of 10 reactions in each of 12 positions, that is, upon the fovea, and at a given distance, *e. g.*, 45 degrees, upon the temporal and nasal side of each eye with each hand, making 120 reactions in all.

Right Eye	Right Hand,	Fovea,	Temporal,	Nasal.
	Left Hand,	Fovea,	Temporal,	Nasal.
Left Eye	Right Hand,	Fovea,	Temporal,	Nasal.
	Left Hand,	Fovea,	Temporal,	Nasal.

This series required an average time of 40 minutes, including several minutes to change the eye screen, and to allow the eye to become adapted to the light; also a short time required to change positions on the same eye. A *set* of reactions consists of ten such series,[11] or 100 reactions in each position, making 1,200 reactions in a complete set. The various positions in each series were so arranged that two series never began or ended with the same position. This precaution would, in a whole set of experiments, tend to equalize any practise and fatigue effects, which might appear in a single series. In cases where more than one series was taken in a day, an hour elapsed between them.[12] Whenever a subject was not in good physical or mental condition, or as soon as he felt fatigued, work was discontinued.

A whole set of experiments at a given peripheral distance, *e. g.*, 45 degrees, was completed before another at a different angle was begun. Such an arrangement might introduce a pronounced practise effect, but the method of treating the results, as will be explained later, makes a direct comparison of the different sets and even of the different series unnecessary.

Four persons have acted as subjects, *T, P, A,* and *M,* all of them

[11] Cases in which a set was made up of only five series will be noted later.

[12] An exception to this statement in the case of subject *A* will be mentioned later.

graduate students in the department of psychology. The first two were well trained in reaction time work, and the last two had served as subjects at various times. An intensive study of a few subjects was undertaken rather than a few tests of a large number of persons, on account of the difficulty in getting trained subjects who could spend the large amount of time required for such an experiment.

CHAPTER V

THE REACTION TIME TO STIMULATION OF DIFFERENT RETINAL AREAS

BEFORE the speed of nerve conduction can be calculated by the reaction time method, whether conduction be over a nerve trunk or through a nerve center, certain facts regarding the parts stimulated and the parts reacting must be known. In the historical sketch given in Chapters I. and II., the difficulties and errors from these sources were pointed out. At the close of Chapter III., in which the conduction paths to be studied in this investigation were outlined, three sources of error were indicated. Two of these sources of error are involved in comparing the reaction time by the hands to stimulation of the temporal and nasal sides of the retina; first, the quality of the different retinal areas showing itself in the difference of reaction time; and second, the difference in the reaction time of the right and left hands. The first of these problems will be discussed in this chapter, and the second in Chapter VI.

I. HISTORICAL

In 1879 Hall and Kries[1] reported an experiment on "The Dependence of Reaction Time upon the Point of Stimulation." They compared the reaction times to stimulation of different points on the skin, but concluded that it is impossible to make the stimuli on different parts of the body comparable. They then measured the reaction times to visual stimuli seen by direct and indirect vision. A Geissler's tube furnished the stimulus. The head was held in a fixed position by a support, so arranged that the eye could be directed to different points in the visual field. One eye was used at a time, the other being held shut. The question of the intensity of the stimulus on the different parts of the retina was disregarded by the investigators, since the results were so definite that a large variation in the intensity of the stimulus made little difference in the results. The fovea and points 30 and 60 degrees on each side and above and below the fovea were tested on two subjects. The average reaction times for each position are as follows:

[1] "Über die Abhängigkeit der Reactionszeit vom Ort des Reizes," *Archiv f. Anat. u. Physiol.*, Suppl. 1–10, 1879.

Subject	Fov.	Temp. 30°	Nas. 30°	Above 30°	Below 30°
H	221	261	245	248	287
K	171	196	186	186	215
		Temp. 60°	Nas. 60°	Above 60°	Below 60°
H	—	281	263	263	291
K	—	277	216	184	248

The number of reactions from which the averages are calculated and the mean variations are not given. No statement is made as to whether or not the value for each position is an average of the two eyes for that position. Hall and Kries concluded from their experiments that the time for the temporal[2] side of the retina is always greater than for the nasal side, and for the lower part greater than for the upper part of the retina. They considered the differences due to the differences in the central, or reduced reaction time, on the assumption that those parts which are most used or exercised have the quicker central time. The central time does not seem to depend on the sensitivity of the part stimulated, according to them, since the reaction time upon stimulation of the tongue is longer than in the case of stimulation of the forehead, although the tongue is said to be twenty times as sensitive as the forehead.

The work of Kästner and Wirth,[3] on the stimulation of different retinal areas, is not directly comparable with the present work or with that of Hall and Kries. In their case certain areas of the retina were associated with one hand or the other, so that when the light stimulus fell upon a certain area the proper hand must be chosen to react. Moreover the points stimulated were not the same in the case of these experimenters. But by taking the averages of certain of their positions at the highest stage of practise, Kästner and Wirth found some similarity between their results and those of Hall and Kries, in that the direction of the differences was the same. In both cases the nasal side and the upper side of the retina gave faster times than the temporal and the lower side. These investigators agree with Hall and Kries that the differences are due rather to central than to peripheral causes.

II. Results of the Present Study

Although the previous experiments upon the reaction time of the hands to stimulation of the periphery of the retina have been by no

[2] The positions as they are given originally by Hall and Kries refer to the visual field and not to the retina. The figures have been reversed in order that they may correspond to the system used in the present work, in which the positions refer to the retina.

[3] "Die Bestimmung der Aufmerksamkeitsverteilung innerhalb des Sehfeldes mit Hilfe von Reactionsversuche," *Psychol. Stud.*, **3**, 361–392, 1907; **4**, 139–200, 1908.

means exhaustive, they indicate that certain differences do exist. Hall and Kries considered the differences between the fovea and the temporal and nasal sides of the retina to be so pronounced, that certain disturbing elements were disregarded by them. Kästner and Wirth confirmed these results.

This study, having a purpose beyond the determination of the reaction time to stimulation of the peripheral retina, has not covered so wide a range as that of Hall and Kries, but consists of a more intensive investigation of the reaction time to stimulation of the fovea, and of points 3, 10, 30 and 45 degrees from the fovea in a horizontal plane.

The following tables, I., II., III. and IV., give the general results of these experiments. Table I. gives the averages for the fovea and the temporal and nasal sides of the retina at 45 degrees from the fovea, Table II. gives the same for 30 degrees, Table III. for 10 degrees and Table IV. for 3 degrees.

Each table is made up of 10 series of 10 reactions each for every subject, so that each figure in the tables is an average of 100 reactions.[4] All experiments at the distance of 45 degrees from the fovea were made with the head in a fixed position and the points were fixated by rotating the eye in its socket, as described on page 38. In the case of subject *T*, every series at 45 degrees consisted of 13 reactions upon each position. An average of the 13 reactions was taken and the three reactions farthest from the average were discarded, and a new average obtained from the ten remaining reactions. This correction made so little difference, that the method was discontinued. However 13 reactions were still taken on each position at 45 degrees for the different subjects, so that the figures in Table I. for all but subject *T*, are each the average of 130 reactions.

The experiments at 30, 10 and 3 degrees whose results are given in Tables II., III. and IV., were made with the revolving reaction chair, described in Chapter IV., by which the whole body was turned to an eccentric position instead of the eyes alone. Subject *A* appears only in Table I. as she left the university before the work was completed.[5]

[4] Certain exceptions to this statement will be noted.

[5] The whole set of experiments consisting of 10 series of reactions were made on subject *A* on one day, in two periods of five series each, with an interval of about three hours between them. The intervening period, however, was taken up by another reaction time experiment, so that the work was practically continuous for about eight hours. (An interval of one half hour was allowed for lunch.) The whole day's work was designed as a fatigue experiment in reaction time, but since no fatigue effect appeared in various mental tests given at the

REACTION TIME TO STIMULATION OF DIFFERENT RETINAL AREAS

TABLE I

LEFT EYE, 45 DEGREES

Subject		Right Hand Fov.	Right Hand Temp. 45	Right Hand Nas. 45	Left Hand Fov.	Left Hand Temp. 45	Left Hand Nas. 45
T	Av.	203.5	227.7	221.6	212.3	236.0	226.1
	M.V. ...	*9.6*	*11.2*	*7.6*	*14.2*	*14.3*	*12.1*
A	Av.	193.6	217.3	207.9	190.8	203.4	198.6
	M.V. ...	*9.0*	*14.4*	*11.5*	*9.7*	*9.8*	*9.1*
P	Av.	176.9	204.6	195.7	165.2	193.9	183.8
	M.V. ...	*3.1*	*5.7*	*5.6*	*4.9*	*8.7*	*8.9*

TABLE II

LEFT EYE, 30 DEGREES

Subject		Right Hand Fov.	Right Hand Temp. 30	Right Hand Nas. 30	Left Hand Fov.	Left Hand Temp. 30	Left Hand Nas. 30
T	Av.	196.4	211.2	209.7	191.2	208.8	199.1
	M.V. ...	*6.6*	*9.7*	*7.0*	*6.3*	*8.7*	*7.7*
P	Av.	179.7	188.8	190.7	178.1	192.0	181.9
	M.V. ...	*2.5*	*5.0*	*4.5*	*7.3*	*3.5*	*4.7*
M	Av.	177.8	195.6	193.3	175.9	187.0	182.6
	M.V. ...	*11.6*	*13.4*	*7.6*	*10.2*	*9.1*	*8.8*

TABLE III

LEFT EYE, 10 DEGREES

Subject		Right Hand Fov.	Right Hand Temp. 10	Right Hand Nas. 10	Left Hand Fov.	Left Hand Temp. 10	Left Hand Nas. 10
T	Av.	185.5	190.7	193.5	191.6	203.2	191.2
	M.V. ...	8.7	*4.6*	*7.4*	*7.0*	*7.7*	*6.4*
P	Av.	184.1	191.3	187.7	174.3	191.1	176.9
	M.V. ...	*4.7*	*3.8*	*2.6*	*4.6*	*4.7*	*4.7*

TABLE IV

LEFT EYE, 3 DEGREES

Subject		Right Hand Fov.	Right Hand Temp. 3	Right Hand Nas. 3	Left Hand Fov.	Left Hand Temp. 3	Left Hand Nas. 3
T	Av.	185.6	187.1	189.3	188.6	199.8	190.5
	M.V. ...	*4.9*	*4.9*	*3.6*	*4.7*	*10.3*	*6.4*
P	Av.	181.9	190.6	196.9	174.7	189.7	181.7
	M.V. ...	*3.7*	*4.3*	*3.9*	*3.5*	*4.8*	*4.2*

end of the period, or in a comparative study of the reaction times, the results are considered valid for the present study. The order in which the reactions upon the various positions were taken would tend also to equalize the fatigue effect.

REACTION TIME TO STIMULATION OF DIFFERENT RETINAL AREAS

TABLE I (*continued*)

RIGHT EYE, 45 DEGREES

Subject		Right Hand Fov.	Right Hand Temp. 45	Right Hand Nas. 45	Left Hand Fov.	Left Hand Temp. 45	Left Hand Nas. 45
T	Av.	205.2	228.0	223.0	213.4	237.3	222.5
	M.V. ...	*12.0*	*11.9*	*9.1*	*9.0*	*10.9*	*6.5*
A	Av.	194.1	212.3	207.0	186.2	213.0	206.1
	M.V. ...	*9.6*	*13.3*	*12.2*	*13.4*	*10.2*	*11.4*
P	Av.	174.5	201.5	190.5	168.8	201.1	196.0
	M.V. ...	*6.7*	*10.0*	*6.0*	*5.4*	*7.7*	*4.3*

TABLE II (*continued*)

RIGHT EYE, 30 DEGREES

Subject		Right Hand Fov.	Right Hand Temp. 30	Right Hand Nas. 30	Left Hand Fov.	Left Hand Temp. 30	Left Hand Nas. 30
T	Av.	196.9	209.9	202.0	191.3	201.6	203.4
	M.V. ...	*5.5*	*7.1*	*7.1*	*5.6*	*8.3*	*7.9*
P	Av.	178.9	192.0	181.9	174.6	186.2	191.9
	M.V. ...	*2.8*	*4.1*	*6.1*	*3.2*	*5.5*	*5.5*
M	Av.	179.7	198.8	186.5	176.5	190.1	183.7
	M.V. ...	*7.2*	*1.3*	*3.4*	*5.0*	*2.0*	*6.8*

TABLE III (*continued*)

RIGHT EYE, 10 DEGREES

Subject		Right Hand Fov.	Right Hand Temp. 10	Right Hand Nas. 10	Left Hand Fov.	Left Hand Temp. 10	Left Hand Nas. 10
T	Av.	185.3	200.7	193.2	192.5	197.8	200.1
	M.V. ...	*6.2*	*5.5*	*6.1*	*7.4*	*7.4*	*6.0*
P	Av.	178.7	189.5	184.0	173.6	181.2	181.7
	M.V. ...	*3.3*	*7.0*	*4.9*	*3.4*	*4.8*	*5.4*

TABLE IV (*continued*)

RIGHT EYE, 3 DEGREES

Subject		Right Hand Fov.	Right Hand Temp. 3	Right Hand Nas. 3	Left Hand Fov.	Left Hand Temp. 3	Left Hand Nas 3
T	Av.	185.3	192.0	189.5	190.9	185.6	196.5
	M.V. ...	*7.2*	*8.7*	*7.6*	*4.3*	*4.6*	*2.9*
P	Av.	182.5	197.9	192.6	176.9	183.8	190.0
	M.V. ...	*4.3*	*4.5*	*5.4*	*3.7*	*6.3*	*4.6*

In Table II. the figures for subject *M* are the averages of only five series, or 50 reactions on each position. All further tests were made upon the two subjects *T* and *P*. At 3 degrees, the averages for subject *T* are made up from five series or 50 reactions on each position.

III. Methods of Calculating the Mean Variations

The mean variations (M.V.) given in the first four tables, are the mean variations of the average of the series of 10 reactions from the general average of all the series, and not of the individual reactions from the general average. Thus they show the variations of the averages from day to day. Mean variations calculated in this way are somewhat lower than those calculated from the individual reactions. The following figures in Table V. show a comparison of three methods of obtaining the variations, in the case of subject *T* in Table I.:

1. The mean variation of the averages of the 10 series from the general average. This is the method used in the first four tables, and accounts only for the daily variations.

2. The mean variation of the individual reactions from the average of the series was first computed. Then an average of these mean variations was obtained. This method does not take account of the daily variations.

3. The mean variation of all the individual reactions from the general average. This includes both the variations from day to day and those within the series.

TABLE V

Comparison of Three Forms of Mean Variation

Method		Right Hand Fov.	Right Hand Temp.	Right Hand Nas.	Left Hand Fov.	Left Hand Temp.	Left Hand Nas.	Av.
(1)	Right Eye	12.0	11.9	9.1	9.0	10.9	6.5	10.7
	Left Eye	9.6	11.2	7.6	14.2	14.3	12.1	
(2)	Right Eye	8.4	11.4	10.2	10.5	9.3	8.5	10.0
	Left Eye	10.2	9.0	12.0	8.7	11.1	11.0	
(3)	Right Eye	14.2	15.3	15.0	13.1	13.6	10.5	15.0
	Left Eye	14.2	20.2	14.1	15.9	17.5	15.7	

The variations within a series are about the same as those among the different series, while the variations of the individual reactions from the general average are about 50 per cent. higher than either. All the three forms of variations would be higher in the case selected than in any of the later experiments, since this was the first test made, and the situation was new.

IV. General Conclusions from Tables I.–IV.

Tables I.–IV. show certain facts common to all the subjects: First, that the length of the reaction times on the eccentric positions is always greater than on the foveal position; second, that the length of the times increases as the distance from the fovea is increased;[6] third, that the reaction times to temporal stimulation are longer than to nasal stimulation. When the results for one eye and one hand are taken alone, this last result is not so clear, on account of the presence of a factor which will be discussed in Chapter VII., but an average of the two hands for any one position shows the temporal side to give the slower reactions. According to the introspections of all of the subjects, the light grows dimmer as it moves toward the periphery of the retina, and it is always dimmer on the temporal than on the nasal side.

V. Practise Effect in Subjects *T* and *P*

Reaction times usually show no great decrease as a result of practise, aside from the general increase in speed due to a growing familiarity with the situation. But in a long series of tests like the present one, where the reaction times at 45 degrees from the fovea were all taken before the distance of 30 degrees was tested, and this in turn before the distance of 10 degrees, practise effect might account for the general decrease in the reaction times as the positions approach the fovea. It seems well therefore to study the practise effect in subjects *T* and *P*, to determine its influence upon the results given in Tables I., II., III. and IV.

In the case of subject *T* considerable practise effect may be noticed in comparing the foveal times throughout Tables I., II., III. and IV. The tables are arranged in the order in which the experiments were made and the foveal times for the different positions are taken in the same way in each case. It would be difficult to ascertain the number of reactions made between each of the sets, as both

TABLE VI

Practise Effect in Subjects *T* and *P*

Subject *T* Data from	Right Eye Right Hand	Right Eye Left Hand	Left Eye Right Hand	Left Eye Left Hand
Table I.	205.2	213.4	203.5	212.3
Table II.	196.9	191.3	196.4	191.2
Table III.	185.3	192.5	185.5	191.6
Table IV.	185.3	190.9	185.6	188.6
Subject *P* Data from	**Right Eye Right Hand**	**Right Eye Left Hand**	**Left Eye Right Hand**	**Left Eye Left Hand**
Table I.	174.5	168.8	176.9	165.2
Table II.	178.9	174.6	179.7	178.1
Table III.	178.7	173.6	184.1	174.3
Table IV.	181.6	177.7	183.5	174.3

[6] The averages for subject *P* at 3 degrees are an exception to this statement.

T and P acted as subjects for each other in different reaction experiments. The following comparison in Table VI., however, shows the absolute decrease in reaction time for stimulation of the fovea.

In the case of subject P the reverse of practise effect appears. The only explanation of this, obtained from the introspection of the subject, is the changed attitude toward the experiment. The subject was well practised in reacting before this work began, and in the course of the long continued experiment, the reactions became reflex. After the first few tests the conscious attempt to make rapid reactions ceased.

VI. Expression of Data in Terms of Differences

It is evident from the preceding study of the practise effect in subjects T and P, that the absolute values are influenced by practise effect and the variations from day to day due to uncontrollable causes. In Tables I.–IV., one would compare the various distances from the fovea by taking the difference between the general averages for the given distances. These figures would be subject to the above-mentioned errors. If one took the differences between the fovea and the temporal and nasal sides of the retina for each series, and averaged these, he would eliminate from these averages the daily variations and the effects of practise. This method is comparable to the second method of obtaining the mean variations, described in Section III., of this chapter. The average differences between positions at the distances of 45, 30, 10 and 3 degrees from the fovea could then be legitimately compared.

Tables VII., VIII., IX. and X. give the data of Tables I.–IV. in terms of differences thus computed. They give the differences

DIFFERENCES BETWEEN POSITIONS AT VARIOUS DISTANCES FROM THE FOVEA

TABLE VII

Differences between Positions at 45 Degrees

Subject		Right Eye Temp.-Fov.	Right Eye Nas.-Fov.	Right Eye Temp.-Nas.	Left Eye Temp.-Fov.	Left Eye Nas.-Fov.	Left Eye Temp.-Nas.
T	Av.	23.4	13.5	9.9	23.9	16.0	7.9
	P.E.	*1.84*	*1.78*	*2.19*	*2.19*	*1.75*	*2.16*
P	Av.	29.7	21.7	8.0	28.2	18.7	9.5
	P.E.	*1.71*	*1.58*	*1.63*	*1.37*	*1.45*	*1.26*
A	Av.	22.5	16.4	6.1	18.2	11.1	7.1
	P.E.	*1.43*	*1.58*	*1.15*	*1.39*	*1.24*	*1.24*

TABLE VIII

Differences between Positions at 30 Degrees

Subject		Right Eye Temp.-Fov.	Right Eye Nas.-Fov.	Right Eye Temp.-Nas.	Left Eye Temp.-Fov.	Left Eye Nas.-Fov.	Left Eye Temp.-Nas.
T	Av.	11.7	8.6	3.1	16.2	10.6	5.6
	P.E.	*1.09*	*1.49*	*1.54*	*1.59*	*1.48*	*1.39*
P	Av.	12.4	10.2	2.2	11.5	7.4	4.1
	P.E.	*1.01*	*1.77*	*1.82*	*1.13*	*1.33*	*1.48*
M	Av.	16.3	7.0	9.3	14.5	11.2	3.3
	P.E.	*1.20*	*1.57*	*1.25*	*1.36*	*2.37*	*2.00*

TABLE IX

Differences between Positions at 10 Degrees

Subject		Right Eye Temp.-Fov.	Right Eye Nas.-Fov.	Right Eye Temp.-Nas.	Left Eye Temp.-Fov.	Left Eye Nas.-Fov.	Left Eye Temp.-Nas.
T	Av.	10.4	7.8	2.6	8.4	3.8	4.6
	P.E.	*1.50*	*1.56*	*1.79*	*1.56*	*1.52*	*1.59*
P	Av.	9.2	7.7	1.5	12.0	3.1	8.9
	P.E.	*1.01*	*0.94*	*1.47*	*1.28*	*0.90*	*1.28*

TABLE X

Differences between Positions at 3 Degrees

Subject		Right Eye Temp.-Fov.	Right Eye Nas.-Fov.	Right Eye Temp.-Nas.	Left Eye Temp.-Fov.	Left Eye Nas.-Fov.	Left Eye Temp.-Nas.
T	Av.	0.7	4.9	—4.2	6.4	2.8	3.5
	P.E.	*1.94*	*1.67*	*2.49*	*2.55*	*1.46*	*1.97*
P	Av.	11.2	11.7	—0.5	11.8	11.0	0.8
	P.E.	*1.18*	*0.81*	*1.31*	*1.09*	*1.28*	*1.54*

between the temporal side of the retina and the fovea (Temp.-Fov.), between the nasal side and the fovea (Nas.-Fov.), and between the temporal and nasal sides of the retina (Temp.-Nas.). Thus in Table VII., Temp.-Fov. under subject T at 45 degrees and on the right eye means that in this position the reaction time upon stimulation of the temporal side of the retina was 23.4 sigma slower than that upon the fovea. In every case but two (Temp.-Nas., Right Eye, at 3 Degrees for both T and P), the position mentioned first has the slower time, thus Temp.-Fov., Nas.-Fov., and Temp.-Nas. The times for the right and left hands have been averaged in these tables since they are intended to show the relations between the retinal positions themselves. The figures are obtained as follows: The differences between the averages of the series for the given positions are first taken. The average of these series-dif-

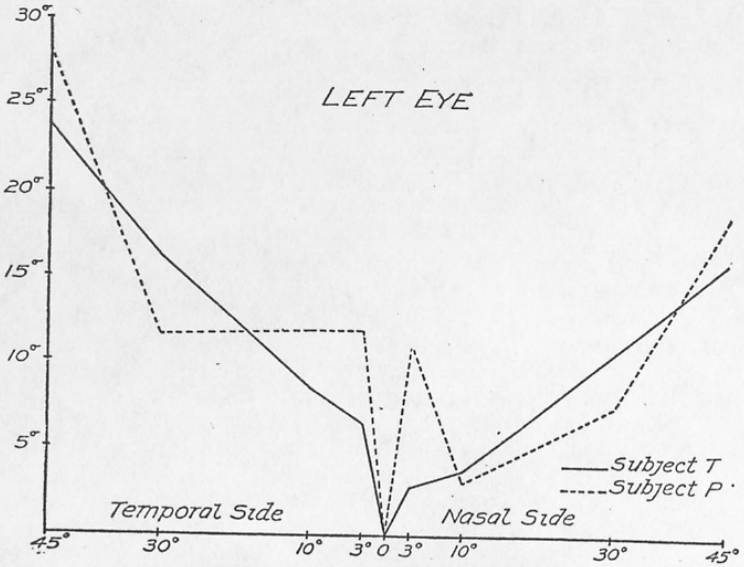

FIG. 3. Curve for the Left Eye, showing the differences in the reaction times for the fovea and the various eccentric positions.

ferences forms the final difference between the two positions. As the reactions by the two hands are combined, each average difference given in the tables is based on 400 reactions. By thus taking the differences between positions within a series as the unit, the variations in the absolute times from day to day through practise and other causes do not influence the results.

The probable error[1] (P.E.) is calculated according to the formula

$$\text{P.E.} = \frac{.8453 \text{ M.V.}}{\sqrt{n}},$$

in which M.V. is obtained according to Method 1, described in Section III. of this chapter, that is, an average of the 10 series-differences is first computed as explained above. Then the variations of these differences from the average are calculated. An average of these 10 variations forms the mean variation. The number of cases, n, equals 20.

[1] The probable errors calculated from the differences between series as units are considerably larger than if the individual reactions were taken as units, and the variations of the individual reactions from the average of the series were used, excluding thereby the variations from day to day. In this case n, the number of cases, would be 200, as compared with 20 by the method used in this work. To illustrate this fact, calculate the P.E. of the difference between temporal 45 degrees and the fovea, for the right eye of subject T (see Table VII.), according to the formula

$$\text{P.E. diff. } A-B = \sqrt{\left(\frac{\text{P.E. } B}{\sqrt{n}}\right)^2 + \left(\frac{\text{P.E. } A}{\sqrt{n}}\right)^2},$$

in which P.E. A is the probable error for the average of all the reactions upon the temporal position, and P.E. B is the same for the fovea. This gives a P.E. of 0.83 sigma as compared with 1.84 sigma, obtained by the method previously described. These lower probable errors are comparable with those obtained by Froeberg in his study on "The Relation between the Magnitude of Stimulus and the time of Reaction," ARCHIVES OF PSYCHOLOGY, No. 8, 1907.

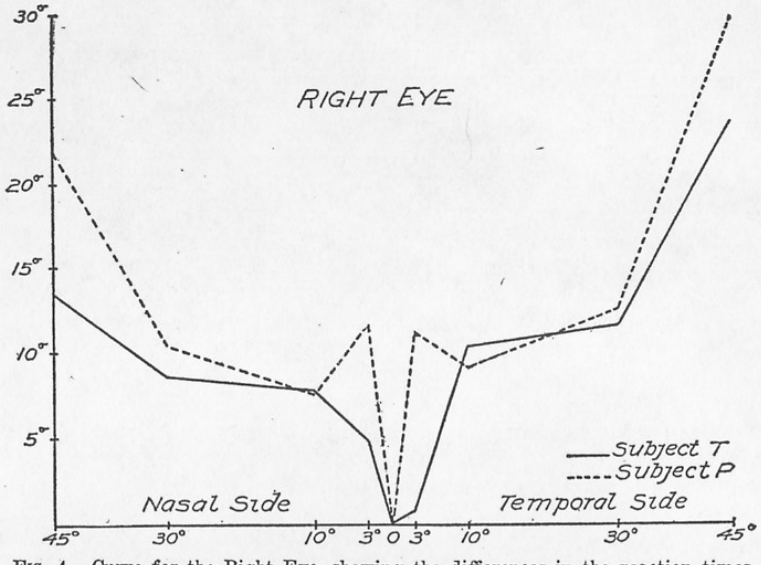

FIG. 4. Curve for the Right Eye, showing the differences in the reaction times for the fovea and the various eccentric positions.

Figs. 3 and 4 show graphically the results given in Tables VII., VIII., IX. and X. Fig. 3 represents the left eye, and Fig. 4 the right eye. In each case the nasal side of the retina is toward the inside of the page and the temporal side toward the outside of the page, that is, they occupy the positions in which one thinks of his own eyes. The abscissas are marked off in degrees and the ordinates are in terms of sigma. Since the data express differences from the fovea, the foveal position is at zero on both the ordinate and the abscissa. Curves for subjects T and P are given, since they alone completed all the positions. The solid line represents subject T and the broken line subject P. The curves for the two subjects agree

in general, the greatest departure being at three degrees, where P's reaction time is very slow compared with that of T and with his own time at 10 degrees. In the curves for both subjects the nasal side is lower than the temporal except at 3 degrees on the right eye in the case of each subject.

VII. Repetition of the Tests at 45 Degrees from the Fovea for Comparative Purposes

At the close of the whole experiment the tests upon T and P at 45 degrees from the fovea were repeated. It will be recalled from the description of Methods in Chapter IV., that all of the experiments at 45 degrees were made with the subject in a fixed position, that is, the head and body held the same position while the eyes were turned in their sockets to the various eccentric positions. The later work at 30, 10 and 3 degrees was done with the reaction chair, by which the head and body were turned and the eyes kept a normal position in the head. The introspections of the subjects showed that the latter method was more satisfactory. In order to compare these two methods, this second set of experiments was made. The results of both the first and the second methods are arranged in Table XI. for comparison. In the second column, Method 1 signifies the fixed position of the body, and Method 2, the use of the reaction chair. The results for the right and left eye are given separately and the data of the two methods for each subject are placed together. The figures in Table XII. represent differences between the positions named at the heads of the columns.

TABLE XI

Comparison of the Two Methods of Reacting at 45 Degrees from the Fovea

Right Eye

Subject		Right Hand			Left Hand		
		Fov.	Temp.	Nas.	Fov.	Temp.	Nas.
T	Method 1	205.5	228.0	223.0	213.4	237.3	222.5
	Method 2	179.1	207.2	193.5	181.0	205.2	194.3
P	Method 1	174.4	201.5	190.5	168.8	201.1	196.0
	Method 2	180.5	198.2	185.2	178.6	190.8	188.8

Left Eye

T	Method 1	203.5	227.7	221.6	212.3	236.0	226.1
	Method 2	183.9	205.0	193.5	180.8	201.8	190.4
P	Method 1	176.9	204.6	195.7	165.2	193.9	183.8
	Method 2	179.1	205.8	195.1	175.8	201.5	182.5

TABLE XII

Comparison of the Two Methods of Reacting in Terms of Differences

Subject	Method	Right Eye			Left Eye		
		Temp.-Fov.	Nas.-Fov.	Temp.-Nas.	Temp.-Fov.	Nas.-Fov.	Temp.-Nas.
T	Method 1	23.4	13.5	9.9	23.9	16.0	7.9
	Method 2	26.2	13.9	12.3	21.0	9.6	11.4
P	Method 1	29.7	21.7	16.1	28.2	18.7	9.5
	Method 2	15.0	7.5	7.5	28.0	11.4	16.6

Table XI. is interesting since the tests by method 1 were the first taken and those by method 2 were the last, after an interval of over one year. A comparison of the absolute times shows a considerable decrease for subject T and an increase for P by method 2. This same peculiar difference between the subjects was pointed out (Section III., Chapter V.) in comparing the times for the different distances from the fovea, in which method 2 was used, so that the change is not due in this case to the difference in method. The great change in the amount of the differences shown in Table XII. for subject P is due to the increased foveal times, a result probably of some physiological condition of the eye, induced by continual use of central vision in reading. However the results by Method 2 do not change the relative values for the positions at 45 degrees.

VIII. Comparison of the Reaction Times with other Retinal Qualities

A great number of investigations have been made of the qualities of peripheral vision, such as sensitivity, acuity, the extent of the visual field, the appearance of flicker, the apparent size of objects and the speed of movement on different parts of the retina. The results of these investigations will be compared with the present study.

1. Astronomers long ago discovered a difference in the *sensitivity* of the central and the peripheral parts of the retina by the fact that a faint star could be seen best in indirect vision. Numerous investigations have been made upon the light and the dark adapted eye, with varying results. A discussion of the subject may be found in "Über die Helligkeitsempfindung im indirecten Sehen," by Kirschmann.[8] In the same report he gives the results of his own work on retinal sensitivity. He compared the sensitivity of the fovea with the different eccentric positions in the following way: The subject looked directly at a revolving disc of black and white sectors and ad-

[8] *Phil. Stud.*, 5, 447–497, 1888–1889.

justed a second disc seen by a given peripheral portion of the retina, so that its brightness should be equal to that of the first disc. The actual difference in brightness value of the two discs was then calculated and expressed in terms of the foveal brightness. The following curves, Fig. 5, are constructed from such ratios, given in Tables 5*A* and 5*B*, on pages 468–471 of the same article. Distances along the abscissa measure degrees from the fovea, and distances along the ordinate measure sensitivity in terms of foveal sensitivity. The broken line represents the right eye and the straight line the left eye.

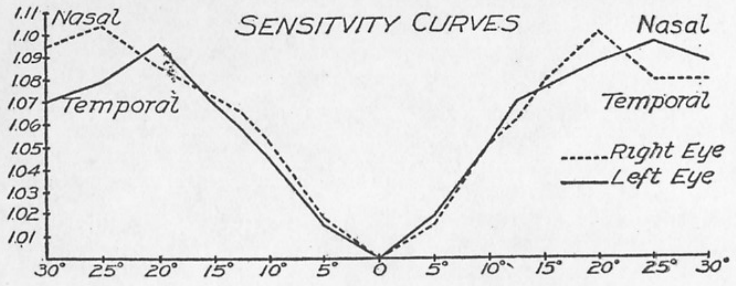

FIG. 5. Curves of Sensitivity for Different Parts of the Retina.

These curves show that the sensitivity of the retina increases as the distance from the fovea increases, as far as 25 degrees, when the sensitivity again begins to decrease. However the region of greatest sensitivity is less than 10 per cent. greater than that of the fovea. The sensitivity of the nasal side is greater than that of the temporal side, except at 20 degrees where the reverse is the case.[9] Comparing these curves with those for reaction times it seems that reaction time is not closely related to the sensitivity of the retina.

2. Ordinary observation teaches that *visual acuity* diminishes rapidly as we pass from the fovea toward the periphery of the retina. The method generally used in testing for acuity is to determine the distance at which certain letters may be read, or to determine the

[9] According to Schön, there is a marked difference between the light sensitivity of the nasal and the temporal halves of the retina. He found that a point 45 degrees from the fovea on the temporal side required for the production of a certain degree of brightness, three times as much light as the corresponding point on the nasal side. See Schön, *Arch. f. Ophth.*, Bd. 22, Abth. 4, 49, 1876; Bd. 24, Abth. 1, 27, 1878. Guillery, in "Vergleichende Untersuchungen über Raum-, Licht- und Farbensinn in Zentrum u. Periphery der Netzhaut," *Zeitschr. f. Psychol. u. Physiol. des Sinnesorgane*, 12, 243–274, 1896, considers the temporal half of the retina less sensitive than the nasal half, but the difference he describes as much less than that found by Schön.

distance two lines must be apart in order to be distinguished as two. The curve of visual acuity for different regions of the retina is shown in Fig. 6, and is adapted from one by Koester.[10] The abscissa measures the distance from the fovea in degrees. The scale for the ordinates is not given. The righthand curve (broken line) represents the nasal side of the right retina, and the lefthand curve (solid line) represents the temporal side of the left retina. This curve has in a general way the same characteristics as the reaction time curve; at least the acuity diminishes as the reaction time increases. In dark adaptation the acuity of the periphery of the retina is greater than that of the fovea. It is interesting to note that the relation between acuity and reaction time might be shown by repeating the reaction experiment at night or with the dark-adapted eye to see whether the reaction-time curve would reverse itself as the acuity curve does.[11]

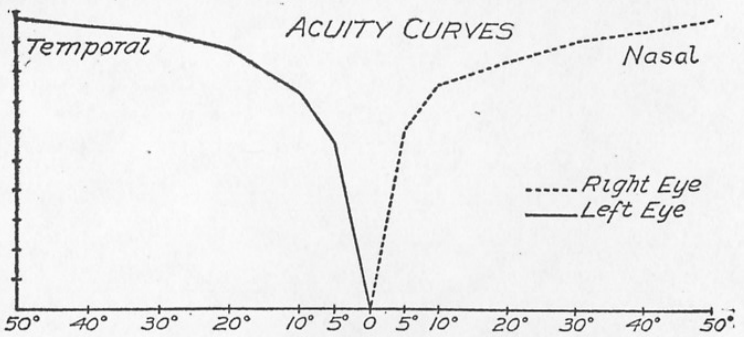

FIG. 6. Curve of Visual Acuity for Different Parts of the Retina. (Adapted from Koester.)

3. The relative speed of reaction upon stimulation of the temporal and the nasal sides of the retina may be compared with the *extent of the visual field* in these regions. In the average eye, the visual field on the temporal side corresponding to the nasal side of the retina, extends at least to 90 degrees, while the nasal side of the visual field, corresponding to the temporal side of the retina, is cut off by the nose at about 60 degrees. An average of the differences

[10] "Über Stäbchen- und Zapfensehschärfe," *Centralbl. f. Physiol.*, 10, 433–436, 1896. The direction of the curves by Koester has been reversed, they are marked in terms of the retina instead of in terms of the visual field, and the scale upon the ordinate has been reduced.

[11] The distribution of the rods and cones throughout the retina might be considered in connection with the reaction time curve, but as acuity is considered to be very closely related to the arrangement of the rods and cones, this latter physical characteristic of the retina will not be discussed.

in reaction time between the temporal and the foveal position for both eyes and for both hands, and an average of the same for the nasal and foveal positions, shows that the difference for the nasal side is approximately two thirds of that on the temporal side. This means that the nasal side gives a quicker reaction by about one third than the temporal side.

4. Exner[12] and Bellarminow[13] have found that *flicker* is more marked in the periphery than in the center of the visual field, and have inferred from this that the intensity of the sensation produced by a certain stimulus is greater there. The latter has found also that flicker occurs more readily upon stimulation of the nasal half of the retina than upon the temporal half.

5. Within the last four years Stevens[14] has published three experiments upon "The Peculiarities of Peripheral Vision," with special reference to the *apparent size of objects* and the *apparent speed of movement* in different regions of the visual field, and their relation to right-handedness. The last report contains a review of previous work on the subject. His general conclusions from his own work are that with few exceptions the right half of an extent in the visual field is overestimated, and that this estimation holds true for both eyes. Such an extent would cast its image upon the left corresponding halves of the two retinas and the impulses set up would reach the left occipital cortex. This predominance of the right half of the visual field does not appear in a study of the sensitivity and acuity curves of the different retinal areas, but in these cases the nasal seems to surpass the temporal of each eye.

IX. Conclusions

1. With the exception of subject *P* at 3 degrees the reaction time increases as the distance from the fovea is increased.

2. The nasal side of the retina gives a faster reaction than the temporal side, in nearly every case when the times for the two hands are combined.

3. This relation between the temporal and the nasal side of the retina agrees in general with the extent of the visual fields corresponding to the temporal and the nasal side of the retina; with the acuity relations of these two sides and with the relations of retinal sensitivity; it also agrees with the appearance of flicker upon the two halves of the retina.

[12] *Sitzungsb. d. k. Akad. d. Wissensch.*, Wien, Bd. **58**, Abth. 2, s. 601, 1868.
[13] *Archiv. f. Ophth.*, Bd. **35**, Abth. 1, s. 25, 1889.
[14] *Psych. Rev.*, **15**, 69 ff., 1908; **15**, 373 ff., 1908. Stevens and Ducasse, "The Retina and Righthandedness," *Psych. Rev.*, **19**, 1–31, 1912.

CHAPTER VI

OTHER TIME RELATIONS

This chapter will deal with several problems: (I.) The Relation between the Speed of Reaction of the Right and Left Hands. (II.) The Relation between the Speed of Reaction to Monocular and Binocular Stimulation. (III.) Homolateral and Contralateral Time Relations between Hand and Eye, that is, a comparison of the reaction time of the right hand to stimulation of the right eye and of the left eye, and *vice versa*. Only the first of these problems directly concerns our investigation proper. The other two are closely related and seem to be of sufficient interest to be included in this chapter.

I. Relation between the Reaction Time of the Right and Left Hands

In addition to the differences between retinal areas discussed in Chapter V, it is necessary to find whether there is a difference in the speed of reaction of the right and left hands, for if there is such a difference it must be eliminated, as suggested at the close of Chapter III. The results of previous experimental work in this field are conflicting, so that it is necessary to repeat the test under the conditions of this experiment, in order to draw conclusions which shall be valid, at least for the subjects taking part in this research.

According to Cattell,[1] the duration of the reaction time is the same for the right and left hands. In the case of light stimuli, his average time for the right hand was 146 sigma and for the left hand 147 sigma. Kiesow[2] took a series of 50 reactions to sound with each of the five fingers of each hand. The reactions were of the sensory type, the source of sound was the Wundt sound hammer and the time was recorded with the Hipp chronoscope. The sound is described as of moderate intensity. The following figures show the averages for the fingers of each hand with the mean variations. I have calculated the averages of the right and left hands together with the mean variation and the probable error of the averages.

[1] "On Reaction Time, etc.," *Memoirs Nat. Acad. Sci.*, **7**, 395 and 411, 1893.
[2] "Beobachtungen über die Reaktionzeiten momentaner Schalleindrücke," *Archiv f. d. ges. Psych.*, **16**, 353–375, 1910.

	Right Hand			Left Hand			
	Av.	M. V.	P. E.	Av.	M. V.	P. E.	Diff.
1st finger	171.7	19.5		172.4	16.8		
2d finger	175.2	17.0		178.0	13.5		
3d finger	166.8	18.5		173.8	13.0		
4th finger	170.5	16.3		176.2	16.5		
5th finger	175.3	19.5		168.7	18.2		
Average	171.9	18.2	1.0	173.8	15.6	0.8	1.9

The M.V. is obtained by averaging the mean variations of the different fingers. The P.E. is obtained according to the formula

$$\text{P.E} = \frac{.8453\ \text{M.V.}}{\sqrt{n}}$$

in which $n = 250$. The difference is quite small but Kiesow believes that there is a distinction between the reaction times for the two hands and considers the problem worthy of further study. It is interesting to notice that this difference is just about the same as that found by Cattell, although the latter considered the times for the two hands the same.

Kiesow, in the same publication reports a more extended research upon the same problem. The reactions were of the motor type and the sound he describes as strong. Seven persons acted as subjects. The averages are given by Kiesow in series of ten for each hand, but I have combined them into general averages. The averages for the first three subjects include 1,000 reactions each, for the fourth 500 and for the last three 250 reactions each. The first four subjects were right-handed and the last three were left-handed. The letters r.h. and l.h. following the name of the subject designate the right- and the left-handed subjects respectively. These averages are given in Table XIII. In the last column are given the differences between the two hands, the minus sign indicating that the left hand is faster.

This table shows clearly that in the right-handed persons, the right hand is somewhat faster than the left hand; in the left-handed

TABLE XIII

REACTION TIME OF RIGHT AND LEFT HAND TO AUDITORY STIMULI (KIESOW)

	Right Hand		Left Hand		
Subject	Av.	M. V.	Av.	M. V.	Diff.
J. C. (r. h.)	105.3	5.3	109.3	5.5	4.0
C. S. (r. h.)	105.2	6.2	109.8	6.4	4.6
L. B. (r. h.)	105.6	5.3	107.6	6.0	2.0
M. P. (r. h.)	108.0	6.9	111.1	6.5	3.1
R. (l. h.)	116.5	8.0	107.5	7.0	—9.0
M. M. (l. h.)	113.4	8.5	110.4	8.6	—3.0
P. E. (l. h.)	114.8	8.5	111.6	7.8	—3.2

persons the left hand is somewhat faster than the right. Kiesow mentions the work of Herlitzka,[3] who found somewhat higher results, by a slightly different method. The differences were in the same direction as those found by Kiesow.

A set of experiments upon the reaction time of the right and left hands was made in this research, in order to discover whether a difference between the time of the two hands would be a disturbing factor, which would have to be eliminated before the data could be properly interpreted. One subject, *P*, is left-handed and the others are right-handed. The tests consisted of reactions to light made as described in Chapter IV., except that both eyes were open and the light stimulus arranged to strike the center of vision of both eyes equally. According to the conduction paths as they have been outlined, association between the hand and the center of vision of each eye would be through equally direct paths, and any difference in time between the reaction of the two hands would be due to other causes such as training. Table XIV. gives the results of these experiments on three subjects. The figures for each hand are the average of 100 reactions for subjects *T* and *A*, and of 200 for subject *P*. The reactions were taken in series of 10 alternately with the right and left hand.

TABLE XIV

REACTION TIME OF RIGHT AND LEFT HANDS WHEN BOTH EYES ARE STIMULATED

	Right Hand		Left Hand		
Subject	Av.	M. V.	Av.	M. V.	Diff.
T (r. h.)	184.4	9.9	184.7	5.2	0.3
P (l. h.)	160.4	4.4	162.5	5.2	2.1
A (r. h.)	178.9	6.5	177.2	5.0	—1.7

The differences between the reaction times of the right and left hands are even smaller than those found by Kiesow. In subject *P* who is left-handed, the right hand is faster than the left by 2.1 sigma; in subject *A* who is right-handed, the left hand is slightly faster, 1.7 sigma; and in the case of subject *T* there is no real difference.

When only one eye is stimulated on its fovea the differences are larger and the relations are slightly changed. In Table XV. these averages for the three subjects are given with their mean variations. Each figure is an average of 400 reactions for subjects *T* and *P*, and of 200 reactions for subject *A*.

[3] "Ricerche cronografiche sui movimenti volontari bilaterali," *Arch. di fisiol.*, 5, 277–284, 1908.

TABLE XV

REACTION TIME OF RIGHT AND LEFT HANDS WHEN ONE EYE IS STIMULATED

Subject	Right Hand Av.	Right Hand M. V.	Left Hand Av.	Left Hand M. V.	Diff.
T (r. h.)	200.5	8.4	202.1	8.8	1.6
P (l. h.)	177.5	3.8	171.7	5.2	—5.8
A (r. h.)	193.9	9.4	188.5	12.5	—5.4

Inspection of this table shows that subject *P*'s *left* hand gives the quicker reaction when one eye is stimulated, the reverse of that shown in Table XIV. For the other two subjects the differences are increased in the same direction. It is these differences upon monocular stimulation which are of significance in this investigation, because all the regular experiments are carried on under monocular stimulation. No explanation is offered for the change in the direction of the differences as the stimulus falls upon one eye or two eyes.

II. RELATION BETWEEN THE SPEED OF REACTION TO MONOCULAR AND BINOCULAR STIMULATION

Table XVI. shows the difference in reaction time when the stimulus strikes only one eye and when it strikes both eyes.

TABLE XVI

REACTION TO MONOCULAR AND BINOCULAR STIMULATION

Subject	One Eye Av.	One Eye M. V.	Both Eyes Av.	Both Eyes M. V.	Diff.
T	201.3	8.6	184.6	5.0	16.7
P	174.8	6.0	160.4	5.0	14.4
A	191.2	11.0	178.1	6.0	13.1

The last column in the table shows the differences. The data for this study are taken from Tables I., II. and XIV. The reactions with the right and left hands to foveal stimulation are combined separately for each eye, making a total of 800 reactions for each eye, except in the case of subject *A*, with a total of 400 reactions. It is the averages of these 800 reactions which appear in Table XVI. under the column marked "One Eye." The figures under the column marked "Both Eyes" are the combined averages of the right and left hands taken from Table XIV. and are made up of 200 reactions for subjects *T* and *A*, and 400 reactions for *P*.[4]

[4] The tests with binocular stimulation were made between the tests recorded in Tables I. and II. This arrangement would equalize the practise effect in the two kinds of tests compared in Table XVI. For this reason the foveal times in Tables III. and IV. are not averaged in with those in Tables I. and II. As subject *A* appears only in Table I., her reactions to binocular stimulation followed those to monocular stimulation. Therefore, if the practise effect were appreciable in the case of *A*, it would make her differences in Table XVI. too high.

There seems to be a clear difference in the speed of reaction when one eye is stimulated and when both eyes are stimulated, and the differences are almost the same for the three subjects, 16.7, 14.4 and 13.1. It is difficult to explain this difference as due to the retinal apparatus. It has been found that the apparent increase in brightness is about one tenth when the two eyes observe an object instead of one eye. But such a small difference in brightness value would offer no explanation for the difference in reaction time. According to the work of Froeberg, a reduction of 50 per cent. in the brightness of a stimulus makes a difference of only a few sigma in the reaction time. Ordinary observation shows that there can not be a great difference in the brightness under monocular and binocular vision, or there would be a difference in the brightness of parts of our visual field, according as an object fell within the range of binocular vision or only of monocular vision. One might attribute the whole difference to the unusual conditions imposed by monocular vision in an ordinary person. But the eye screen employed allows the unused eye to remain open and after a very short time seems to give no discomfort. As stated in Chapter IV., the subject was often unable to tell which eye was closed and which was open without feeling with his hands.

If the difference in the speed of reaction upon stimulation of both eyes or one eye, is a central one, that is, if it is due to a difference in the speed of conduction through the brain centers, then the dynamogenic effect of simultaneous stimuli might afford an explanation.[5] Each fovea is represented on each occipital cortex, so that a stimulus striking the fovea of one eye would react upon both visual

[5] Dynamogenesis is discussed by James and others. (See James, "Principles of Psych.," 2, 379 ff., 1908.) Feré in "Sensation et Mouvement," 1889, describes a large number of experiments to show the dynamogenic effect produced through the difference senses. In the cases cited by Feré, the reinforcing stimuli are received through sense organs other than those to whose stimulation the subject is reacting, and the effect is explained as a diffusion or overflow of the nervous energy. This reinforcement would occur, the writer believes, to an even greater extent, where both stimuli act directly on the same sense organ and hence on the same cerebral center.

The latest work on dynamogenesis is that of Todd, "Reaction to Multiple Stimuli," ARCHIVES OF PSYCHOLOGY, No. 25, 1912, in which the author finds considerable reinforcement effect in the case of visual, auditory and tactual stimuli.

centers in the cortex. A stimulus falling on the fovea of each eye would act as a double stimulus upon each visual center. Since it is one of the generally accepted qualities of a center, that the time lost therein decreases as the intensity of the stimulus increases, the greater energy set free by the double stimulus would account for the decrease in reaction time.

III. Homolateral and Contralateral Time Relations between Hand and Eye

The third problem to be considered in this chapter is that of the time relations between hand and eye, on the same side of the body, and on opposite sides of the body. There is a general belief that the eye and hand, foot, etc., on the same side of the body are more closely related than the eye and those members on the opposite side of the body. The following quotations are taken from Gould's[6] book on "Right-handedness and Left-handedness."

> Right-handedness is necessarily bound up with right-eyedness, with right-earedness, with right-footedness. . . . We are usually as right-eyed as we are right-handed. The reason for this general choice of the arm and hand, of eye, of ear, and of leg and foot for conjoined expert tasks is easily recognized. It insures a speedier and more accurate synthesis of the cerebral functions which must be coordinated into a single act and result. The independence of the two halves of the brain makes it necessary that the bodily organs most commonly acting together and most interdependent should be incited and controlled by the cerebral centers in close contiguity and in one side of the brain. There is a measurable slowness of nerve current transmission, . . . and even if the connecting links between the two brain-halves were much more intimate and numerous and short than they are, rapidity and accuracy of correlation and unification in willed act would be impaired, and the safety and decision of the entire organism imperiled, if one or two of the coacting centers were in opposite hemispheres (pp. 30–31).
>
> Physiologically, therefore, the reason why an infant puts forth the right hand to grasp objects is because the right eye is the one which is nearest perfect visually, anatomically, or optically (p. 44).

The preceding quotations refer to the general relation between members on the same side of the body. The following studies relate to the particular relations existing between the sensory and motor apparatus in the same member.

Numerous investigations have been made to determine whether the reaction time is faster when the stimulus is applied to the reacting member, and the conclusions do not all agree. The experiments of Exner[7] showed that upon electrical stimulation of the

[6] "Right-handedness and Left-handedness," 1908.

[7] See Exner, "Hermann's Hanb. der Physiol.," 2, Pt. 2, 264, 1879.

hand, the reaction was 10 sigma longer when the stimulus was applied to the reacting hand. Sanford[8] repeated the experiments of Exner, on several subjects, using the induction shock as a stimulus. He found just the opposite results from those of Exner, that the times were faster in every case when the stimulus was applied to the reacting hand. The case of stimulation and reaction by right hand gave times faster than those upon stimulation of the left hand and reaction by the right hand, by 14.3, 2.4 and 3.3 sigma for the three subjects. When the stimulus is applied to the left hand, the reaction by the left hand is faster than that of the right hand by 1.7, 16.9 and 3.7 sigma for the three subjects.

Cattell[9] found the reaction time, when the stimulus was applied to the reacting hand to be 21.1 sigma shorter for one subject and 9.4 sigma shorter for another subject, than when the other hand reacted. He says:

> This might be expected, as the movement is a natural reflex—a person will without reflection withdraw the hand when it touches a hot surface.

The work about to be reported is more analogous to the first study quoted, the relation between members on the same side of the body. Table XVII. shows the relation between hand and eye on the same and opposite sides of the body, for subjects *T* and *P*.

TABLE XVII

Homolateral and Contralateral Relations between Hand and Eye

	Right Eye				Left Eye			
	Right Hand		Left Hand		Right Hand		Left Hand	
Subject	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
T (r. h.)	193.2	7.7[10]	197.0	6.6	192.8	7.5	195.9	8.1
P (l. h.)	178.4	3.8	173.7	3.8	181.1	3.5	173.0	4.8

Each figure is an average of 400 reactions, being the average time for the foveal position in each of the Tables I., II., III. and IV. For subject *T*, the faster times are obtained where the right hand reacts, regardless of the eye, in fact the time is a trifle shorter for the left eye, that is the eye *opposite* to the reacting hand. For subject *P*, the faster times occur where the left hand reacts, the time being practically the same whether the stimulus falls upon the right or the left eye. The conclusion from this table must be that, as far

[8] "On Reaction Times when the Stimulus is Applied to the Reacting Hand," *Am. J. Psych.*, 5, 351–355, 1892–1893.

[9] "On Reaction Times, etc.," *Memoirs Nat. Acad. Sci.*, 7, 410, 1893.

[10] These deviations are the averages of the deviations given in Tables I., II., III., IV., for the given positions.

as the reaction times are concerned, the relation between hand and eye on the same side of the body is no closer than that between hand and eye on opposite sides of the body.

One would not expect an especially close connection between hand and eye on the same side of the body, as a result of the anatomical relations between them. For according to the arrangement of the optic fibers as they were discussed in Chapter III., each eye (speaking of the central vision only, which the figures in Table XVII. represent) is equally represented on each cerebral cortex. Even considering peripheral vision, one would not expect one eye, as a whole, to be related to a given hand, but the left side of each eye would be most directly connected with the right hand, and the right side of each eye with the left hand. (These relations may be easily seen by glancing at Fig. 1.) This means that an object in the right visual field would cast its image upon the left side of each retina, and would be most directly connected with the right hand, or that hand nearest to the object seen. Even if the right eye were defective, a stimulus coming from the right visual field would still find its most direct course to the right hand, as the stimulus would fall upon the temporal side of the left eye as well as upon the nasal side of the right eye. To speak physiologically therefore, better vision in the right eye would not account for right-handedness, as Gould states in the work quoted. On the contrary, the anatomical relations of the separate halves of the retina with the occipital cortex and this in turn with the hands, would make the right hand most directly associated with objects in the right visual field and *vice versa,* but not with the right or the left eye as a whole. Right-handedness would not necessarily mean greater development of the left occipital cortex and the consequent evolution of the left hemisphere as the dominant one (see Gould, *loc. cit.,* p. 43).[11]

[11] Stevens, quoted in Ch. V., in "The Retina and Right-handedness," shows that in the right half of the visual field in right-handed persons, objects appear larger than in the left half of the visual field. On these facts he bases his theory of right-handedness. This theory conforms more closely to the anatomical arrangement of the optic fibers than the theory proposed by Gould. The reactions by the right hand to stimuli coming from the right visual field (acting upon the nasal side of the right eye and the temporal side of the left eye) are faster in subject *T* by 0.6 sigma, than to those coming from the left half of the visual field, when reacted by the left hand. In subject *P,* the difference is 5.5 sigma in the opposite direction, that is, reaction by the left hand to stimuli coming from the left half of the visual field is quicker than reaction to stimuli from the right half of the visual field by the right hand. This result is interesting since subject *T* is right-handed and *P* is left-handed. Although the difference in the case of *T* is too small to be significant, the tendency of the two subjects shows for reaction time, what Stevens showed for size of objects, a preference for the right half of the visual field in right-handed persons and for the left half of the visual field in left-handed persons.

The case where the stimulus is applied to the reacting member is quite different from that of vision. By the anatomical arrangement of the sensory and motor fibers, that is, the total decussation of both the motor and sensory fibers leading to and from the limbs, the muscles of one hand would be most directly associated with the sensory nerve endings in that hand, and a reflex over that arc would be most simple.

Conclusion.—To conclude from the data set forth in this chapter, there is a difference in the reaction time of the right and left hands, in the subjects tested, which must be accounted for in the calculation of central time as proposed in the preceding chapters, and which will be taken up in Chapter VII. Further, we may conclude that when the stimulus acts upon both eyes the reaction time is faster than when only one eye is stimulated, probably the dynamogenic effect of the double stimulus. And from the last section of the chapter we may conclude that the relation between hand and eye on the same side is no closer, as far as reaction time is concerned, than between hand and eye on opposite sides of the body.

CHAPTER VII

SYNAPSE TIME

THE purpose of this investigation is to find a means of measuring the time lost in the transmission of an impulse through a synapse within the human nervous system, and to obtain an approximate measure of this lost time. The preceding six chapters have prepared the way for its discussion.

1. They show (Chs. I. and II.) the difficulties and errors which have occurred in the previous studies of conduction through nerves and nerve centers; they show also that in the living human being, the reaction-time method is the only means by which the problem can be approached.

2. They show (Ch. II.) that the problem may be solved by comparing the reaction time over two nerve paths identical except that the one must cross from one side of the brain or cord to the other, thereby involving one additional synapse or system of synapses.

3. The conduction paths involved in stimulation of the eye, and reaction to this stimulus by the hand are shown (Ch. III.) to fulfill these requirements by virtue of the peculiar division of the optic fibers in passing through the optic chiasm. Chapter III. analyzes these conduction paths and points out certain preliminary problems which the use of these paths involves.

4. Chapter IV. describes the apparatus and methods which are employed in the study of these paths.

5. Chapter V. discusses the first of the preliminary problems, the difference in the quality of the different parts of the retina, showing itself in a difference in the speed of reaction to stimulation of these parts, and shows that account must be taken of this difference.

6. Chapter VI. considers the second of the preliminary problems, the difference in the reaction time of the right and left hands. It shows that when one eye only is stimulated, there is a difference in the reaction time of the two hands, which would, unless removed, probably obliterate the differences in time due to synapses. In addition, this chapter takes up two other problems not directly associated with the main probem, but having a certain intrinsic interest.

We have found that the *right* hand is most directly associated

with the *right* retina on its *nasal* side (*A*, Fig. 1) and with the *left* retina on its *temporal* side (*A'*, Fig. 1); also that the *left* hand is most directly associated with the *right* retina on its *temporal* side (*B*, Fig. 1), and with the *left* retina upon its *nasal* side (*B'*, Fig. 1). These four conduction paths from eye to hand will be called direct, as they are the ones which do not involve the association tract between the two motor centers.

Those paths which do involve this association path between the motor centers, will be called indirect. They are the paths traversed when the *right* hand reacts to a stimulus upon the *temporal* side of *right* retina, and upon the *nasal* side of the *left* retina; also when the left hand reacts to a stimulus upon the *nasal* side of the *right* eye, and the *temporal* side of the *left* eye. To put these conduction paths into an abbreviated form so that they may be seen at a glance, we will use R.E. and L.E. for right and left eye respectively, R.H. and L.H. for the right and left hand respectively and Temp. and Nas. for the temporal and the nasal sides of the eye, and arrange them as follows:

Direct	R.H.	R.E. Nas.	Indirect	R.H.	R.E. Temp.
		L.E. Temp.			L.E. Nas.
	L.H.	R.E. Temp.		L.H.	R.E. Nas.
		L.E. Nas.			L.E. Temp.

Comparison of any one direct path with any one indirect path will have in it as a disturbing factor either the difference in time due to the retinal area stimulated, or to the difference between the reaction time of the two hands. For example, to compare the first line of the direct with the first line of the indirect paths in the chart, and put them into the form of an equation, we have

R.H. R.E. Nas. < R.H. R.E. Temp.

No difficulty arises from the hands since both sides of the equation contain R.H. But one side contains Nas. and the other Temp. and as the temporal side of the retina, independently of the hand associated with it, gives a longer reaction than the nasal side, this would affect the result. Compare the first line of the direct with the third line of the indirect paths and we have

R.H. R.E. Nas. < L.H. R.E. Nas.

In this case Nas. appears on both sides of the equation, while the difference between the right and left hands remains as the disturb-

ing factor. But when the whole four direct paths are combined into an equation with the four indirect paths we have

$$\left.\begin{array}{l}\text{R.H. R.E. Nas.}\\ \text{R.H. L.E. Temp.}\\ \text{L.H. R.E. Temp.}\\ \text{L.H. L.E. Nas.}\end{array}\right\} < \left\{\begin{array}{l}\text{R.H. R.E. Temp.}\\ \text{R.H. L.E. Nas.}\\ \text{L.H. R.E. Nas.}\\ \text{L.H. L.E. Temp.}\end{array}\right.$$

Now Nas and Temp. and R.H. and L.H. are equally distributed on each side of the equation. The averages of these two sides of the equation should give results in which the right hand offsets the left and the nasal side of the retina offsets the temporal side, so that both the disturbing factors are eliminated. It is the possibility of thus combining the several factors in question that makes these paths especially fitted for the present study. Solving this equation, then, should give a difference which is due to the time consumed in the passage of the impulse across the synapse or synapses involved.[1]

$$\left.\begin{array}{l}\text{R.H. R.E. Temp.}\\ \text{R.H. L.E. Nas.}\\ \text{L.H. R.E. Nas.}\\ \text{L.H. L.E. Temp.}\end{array}\right\} - \left\{\begin{array}{l}\text{R.H. R.E. Nas.}\\ \text{R.H. L.E. Temp.}\\ \text{L.H. R.E. Temp.}\\ \text{L.H. L.E. Nas.}\end{array}\right. = \text{Synapse Time.}$$

Table XVIII. gives the values obtained from the solution of this equation, for the four distances from the fovea, 45, 30, 10 and 3 degrees.

TABLE XVIII

SYNAPSE TIME

Subject		45 Deg.	45 Deg.*	30 Deg.	10 Deg.	3 Deg.	Av.
	Av.	−1.5	0.5	4.5	6.2	6.2	5.6
	M.V	*13.2*	*13.6*	*6.9*	*7.9*	*6.9*	
	P.E.	*1.78*	*2.55*	*0.92*	*1.05*	*0.92*	
	Av.	1.7	5.7	7.0	4.6	6.4	6.0
	M.V.	*10.6*	*13.2*	*7.2*	*8.2*	*5.0*	
	P.E.	*1.41*	*2.48*	*0.96*	*1.09*	*0.67*	
	Av.	−1.6					
	M.V.	7.7					
	P.E.	*1.02*					
	Av.			2.0			
	M.V.			*8.3*			
	P.E.			*1.50*			

[1] The difference thus obtained would obviously include the length of nerve between the two motor areas in the two hemispheres. If the speed of transmission of the nerve impulse be taken as 30 meters per second, then in one sigma it would travel 3 cm. Considering the length of these fibers to be 6 cm., their conduction time would be 2 sigma, which would be a constant quantity.

Four subjects are represented in the table, *T* and *P* when the temporal and nasal position are each 45, 30, 10 and 3 degrees from the fovea; subject *A* when they are 45 degrees from the fovea; and subject *M* when they are 30 degrees from the fovea. These distances are represented in the vertical columns of the table and the subjects in the horizontal lines. Two columns marked 45 degrees appear in the table. The second one marked with a star contains the differences obtained from a repetition of the first experiment at 45 degrees. It consisted of 5 series or 50 reactions upon each position, half the number which make up the figures in the first column of the table. The original averages for the figures in the first column are given in Tables I.–IV., and for those in the second column, in Table XI. This later work was repeated only on subjects *T* and *P*. As subject *A* served only for tests at 45 degrees, and *M* for tests at 30 degrees, values for these subjects appear in columns marked 45 and 30 degrees. The last column in the table requires further explanation and will be discussed later.

Each figure in the table (with the exception of those for subject *M* and those for *T* and *P* in the second column at 45 degrees) is based on 800 reactions,[2] while the whole table comprises about 10,000 reactions.

Consider first the differences obtained at 45 degrees from the fovea, given in the first column of Table XVIII. In subject *T* the difference is a negative one, that is, the path which has been described as direct gives the longer reaction time by 1.5 sigma. In subject *P* the difference is 1.7 sigma in the positive direction, the direct path faster; in subject *A* the difference is also negative by 1.6 sigma. In these three cases the mean variations are high and the differences fall within the limits of the probable errors, 1.78, 1.41 and 1.02. The negative values for the differences are therefore not significant, since the chances are small that they are real. The difficulty and uncertainty, described by the subjects in reaction to stim-

[2] The differences given in Table XVIII. were not obtained by subtracting one grand average of 400 reactions from another similarly obtained, but they are the average of 40 differences between series of 10 reactions each. And the mean variations are the variations of these series differences from the average difference. By this method of calculating the mean variation, the P.E. is obtained according to the formula

$$\text{P.E.} = \frac{.8453\ \text{M.V.}}{\sqrt{n}}$$

where n equals 40. By a different method of calculating the M.V. described in Ch. V. (note, p. 50), the P.E. would appear considerably lower, as n would equal 400.

ulation of this extremely peripheral position, are supported by these large mean variations. The fact that a valid difference due to the synapse time fails to appear in this instance, supports rather than detracts from the results obtained upon the less eccentric positions. It has been suggested that the difference would be less in the cases which I have designated direct, because it is customary to react on the side from which the stimulus comes, whatever the nature of the stimulus may be. But just where this cause should act most forcibly, at an extremely eccentric position, the differences fail to appear, and at 3 degrees where the head and body are turned almost directly toward the stimulus, a real valid difference occurs. Therefore considering the unreliability of the figures from which the values at 45 degrees are obtained, and the generally unfavorable conditions attendant upon reaction to stimulation of such an eccentric position, the writer feels justified in excluding these averages from the calculation of the average synapse time.[3]

The second column in the table, marked with a star, was partly explained above. In these tests the revolving chair was used instead of rotating the eyes in their sockets. In this case the differences shown in the table are both positive, 0.5 and 5.7 sigma, but again the probable errors are so high as to make the difference, for subject *T* at least, of no validity. It is upon the less eccentric positions that I consider the differences by far the more reliable, aside from my knowledge of the probable errors of the figures.

The third column in the table shows the differences at 30 degrees. For subject *T* the direct path is 4.5 sigma faster than the indirect path. As the probable error is less than one (0.92), the chances are less than 1 out of 1,000 that the difference is not a real one. For subject *P* the direct path is 7.0 sigma faster than the indirect one, with a P.E. of only 0.96. The tests upon subject *M* were at 30 degrees from the fovea and the differences are given in this column. Only five series of reactions were taken upon this subject, as stated in Chapter V. The difference is 2.0 sigma in favor of the shorter path, but the P.E. of 1.50 is too high to make this difference very reliable. However the tendency toward faster times over the direct paths supports the results from the other two subjects.[4]

[3] It was the original intention of the experimenter not to include the reaction time to stimulation at 45 degrees from the fovea, in the study of synapse time, for the reasons given above. The work was done on this position in order to make the curve of reaction time to stimulation of different retinal areas more complete. Reactions were also attempted at 60 degrees, but tests at this distance were deemed unnecessary.

[4] Experience with several subjects convinced the writer that such an intensive study as the present one must be limited to one or two subjects trained in reaction time work and familiar with the requirements of psychological experiments. In addition to this, they must have an immense amount of time at the disposal of the experimenter. For these reasons the main conclusions will be drawn from the data upon subjects *T* and *P*.

At 10 degrees, in the fourth column of the table, subject *T*'s time is faster over the direct path by 6.2 sigma, with a P.E. of 1.05. For subject *P*, the difference is 4.6 sigma in favor of the direct path with a P.E. of 1.09. Although the P.E. is slightly over 1 in both these cases, the chances are still less than 1 out of 1,000 that the difference is not a real one.

The fifth column of the table shows the synapse time when the stimulus is applied at 3 degrees from the fovea. The direct path for *T* is 6.2 sigma faster than the indirect, exactly the same value found at 10 degrees, and the P.E. is lower, 0.92. For subject *P* the direct path is 6.4 sigma faster than the indirect, with a P.E. of 0.67. This difference for *P* is just about the same as that found for *T* at 3 degrees. The similarity between the results for the two subjects and the low probable errors further confirm the statement made above, that the less eccentric the position the more valid is the result.

The last column in the table gives the average synapse time for subjects *T* and *P*, including in the average the differences found at 30, 10, and 3 degrees.[5] There is no particular advantage in computing the average of these figures, except to make a general comparison with the results of other experimenters, for an average does not show the great similarity in the results for the two subjects in the three distances from the fovea. The values for the synapse time obtained by experimenting upon the different eccentric positions agree very closely. The reliability of these figures must be raised considerably above that shown by the P.E. when one considers that in three different situations with weeks intervening between the separate experiments, such similar results have been obtained.

If the arguments in the introductory chapters of this work, which are based on the most generally accepted theories of nerve action and upon the results of recent researches in this field, are correct, we have determined the time required for the nerve impulse, whatever its nature may be, to traverse one synapse or system of synapses. Moreover this has been done without using any of the conflicting calculations of the speed of conduction in the plain nerve.

[5] The differences at 45 degrees have been excluded from the averages for the reasons given above. The following figures give the averages including the figures in columns 1 and 2, that is, the two sets at 45 degrees: *T* 3.2 and *P* 5.1 sigma.

No work has been done upon human beings, where the time value has been limited to one nerve unit, and only a few researches of a similar nature have been made upon animals. The results of Wundt's experiments upon the spinal cord of a frog were given in Chapter II (p. 20). He stimulated the sensory nerve leading from the gastrocnemius muscle at its entrance into the cord and recorded the time of the reflex muscular response in the muscle on the same side of the body. He then stimulated the sensory nerve on the other side of the body and recorded the latent period of the same muscle as before. In the latter case the reflex was crossed, that is, the excitation had to pass through the cord by means of a short association fiber[6] to the other side where it connected with the motor nerve leading to the muscle. The difference between the lost time of the two paths was 4 sigma, which Wundt attributed to the one additional synapse.

Sherrington found the latent time of the flexion reflex in the dog for a strong stimulus[7] to be 30 sigma. Assuming that the speed of conduction in the nerve is 30 meters per second, and allowing a certain time for mechanical latency in the muscle, he accounted for 27 sigma of this total amount. Three sigma, therefore, would be the time lost within the center in the spinal cord, and if one synapse were involved in this center, its time would be 3 sigma.

Comparing the results of Wundt on the frog, where the mechanism is comparatively simple, and those of Sherrington on the dog, where the nervous system is more complex, with those obtained in the present work upon the human cortex, we find for the frog, 4 sigma, for the dog 3 sigma and for man, 5.6 and 6.0 sigma as the time lost in a synapse. But if we make allowance for the time of transmission over the length of fiber between the two motor areas in the human brain, as stated above (p. 68, note), we have 3.6 sigma and 4.0 sigma as the time lost in the synapse for man. Therefore to judge from

[6] The short association fibers connecting one side of the cord with the other side are described by Howell (''Textbook of Physiol.,'' 1908. See Fig. 68) as ''commissural cells whose axons pass chiefly through the anterior commissure to reach the anterior column of the other side.''

These fibers are shown diagrammatically by Starr (''Atlas of Nerve Cells,'' 1896, 24, Fig. 3). He says, ''A few collaterals pass to the median gray matter and terminate in brush-like expansions about the commissural cell whose neuraxon passes to and terminates about the motor cell of the opposite side.''

[7] It may be well to repeat here that the light stimulus used in our work was rather strong, and that the central time would, on this account, be about its minimum. The light was made strong intentionally so that later work could be done with reduced intensities, for the purpose of comparing the synapse time under these varying conditions.

this evidence, we may say that, as far as time value is concerned, a synapse is a synapse whether it be in the simplest or the most complex nervous organization. The same speed of transmission over the plain nerve has been found in these cases. But the similarity in the case of the synapse is far more significant for those who believe that the synapse is the critical point in the study of brain activity.

The conclusion to be drawn from this experiment is that the method outlined in the preceding chapters offers an opportunity for the measurement of the time lost in conduction over a synapse or system of synapses in human beings, that this time for two subjects is 3.6 and 4.0 sigma, and that it shows great similarity between the times found for conduction through synapses in lower animals and in human beings. With the possibility of measuring synapse time, those theories which attribute the effects of ether, chloroform, alcohol and various drugs to a blocking of synaptic conduction, and those which account for practise, memory, training, attention and the like by changes in the conductivity of the synapse may be subjected to an experimental test.