

## V.—RESEARCH AND DISCUSSION.

### BILATERAL ASYMMETRY OF FUNCTION.

By G. STANLEY HALL and E. M. HARTWELL,  
*The Psychophysical Laboratory, Johns Hopkins University, Baltimore.*

#### I.

The problem of the relation of right- and left-sidedness to the more general law of bilateral symmetry has not yet been studied with the method or comprehensiveness which it requires and which is now possible. The vast clinical, physiological, popular, and historical literature upon the subject (of which we are preparing a bibliography), presents so much interesting material that before recounting our own studies, we must first briefly resume some of the more important results now claimed.

It has been said, on a basis of more or less careful and averaged measurements or other observations, that the right and left eyes often have slightly different near and far points and different powers of accommodation and discrimination, both of form and colour; that the bulbi have different degrees of rotary mobility and the pupils unlike apertures; that it makes a difference in apparent projection-distance whether an object be seen with the right or left eye, so that we ought not to say identical points with reference to an object, but coincident points, as if the retinæ were laid one within the other like two cups; that if we point at an object with both eyes open we shall find, on closing each eye alternately, that we have instinctively pointed in the line of the right eye, or *vice versa*, if we are left-handed; that the outer angle which a vertical makes with a horizontal line in monocular vision seems greater by about half a degree for the left than for the right eye; that the error in putting the finger through a ring is greater when the right than when the left eye is closed, so that a true, mean, cyclopean eye would be slightly to the right of the median line; that in short the right eye is commonly the best for microscopic or macroscopic work, and is less liable to many forms of disease and congenital defects. And yet, though an expert stereoscopist does not usually mistake patterns a part of which is presented to each eye for those that are monocular (with only a *tabula rasa* before the other), the two eyes are of course so intimately connected that they probably act from one root and practically as one organ, and only disease or artifice can make their axes diverge or move asymmetrically up or down. Their motor seem regulated by their retinal functions, so that, according to Ludwig, if the retinæ are

extirpated, the eyes often cease to rotate, then to accommodate, then to wink together. If one eye be covered, the other pupil expands to nearly twice its former size, or else the room grows dark; if a bright image be impressed on one eye, and then it be closed and the other opened under suitable conditions, the after-image sometimes appears in normal projection. The comparative reaction-time for each eye; the physiology of reading mirror-script, or writing after the early Greek fashion, alternately right and left; which eye is most often and soonest affected in the disparate moments of drunkenness and in strabismus; whether lateral hemiopia is more common or complete on the right or left; in which direction rotation soonest produces optical dizziness; the number of fibres crossing each way in the optic chiasma;—these and many other points, including the ontogenetic and phylogenetic growth of the visual function generally from its dawn in animal life, must, we think, be much better understood before we can accept even Helmholtz's conclusion as to whether or how far it is a psychic act to join the activities of the two retinæ, or explain the hypnotic colour-blindness or accommodation-cramp of one eye, the other remaining normal, or the binocular functions generally; and even then, we are convinced, the entire problem of bilateral symmetry and function of the other double organs of the body must be brought into relation with them before such questions as these can be cleared up. Each must shed light on all, and all on each, and the study must be made comparative, to include the lower animals.

The other senses offer less data. It has, however, been stated that the left helix is apt to be less perfectly developed, lower, more prominent, further from the eye; that the left ear has less auditory power and greater liability to certain diseases; that in conflicting or contrasting sounds, the impression made on the right auditory nerve is more likely to prevail; and that one ear sometimes hears the same tone higher than the other. Even taste and smell, according to Valentin, present phenomena analogous to rivalry between their two lateral moieties when different tastes or odours are simultaneously applied to each; but there was no differentiation, no record of preference for right or left.

Of the dermal and muscular senses, there are many illustrations of the Shakespearean line, that "The hand of little employment hath the daintier sense". Weber observed that things lifted with the left hand seemed heavier, and that sensory discriminations (especially tactile, but perhaps not thermal, we should say) were finer on the left side of the body, which Wundt and others have spoken of as passive and sensory, while the right is called the active motor side. If a plate of metal, or a mustard plaster, be laid on the insensible side of an hysterical hemianæsthetic subject, sensibility is more or less completely restored in a few minutes, and often for many hours, at the point of applications,

but simultaneously reduced or lost on the corresponding point of the sound side. Analogous restorations were observed by the Burq-Charcot commission of the French Biological Society in 1878, in the field of each of the other senses, on the application of metals. The phenomena of transfer, designated by Adamkiewicz a "bilateral function," like sweat-secretion, though quite often complicated with simulation and lasting sometimes for many hours, is, in a sense, the reverse of the familiar increase of discriminative sensibility on the corresponding part of the other half of the body during psycho-physical observations.

The most familiar asymmetry in both form and function is in the hands and arms. One man in from about twenty to forty, according to various enumerations, is left-handed. Ogle found that fifty-seven men and twenty-eight women in one thousand were left-handed, and cases of true ambidexterity are very rare, as tools, machines, and many occupations and specialisations of man, unlike those of woman, often make it practically impossible. The difference is very manifest in the shoulders and chest, while the right arm is often nearly a third of an inch longer, displaces several cubic inches more of water when immersed in a tube up to a given point, as we have observed, and is sometimes one-third stronger, so that the deflections of the needle caused by muscular effort is greater on this side. The weight of the arms is so important in correcting the oscillations of the centre of gravity in walking that, if one be lost, a runner needs another of the same weight. This inequality alone brings this centre somewhat to the right. The two hands at rest are unequally open, and pronated or supinated, and an ingenious acquaintance is quite successful in inferring, at an evening party, a stranger's occupation by the way in which the hands and arms are carried and moved. Even the papillary striation, often almost as characteristic of an individual as his photograph is of his features, is different on the corresponding finger-tip of the two hands. The legs also, despite their similar action in walking, their most common act, present differences, like though less, as is seen in the unequal wear of shoes, &c. In one series of measurements, the right leg was found from one to seven-eighths of an inch the longer, and the right tibia has been found to contain more calcareous salts and less inorganic matter. The careful weighing of the muscles of the legs and of the back, excised from the body, showed the right to be in excess. Many have a decided preference for the right leg in jumping, kicking, wrestling, &c.; and it has been said that, from a square standing position, it is most natural to step off right leg first. Few sit cross-legged either way equally well, or turn out the toes equally. Few also can walk on even ground or swim straight, as the mole burrows, with their eyes closed. The power of orientation is soon lost; we wander and then take a fresh start, only to deviate again in the same direction. We are now making further studies here.

In the general conformation of the surface of the body and of its internal parts, observation and anthropometry detect quite uniform, though usually slight, differences. Few noses are straight, but one enumerator found most to turn to the right, another to the left. Few cheeks are equally full; few can protrude the tongue, gape, smile, corrugate the forehead, wink, make faces generally quite evenly, while in monomania, and even great fatigue, unequal innervation of the two sides of the face is common. The teeth have been said to develop soonest, to be strongest, sometimes larger and more numerous, and to decay latest on the right side. Hair and beard are more abundant, nails are thicker, and sometimes have a "lick," or grow strongly towards the right; and both hair and beard have been said, though with quite insufficient observation, to grow fastest on the right side. Greyness is very often asymmetrical. Asymmetry of the skull and its sutures is almost universal. In about two hundred impressions from different conformators, which we have carefully measured, we have found most symmetry in the occipital, with prominence to the left in the frontal, and still more in the temporal, regions. The right abdomen is more prominent. In right-handed people the left testicle is usually largest and most dependent; and the right in left-handed people. The right breast has been observed to have the best and richest milk, and to be preferred by infants; and the right parotid to secrete the most saliva.

The position of the internal organs is nearly medial in the human embryo till the second month, when the apex of the heart is crowded to the left by the liver. From accidents of position, temperature, pressure, &c., during this period, the viscera are sometimes, though rarely, entirely transposed. This does not, however, insure congenital left-handedness, as Hyrtl inferred, from callosities, &c., to be the case with the two subjects of his first record. Complete transposition is too rare for confident conclusions, but must tend strongly to left-handedness, as the normal position of organs must tend to dextral pre-eminence. In normal states of rest, though the blood is no purer or hotter on one side than on the other, as Aristotle asserted, it is probably conveyed more directly and with more force through the slightly larger left carotid artery. The right hand is likely to be warmest, and the right side to sweat easiest. In violent exercise in the sun, Blake found the left side about one degree hotter in axilla, but no difference in a state of rest. Mosso's volumetric measurements indicated that in hypnotic catalepsy there was slightly more blood in the left arm, while the radial pulse of the right arm is strongest in fainting, and in dying can be felt after the left stops; the latter side being the first to assume cadaveric rigidity. The right vagus nerve seems to act more strongly than the left on the heart. Though Stocker found the left thorax to be more than half an inch largest about, the right bronchus is

wider and shorter; and Petit asserted that new-born children breathe first with the upper lobe of the right lung. It has been said that of organs in pairs, those on the right side are apt to be slightly farther to the front. On the relative size of the kidneys, observations differ; but the gravid uterus more often inclines to the right, and the umbilicus is turned to the left. The average predominance in weight of the viscera of the right side is, according to Buchanan, about 15 oz., and in deep inspiration the centre of gravity is shifted slightly backward and to the right, and makes that side freer and readier for action.

Pathological, which is so closely connected with vaso-motor, asymmetry is very common, and many morbid processes are arrested at the median line. Semeiology infers, from the widening of one pupil, which of internal double organs is most diseased. Fevers and the resulting weakness are greatest on the right, which is also affected most and soonest by organic and mineral poisons, blisters, and intoxicants, so that convulsions which begin on the left side are rarely of toxic origin. In opisthotonus, the body curves to the right. Of seventy cases of pneumonia observed by one writer, sixty were on the right side; the complications due to stenosis are often unilateral. Sick headache, or hemicrania, which alternately attacks the right and left side, is severer on the latter. If there is congenital or degenerative left-sidedness, or if an ear, lung, kidney or other organ or member is defective or wanting, it is likely to be on the left side, which is also more likely to be the seat of anaemia, atrophy, cancer, and, according to one opinion, epilepsy. These may be called diseases of arrest or defect, which one writer thinks favoured by summer, while all that augments nutrition, as, for example, cold weather, favours those diseases which affect the right side most strongly, and at the same time resists sinistral maladies. On this side also extra thumbs, toes, and other organs and hypertrophies are most common.

From this general asymmetry animals are not exempt, though most observations are far less reliable. It has been stated by scientific men that double organs in the horse, dog, or other animals, are larger on the right side; that worms, in starting, writhe to the right first. Fliedl states that mollusca roll to the right by preference. It has been said that parrots prefer to stand on, and dogs to lift, the right leg. Huber observed an ant to run around about one thousand times an hour for seven days in a circle of an inch in diameter, indicating thereby incoördination of the two halves of the nerve centre. It is probable that the alleged ambidexterity of monkeys and infants is only relative. One of us observed an infant of nine months, whose hands were held symmetrically to its sides and freed at the same instant, grasp a desired object placed directly in front of it on the table fifteen times out of twenty with the right hand, often even when the object was placed somewhat to the left. Professor Brewer, who

has not yet published his figures, found, of several thousand foot-marked horses, more white feet on the left than on the right side, the left hind-foot being most often marked, and the right fore-foot least often. Common spotted, as well as calico or "pinto," horses, have most white on the left side. The same rule, we are told, seems to hold with horned cattle, dogs, hogs, and perhaps wild animals where there is no possibility of fancy-points to be bred to. Nearly all dogs carry the tail to the left. Perfect bilateral symmetry in colour is rare, though there is always a tendency to it. White hair the author regards as a sign of weakness.

In the cerebro-spinal axis, divided by deep median fissures into two corresponding halves and connected by various commissures, asymmetry is no less marked. The anterior cornu of the cord, especially in the cervical and lumbar enlargement, is somewhat larger on the right. Either side of an intact spinal cord of a decapitated frog may be well exhausted by reflex experiments, without much impairing the functions of the other side. If the stimuli increase to great strength the reflexes are diffused to more muscles on the same side before affecting those symmetrically opposite, according to Pflüger's well-known law. As men are said to make the worst face on the side of the greatest effort in severe one-sided muscular strains, if the cord be split with proper precautions in the median plane, each side may preserve the reflexes from that side apparently intact. Setschenow did not observe in this case the double-sided anæsthesia, or reflex depression of Brown-Séquard. Cross semisection of the cord reduces or destroys the power of voluntary motion below on the same side without much affecting it on the other, but increases sensation on the side of the lesion, and depresses it on the other side. Two opposite semisections need not be so near together to destroy the power of voluntary motion on both sides below as to destroy sensation. Whatever other inferences respecting the existence of inhibitory fibres, the course of fibres in the cord, conduction within the grey matter, &c., the many careful observations of this class may justify, they have at least led to the belief that very many posterior or sensory fibres cross soon after entering the cellular grey, while most fibres representing the power of voluntary motion, pass down the same side. Brown-Séquard thinks the left of the cord is more concerned with nutrition, and the right with the functions of animal life.

Of the cerebral ganglia, it has been estimated by various painstaking observers that the entire left brain weighs more than the right; that the specific gravity of the grey substance is greater on the left. Meynert thinks that the left brain has the deepest and fullest, but the right brain the most convolutions; but some have thought that the number of folds was greatest on the left only in the occipital regions, and that there was the most white matter in the right frontal and the left occipital and cerebellar brain.

So great is the asymmetry of the gyri, as well as the cerebral functions, that Exner was obliged to make out separate tables for each hemisphere in his extended study of psychophysical localisation from hospital records. A notable case of this sort was observed by Dr. Dwight in the brain of Chauncey Wright. Various kinds of asymmetry have been noted in the caudate nucleus, the olivary bodies, and especially in the fissure of Rolando, and in the arterial system of the hemispheres. It has been stated, and also denied, that the left frontal convolution develops first; it has also been said that embryonic features are more likely to persist in the right. If there is a defect of development in the right hemisphere, as is more common, or if there is lesion there, the left portion of the cerebellum, connexion with which may be traced along the lines of tract-development and secondary generation, is likely to be affected. The homologous hemispheres are connected by the commissures and decussations, the functions of which are rarely affected by disease, and which have been but little investigated, and very probably have more conductive power and less resistance than even the fibres of the projection-system. According to Meynert, the basis or pes crucis, arising chiefly from the corpus striatum and the lenticular nucleus, crosses in the medulla to the opposite lateral column of the spinal cord, and this is the way over which voluntary impulses pass from the brain to the muscles, while the fibres of the tegmentum, arising from the thalamus and corpora quadrigemina and mediating reflex movements, do not decussate. Flechsig, who derives a large part of the fibres of the basis directly from the cortex through the internal capsule, finds their decussation in the pyramid unsymmetrical, more crossing from the left brain to the right of the cord than in the opposite direction. Sometimes nearly all, and in rare cases almost none, of the pyramidal fibres decussate, great individual variation being observed. The chief transverse commissure, the corpus callosum, first makes its appearance in placental mammals, and is, according to Huxley, "the greatest and most sudden modification exhibited by the brain in the whole vertebrate series". Of its functions, little is specifically known. The few recorded cases of its congenital defect or absence have been marked by great bodily and mental weakness. Brain-diseases are usually asymmetrical, and certain of their most marked forms, hemiplegias, encephalitic processes, yellow spots, &c., &c., are most commonly seated in the left hemisphere. Deviation from bilateral symmetry in skull or brain, though in extreme cases always attended by mental defect, may be considerable without morbid symptoms. Persistent and morbid sense-illusions are often unilateral; in melancholia the two sides of the face often differ noticeably in motor innervation. Aphasia in fourteen out of fifteen cases, according to one estimate, is a disease of the left brain. In this disease the language of ideas may be lost, while the primitive, more emotional bilateral



gesture-language may persist. If the left brain be hypnotised, as it may be more or less, independently of the right, finer movements, like writing, are difficult with the right hand. Brown-Séquard and Charcot, however, have found that most cases of hemiplegia are also paraplegic; the apparently intact extremity being much weakened, the leg more than the arm. Pitres found the left extremities less weakened in right (left brain) hemiplegia than the right limb when the left side was affected. In a study of ten cases of right, and thirteen of left hemiplegia with a Duchenne dynamometer, Berger and his pupil, Friedländer, have recently verified these observations, and found a few cases in which greater energy could be developed by the affected than by the intact leg but, instead of finding the loss of power in the sound limb greater in recent cases, could not observe any influence due to the duration of the case.

This duality has often been contrasted both with the medial position of some of the medullary centres and with the apparent unity of thought and the functional simplicity of the soul, which latter postulate, as is well known, inclined Descartes to locate it in the pineal gland. Dr. Wigan, however, did not hesitate to speak of two brains which might carry on two independent trains of thought, but which it was the object of education to make co-work, each as the sentry and security of the other. Scholars are able to think of only one thing at a time, and hard study occupies both brains, so that neither is left to work off its energy by causing dreams. We are made of two beings, he held, and, if the two brains are about balanced, vacillation is certain. In fact, one brain is nearly always superior, and controls the other. One brain may be insane, and, if the stronger one be sound, may be long controlled, and its defect concealed by an effort to hold the "self" together. The power to compel the weaker brain to the will of the stronger marks one of the greatest differences between men, and there are many colloquies between the hemispheres. Insane incoherence is like reading a few words from one book and then a few from another on entirely different subjects, with rapid alternations; a few such duplex trains of thought, Dr. Wigan believes, he has restored to sense by proper disjoining, and rejoining. Dual consciousness, reverie, castle-building, counting steps absent-mindedly, imaginary aggrandisement, supernatural suggestion, another person thinking in the brain, struggles with temptation, characters compounded of bravery and cowardice, hypocrisy and enthusiasm, chess-playing, the half identification with their *rôles* by actors, lucid intervals, the case of lunatics whose illusion is not absolute (who are John Smith or deity, who are kings but strive to conceal it, or who struggle long against morbid or criminal impulses),—these all illustrate and are explained by the duality of mind and its organ as incidents in the struggle and alternate supremacy of two rivals which should co operate as amicably as the Siamese twins. Holland thought



that some of the phenomena of insanity—sinning against knowledge and conviction, rapidly contrasting states of mind, &c.—might be explained by disparity, incoördination or disturbed equilibrium between the hemispheres. Even Lotze and Friedrichs conjecture that one half of the brain may be conscious of psychic disease in the other, while Pick thinks it is through the functions of the sane parts of the brain that it is possible to become conscious of disturbed sanity. Hoppert and Jensen believe double thinking, or illusions of memory, when a new impression or experience brings with it a sense of familiarity, is due to the dual function rather than, as Buccola and others before him prefer to think, to a recrudescence of forgotten dreams and reveries. Flechsig thinks the hemispheres may function alternately. The morbid impulse to write mirror-script may be due to centres on the weaker side suddenly becoming the dominant ones. A normal differentiation of function, culminating perhaps in or near the island of Reil and the cortical centres above, may perhaps be assumed. Several observers now hold that the motor area is larger in the left hemisphere, which Hughlings Jackson calls the leading side. The voluntary power to speak words has been located here, and the automatic power of speaking in the corresponding centres of the right of the brain. Stricker compares the two hemispheres to two coachmen, each with a pair of lines, driving the same horses; the right coachman is strong and trusty, but the left one is more skilful in fancy evolutions.

The human infant, in making synchronous movements with both arms, makes at first many more symmetrical than congruent movements, *i.e.*, more movements involving corresponding muscles of both arms than those in the same direction with non-corresponding muscles. These latter movements appear to be learned later, then one hand learns to act, the other remaining at rest, and finally both hands learn to act independently at the same time. An expert "will-virtuoso" is even able to write a Hebrew sentence from the Old Testament in one direction with one hand, while the other is writing a French madrigal, alternate lines backwards perhaps, and both with extreme rapidity. A thorough and psychological piano-teacher lays far less stress at first on the running scales involving congruent motions, than upon exercises which early and completely dualise the action of the two hands, both in *tempo* and in direction. These phenomena involve no such "division of the attention" as has been inferred, but one hand learns to act more automatically, and the focus of attention to alternate rapidly from right to left. Life is not, however, as has been seen, an even struggle for a monopoly of function between the two halves of dual man. Nurses carry children on their own right arm, leaving the child's right arm a freer field of motion. They hug them on the right side, disturbing the equilibrium of blood-pressure. Early in history the right hand became associated with the south, with the sun, faced in worship, with

gods and good omens, and the left with the north, demons, shadows, &c., and was left to perform all the unclean acts of life. The right is the hand of greeting, blessing, oath-taking, writing, throwing, fighting with sword or spear, &c., while the left is the naughty hand, to follow which leads to the bad, the Cinderella, held to often hard but ignoble service. Even superstition has added its weight to the influence of so many occupations, and leads to lying, sitting, seeing, &c., one-sidedly, making the average modern male body, to those who are used to seeing it unclad, as lop-sided as that of the Greek was symmetrical. There may be great selective advantage in the capacity of locating some functions mainly in the left and others in the right hemisphere, and it is not impossible that there is some mysterious advantage to self-consciousness or double-dealing with ourselves in the predominance of one side over another, *e.g.*, possibly the oft-cited asymmetry of Kant and others, or even in the fact of somatic duality; but such possibility must not blind us to the danger of ill-balanced work, so often falsely called overwork.

Finally, there is a mystic side of this problem, which has attracted or repelled many, and been referred to in many ways. Why are *p* and *q* so often confounded by children and others, *p* and *b* never; or why must we so often stop and think which is left and right, but never which is up and down? Ullrich has hardly given an explanation in saying that the first form of letters are halves of a horizontal, the last of a vertical symmetry, and that the latter requires a repetition of the same sensation, the former not. Again, when the function of reflex action was first established, it was argued by metaphysicians that so slight and accidental a distinction as that between anterior and posterior, could not make so profound a difference as that between the active and passive life of the soul, which was a simple spaceless entity. So, more recently, it has been said that, so far as the brain represents it, the soul must be double. To this it has been replied that an extended seat of the soul must now be admitted, that even the corpus callosum may fail without annihilating soul-life, that a monadic Ego may occur twice, and that the soul is a solidarity and not a functional or non-extended unity. Why the nervous system was so formed that a frontal, medial, and horizontal plane through it should represent functions so distinct as the sensory and motor arm of a reflex arc, the right and left "function" and the direction of gravity respectively, is a question to our mind quite without sense. Not so, however, the question, what influence upon the psychic development of animals and man is due to the power to bring two symmetrical parts of the body into contact, which a fish, *e.g.*, does not possess. If we bring the two hands together, the one being hot and the other cold, we experience two sensations and not an intermediate temperature. So too if we could do as Socrates is said to have boasted himself able to do, *viz.*, rotate both eyes inward till, over a low nasal bridge, each could look

squarely into the other, the optical images would not fuse, while in ordinary stereoscopy we have only to exchange the impressions of the two eyes to invert the perspective. Again, how is it that, despite the independence of the two halves of the body which, *e.g.*, inclines many to make a face on the side of the muscles most strained in great effort or of the pain most keenly felt, yet the homologous points on the two hands are related, not like the identical points of the eye, or like the upper and lower note of the octave which blend into each other, but by a peculiar psychic affinity, so much closer in a sense than that between two adjacent, but just clearly distinguishable, local signs on the same side?

## II.

After bringing together from original sources, and carefully considering the above facts and opinions, not all of which can be regarded as final, we are led to think that other methods than those hitherto applied might bring us into closer quarters with the comprehensive bilateral problem. Of these two were considered. 1. Operations on the corpus callosum of animals, and perhaps the pyramid, to partially isolate the action of the hemispheres, and also to reduce the action of one of them. 2. More accurate measurements of the bilateral asymmetry of function. This section is devoted to the general results of the latter method, so far as applied to the arms.

In the first series of experiments, a ruler about six feet in length was fastened on edge transversely on a table. The person whose movements are to be observed sits with carefully measured squareness before the middle of the table, and places his index fingers on each side of a pin that marks the middle of the edge of the ruler. He intends and then executes a sudden movement along the edge of the ruler to the right with the right, and to the left with the left hand simultaneously, endeavouring to make the excursions of both hands alike. His eyes must of course be closed, for they detect and correct for far slighter asymmetries of movement than the hands. The other side of the ruler is marked off each way from the central pin by millimetre scales, and a second person sitting at the other side of the table reads off and records in the protocol-book the distance of each excursion, an ink-line being drawn down the middle of the index finger-nails to aid the accuracy of the readings. Fifty or more such records can easily be made in half-an-hour, and many thousands altogether have been made and arranged. Observations were made, for control, upon many people, but were chiefly confined to two right-handed and two left-handed young men. From tables far too extensive to print here, we have formulated the following conclusions for such movements as the above.

A. I. The preferred hand makes the greater excursion. This

was generally most conspicuously the case if the movement was made mainly from the shoulder, but was usually also the law for movements made at the elbow, wrist, and knuckles. One person seemed, from these movements, right-sided at the shoulder and elbow, and left-handed at wrist and knuckles. The ratio of the excess-distance of the preferred hand to the whole excursion varied greatly with different persons, and somewhat, though much less, with the same person at different sittings. Between twenty and fifty centimetres from the central pin the asymmetry of movement was greatest, and was less for both greater or less excursions, as if the median plane and the position of fully extended arms were the bases from which intermediate positions were estimated. Weighting each hand alternately had no constant effect, but if, instead of slipping the finger-tips directly upon the ruler-edge, they rested upon and moved slides, and one of these was made to move with greater resistance than the other, the amplitude of movement was reduced. In one single series of observations, when the sitter was unusually fatigued at night, the non-preferred hand constantly made the greater excursions, and on another occasion of fatigue the same person made an extraordinary excess of movement with the preferred hand. Neither of these results, however, could be obtained again by strongly fatiguing one arm just before the sitting. In all these cases the movements were made with one sudden impulse of innervation, as nearly equal right and left as possible. If the impulses be more slowly sustained, or corrected at their close, to give fuller play to afferent impressions, unilateral excess is slightly less.

II. If these movements, instead of being simultaneous, be successive, with intervals of one and of four seconds between, there is a tendency to reduce the excess of the preferred hand, and, in some individuals, to make an equal or even greater error in favour of the non-preferred hand, *i.e.*, for a left-handed person, whose left-hand goes farthest in simultaneous movements intended to be equal, to now make the greater excursion with the right hand, and *vice versa* for a right-handed person. The degree of right- or left-handedness seems, however, to be involved. The right and left hand preceded alternately in these observations, but our figures show as yet no constant difference, due to the precedence of either hand.

III. If, with both eyes open, the experimenter stick a pin into, or move one fixed to a slide upon the ruler to, a certain point, and then, with careful ocular measurement, attempt to place the other pin an equal distance on the other side of the middle point, there is still a pretty constant, though much smaller, excess on the side of the preferred hand. This indicates that, to binocular vision, a line at right angles to the median plane seems a little longer to the left than to the right of it, if the observer is right-handed—an error in the same sense as that of the hand in simultaneous movements. One case was found, however, in which the

exact opposite occurred, the excess being on the side of the non-preferred hand. This observation can only be made within limited angular distances. If the pins are too far apart, so that, when the eyes are fixed on one, the other is seen far in the field of indirect vision, the error is more irregular, and, so far as our limited figures cover this point, greater in the same sense as above. These observations must thus be restricted to small angular distances.

B. In a second series of observations, two rods or rulers, similar to that described above, were fastened, one in a perpendicular, the other in a horizontal position, crossing each other in the middle at the height of the shoulders. These four quadrants we numbered from the side of the recorder, the upper quadrant at his left being No. 1, and around with the hands of a watch to quadrant four at his left hand below. The person under observation assumes the primary position, with erect body and eyes closed, extending both arms horizontally and nearly straight, and laying his two index fingers together in angle of the first quadrant. The fingers being then moved simultaneously as in A. I., the left passes up along the perpendicular rod, while the right finger moves through a distance intended to be equal, outward to the right along the horizontal rod; both distances being noted from the other side as before, and the observer passing later to the other quadrants in order. Here the effect of the gravity of the arms was almost always predominant, and even in the longest series of observations, after the experimenter had learned his error, was never compensated for. Whichever arm moved up made a less, and whichever arm moved down made a greater, excursion than the arm which moved horizontally at the same time. Yet if the right arm of a right-handed person moved up and the left out horizontally, as in the second quadrant, the excess of the latter over the upward movement was less than if the left went up and the right outward, as in the first quadrant, while in the two lower quadrants the excess of the downward over the horizontal movements was greater when made by the right than when made by the left hand. If, then, as seems reasonable to infer, our knowledge of the plane surface in which this cross lay were dependent upon the muscular and innervation-sensations involved in these movements alone, an inch in this surface would seem much longer above the level of the shoulders than below them, and somewhat larger to the left of the median line than to the right, for a right-handed person:—a supposition, of course, only abstract, because, in fact, we learn to judge of all the space within reach of our hands and arms by the movements of both arms in both directions, and especially by the eyes. When the hands were alternately weighted, the relative excess of the downward, and the deficiency of the upward movements was easily increased.

Many series of successive movements, corresponding to A. II.,

and of ocular judgments of relative distances of movable pins, corresponding to A. III., were made, but not enough to warrant conclusions as yet, in the complex cases of B.

C. I. Two large thimbles were made for the two index fingers, one of which carried a light board fifteen centimetres square, to the plane of which the finger, when inserted in the thimble, was perpendicular, while the other thimble was weighted to equal the weight of the first, plus the board. Upon this latter was fastened a piece of heavy paper, with concentric circles, one centimetre apart, printed on it, the common centre being adjusted to exactly coincide with the position of a short needle on the end of the other thimble, so that if the index fingers, thus armed, were brought accurately together, the needle of one thimble would pierce the paper on the board carried by the other exactly in the middle;<sup>1</sup> the paper being of course removable, when the holes became too numerous to be accurately counted or located. This experiment was made with closed eyes, both arms being moved systematically from the shoulder. Besides this first movement just described, two other series of records were made, both by approximating the arms to the median plane by symmetrical shoulder-movements, in the one case directly over the head (II.), and in the other low down behind the back (III.). In each case effort was made to bring the index fingers, armed with recording apparatus, as accurately together as possible, with an impact strong enough to leave a trace, but at the same time so gently that, even if there was considerable error, the direction could not be inferred from the leverage of the recording table, for in that case it would be instinctively corrected at the subsequent movement. In observing the record thus made, it was found first that the points of the pins were by no means accurately in the centre of the concentric circles, like shots about the bull's eye of a well-used target, but about another and often rather remote centre, the position of which, best estimated by simple inspection, is comparatively constant for the same person. One extremely right-handed and one extremely left-handed person brought the preferred hand constantly farther from the axis of rotation at the shoulder in each of the three positions than the non-preferred hand, as if the preferred arm were slightly longer, and experience had not taught the proper compensation. Another strongly right-handed man brought the left finger farther front in II., farther back in III., with no discernable difference of elevation in II. The preferred hand was

<sup>1</sup>The apparatus here described, and that used in A. were both devised by Professor H. P. Bowditch of the Harvard Medical School, with whom these experiments were originally begun. The paper described above is the same as that used by Bowditch and Southard. See their article entitled "A Comparison of Sight and Touch," in *Journal of Physiology*, Vol. iii., No 3, Plate xvii.

uniformly highest in position I., and likely to be so in III. Though our data comprise many thousand records, they warrant no inference which hand is farthest front in II. The individual error here is constant, but bears no relation yet discernible to either right- or left-handedness, or to relative eccentricity of localisation. In another series of records (IV.), the fingers were both moved in the median plane in front, one upward, the other downward. Here the same finger was outermost as before, and there was also generally a slight tendency to overlap, but which hand, if either, tended more strongly to cross the plane into the dominion of the other, has not yet been determined. The deviations of a conjectured median plane, thus determined from an exact geometrical one, would no doubt be as great, and as hard to determine, as the difference also known to exist between the mathematical and the empirical horopter; failure to come quite round to the same vertical plane was constant in none of our subjects. If, finally, the contact was made by bringing one hand well round into the domain of the other (V.), the approximations were less accurate than if made in the median plane. These movements are a little, but only a little, more accurate in front, where the volitional action of the hand is usually guided by the eyes, than above the head and behind. If we could determine the farthest possible point in each direction, and for each position of the joints, amount of pronation, supination, &c., that could be touched with each index finger, a constant primary position of the body being of course assured, and the effects of fatigue upon the form of such a surface being eliminated; if we could then construct, within this surface, other iso-potential surfaces representing the angular translocating power of each arm straight and with different degrees of flexion; if through these surfaces we could construct lines of greatest and least flexion-power, &c.—we should have not merely a record of the mechanical properties of the framework of the arm, but superimposed upon this common element would be differences between persons and each arm of the same person, which would represent his and its entire motor-history and experience; causing endless variation in the lines of easiest, hardest, swiftest motion, position when at rest, muscle-sense and judgment, &c., and giving distinct individual habit and character to each limb, muscle and centre of motor innervation, which, even when trained, not only in skilful but in pretty equal use of the hands, we fail to know and compensate for without the use of the eye.

D. An extended series of reaction-times was measured for the four persons under observation, two of whom were right- and two left-handed, with an arrangement of apparatus similar to that described by Wundt (*Physiologische Psychologie*, Bd. II., s. 231), for which we were indebted to the kindness of Mr. C. S. Peirce, and which was used as follows. The hearing power of each ear being found to be about normal and equal, both were equally



exposed to the noise of a falling ball with warning, and five quickest reactions, by pressing the key, were made alternately with the right and with the left hand. From fifty to eighty reactions could thus be made without fatigue at one sitting, the records of which were read from the dials of the Hipp-chronoscope, and recorded and averaged. As a result of many hundred records, it was found that, for three of the four persons tested, the reaction-time on the stronger or preferred side was greater than that made by the non-preferred hand. This difference, though slight, was uniform and constant. The fourth student, right-handed, but not extremely so, made the quicker reactions, scarcely less uniformly and constantly, with the right hand. Should the rule which holds for the other three turn out to be a general one, we may have to reflect how the current view, that regards the left of the body and the right of the brain as predominantly passive, and the right side of the body and the left hemisphere as mediating more than half the motor functions, can be made to comport with Wundt's identification of apperception with the generation of the motor impulse. How, we should have to ask, upon his hypothesis, can the latter process be more rapid on the non-preferred side?

E. A dynamometer was designed, consisting of a stiff spring with two long inflexible arms, one of which carried a pencil and the other a broad metallic table for a piece of stiff paper, upon which the pencil recorded the degree of approximation of the two arms made by the hand of the experimenter. After each record the plate was slipped along a few millimetres for a new record by an assistant, who marked each line *r.* or *l.*, according to the hand used. The power put forth by the hand in clenching the spring is thus represented inversely by the recorded distance between the arms. This simple instrument, though by no means free from objection, we found sufficiently accurate in a long series of comparative movements for our purposes. Our results upon the above four persons were as follows.

I. The preferred hand can always exert the more force, showing that its pre-eminence is not in skill alone. This is the case in every series, averaged from eight or ten maximal clenches alternately with the right and left hand. There is sometimes, however, a sudden excess of power in the non-preferred hand. There is also, subordinate to the general effects of fatigue, very speedily and strongly manifest here, a change in the maximal power of both hands together, now slow, now abrupt.

II. A maximal clenching movement with one hand is weakened if a like maximal movement be made at the same time with the other hand. This, which is the opposite of the result recorded by Quetelet, who found the power of each hand increased if the other was making the same effort at the same time, was uniform with the four individuals we tested. The preferred hand had more power to interfere with and weaken or

draw upon the power of the non-preferred hand than the latter had to weaken the former. If, instead of a symmetrical movement, the other hand made a maximal effort of tensing the extensor instead of the flexor muscles of the hand, or opening it as far and forcibly as possible, no constant effect on the simultaneous clenching power of the other hand was observed.

III. A submaximal standard clenching effort was made with one hand, and, after the lapse of two seconds, an attempt was made to repeat this effort by making another of the same intensity. The most constant result here obtained was that, when it was attempted to repeat the standard movement with both hands simultaneously instead of with one, the effort was too great, indicating summation in repeated sub-maximal movements; when the standard movement was repeated with but one hand it was generally underestimated.

IV. The attention, so far as controlled by fixing the eye on one hand, has power to intensify the maximal energy of the clenching effort of the hand to which it at the instant is directed, and was so potent and disturbing a factor that it had to be controlled by being directed to some intermediate object. The attention seems to have more power over the right hand than over the left hand, but, if fixed on the left, very commonly causes its maximal power to develop slightly in excess of the right.

Throughout the above observations we have been increasingly impressed with the very wide range of individual variation, and we have no data as yet for inferring a more general validity from what we have found to be the case with some or all of the four cases to which our observations have been more or less restricted. We need careful studies, both anatomical and functional, of a great number of cases; farther and more detailed research in each of the above directions, A., B., C., &c., and by other methods, before we can distinguish confidently between individual and general laws. We are, however, convinced (1) that every deviation from perfect bilateral symmetry of form or function is to be accounted for without recourse to occult causes of any sort; (2), that the key to the entire bilateral problem which shall reveal a common principle for all the various paired organs is to be sought in the study of bilateral muscle-tension and contraction, the only act of will; and (3), that the solution of this problem, when reached, now seems likely to shed light on the nature of consciousness.

---