THE PERCEPTION OF SPACE BY DISPARATE SENSES.

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Introductory.

In the philosophic doctrine of "common sensibles"—the κοινὰ αἰσθητὰ of Aristotle—the general problem of the relation of space-conceptions to the senses which furnish them receives its first notice. Hobbes regards motion, rest, size and shape as notions common to sight and touch. Locke names as a distinct class of simple ideas those which owe their origin to two senses; thus space, extension, figure and motion are made common to sight and touch. Either sense gives an adequate idea of space; and the two ideas are in perfect agreement. Berkeley,[1] however, held that these two notions of space were distinct and heterogeneous; that they were regarded as one because they were constantly joined in experience. By a proposal of Molyneux the discussion was brought to an issue by testing the space-ideas of persons born blind and restored to sight by a surgical operation. Such persons are unable to identify the object now seen with the object formerly touched until this identification has been slowly learnt by experience. In this process touch is the teacher and sight the scholar.[2] Mr. T. K. Abbott[3] opposes Berkeley and regards each sense as having its own space-idea, which is little influenced by association with another. Prof. Stumpf[4] ascribes some space-relations to each of the five senses, and regards the resulting conception as essentially innate and single. A more recent writer, Dr. E. Montgomery,[5] supposes an organically evolved pre-established harmony between the several space-senses. He assumes a central organ which gives sensations their spacial value, and puts the matrix of tactile space in the optic thalami, of the knowledge of the position of our body in the cerebellum, of visual space in the corpora quadrigemina.

[1] "It is a mistake to suppose that we see and feel the same object."

[2] One patient did not realise the impressions of his new sense until "he perceived the sensations of what he saw in the points of his fingers as if he really touched the objects". Another was quite confused by not being able to combine sight and touch. "I cannot tell what I do see." "I am quite stupid."

[3] *Sight and Touch*, London, 1867.

[4] *Ueber den psychologischen Ursprung der Raumvorstellung*, Leipzig, 1873.

[5] "Space and Touch," in MIND 38, 39, 40.

Mr. Spencer and especially Prof. Bain lay most stress on the influence of the muscular sense in forming space conceptions.[1]

In order to approach the problem by experimental methods it will be necessary to define accurately such terms as sight, touch, motion. The following classification, though provisional and imperfect, will perhaps be found convenient. We can obtain the notion of extension—

I. By the stimulation of a definite portion of a sensitive surface,

(1) Of the retina (where the distance of the stimulating object must be inferred);

(2) Of the skin,

(*a*) By the application of a pair of points, leaving the intermediate skin unstimulated, or (*a'*) stimulating it by the application of a straight edge,

(*b*) By the motion of a point along the skin (see MIND 40, pp. 557 ff.);

[(*a*) and (*b*) may be contrasted as simultaneous and successive.]

II. By the perception of distance between two movable parts of the body, *e.g.*, between thumb and forefinger;

III. By the free motion of a limb, *e.g.*, the arm.[2]

The operations to be known as reproducing judgments by the *Eye*, the *Hand* and the *Arm*, are respectively—judging lengths by fixating the eyes upon them without motion of the eyeball, a form of I. (1); judging distances between thumb and forefinger, a form of II.; and judging distances by guiding a pencil over them with a free arm-movement, a form of III.

The problem was to compare the judgments of linear extension made by these three senses, and to determine their relative accuracy. The method consisted in presenting a definite length to one of these senses of the subject, who was then required to adjust a second length equal to the first by the use of the same or of another sense. The judgments were confined to lengths between 5 and 120 mm. The lower limit is set by the inconvenience of seeing, drawing and measuring such small lines; the upper by the greatest 'span' between thumb and forefinger, as

[1] For an account of this whole subject see *Common Sensibles* by Dr. Theodor Loewy, Leipzig, 1884 ; and *Sight and Touch* by T. K. Abbott.

[2] To this list ought perhaps to be added the perception of distance by a passive moving of the body, as in riding. (See Mach, *Bewegungs-Empfindungen.*) In all the above processes variations may be made. In I. (1) motion of the eyeball may be admitted or excluded ; direct or indirect vision with one or with both eyes. In II. one part may be movable, the other not, as in estimating distances between the finger and forehead. In the variation used, the sensations are due to the tensing of muscles and skin.

well as by the longest line distinctly visible without motion of the eyeball. More direct methods of testing the relative fineness of these senses and of their memory for absolute lengths were also employed. In several of the operations the two sides of the body were involved, and it became necessary to study the effect of this circumstance.

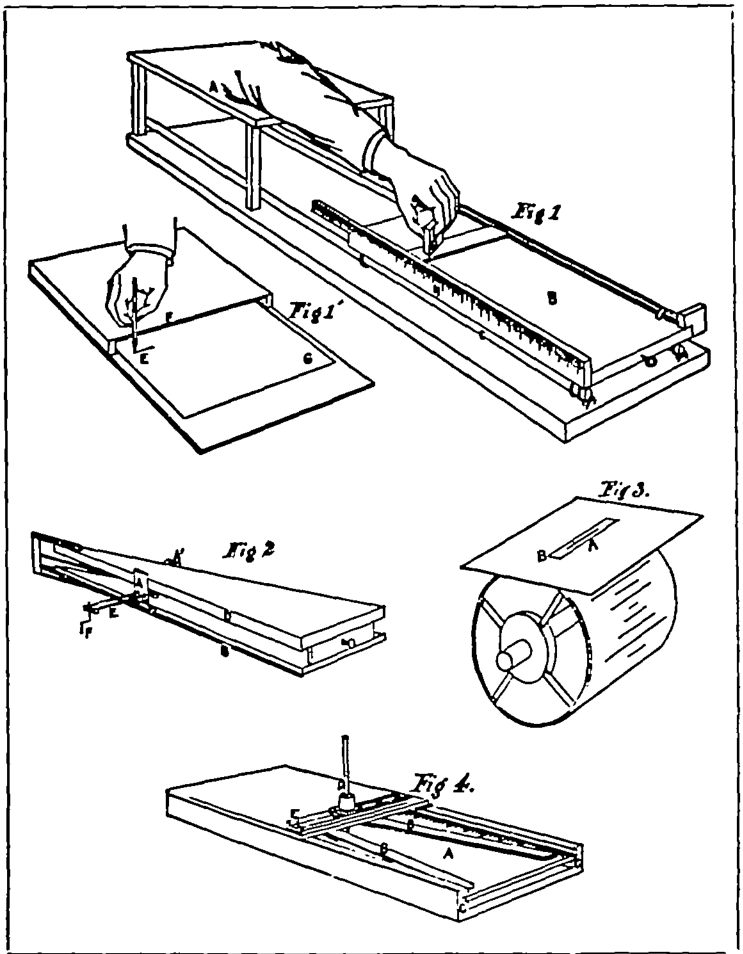
Method and Apparatus.

The sense which receives the linear impression is termed the *receiving sense*; that which expresses it by a length that is judged to be equal to the first, the *expressing sense*. If, for example, I look at a line and (without seeing my arm) draw a second line that seems equal in length to the one looked at, I am expressing in terms of motion an impression received in terms of sight, or reproducing sight by motion, the eye by the arm. Unless otherwise stated the operations are to be considered as simultaneous, the receiving and expressing senses acting at the same time, and the attention probably flitting from one to the other. The method and apparatus are equally suitable for successive judgments, which were made in some cases to obviate the use of both sides of the body. From a description of the method by which (1) an impression was received and (2) expressed by each sense, it will be easy to infer the method of reproducing any one of the three senses by itself or by any other.

A. *Receiving by the Eye.* A series of lines varying in length from 5 to 120 mm. were drawn upon cardboard and this attached to a horizontal cylinder (Fig. 3). Above this was a screen, through a slit in which any of the lines could be made to appear. The lines were seen perpendicularly to the axis of the eyes, and from above at an angle of about 30°.

B. *Receiving by the Hand.* Any one of a series of wooden blocks, 1½ inches wide and varying in length from 5 to 120 mm., with slips of glass cemented on each end to ensure equality of surface and temperature, was grasped in a convenient position between the thumb and forefinger of either hand. This gave a definite sensation of a length 'spanned'. To ensure regularity in the operation, the block (D, Fig. 1) was mounted on a stand, and the latter fastened in the grooves of the car (B, Fig. 1).

C. *Receiving by the Arm.* The apparatus used (Fig. 4) is called the Motion-triangle, because the amount of motion is regulated by the distance between two ledges set in the form of a triangle, the motion being parallel to its base. The hand grasps a cork carriage (D), through which the point of a glass pencil projects downward, to be stopped at each end of its course by the ledges (B B). Any desirable length of movement is obtained by simply sliding the board (A), upon which the ledges are fixed, in or out, along the grooves (C C), the length being indicated on a scale attached to the board. The base of the triangle is 6 inches in length, its altitude 20 inches. The slide and the base of the carriage were made of glass and kept frictionless by the use of oil.



ILLUSTRATIONS OF THE APPARATUS.

Fig. 1 represents the method of receiving an impression by the Hand, in this case the left hand; the impression thus received is expressed by the right hand Fig. 1′ at E, by a free movement of the arm. The eyes of course are closed. A, the platform upon which the arm rests; B, the sliding car, moving upon glass tubes C, and carrying the block D mounted on a stand. The pencil, guided along the straight edge F, draws a line E on paper tacked upon a board G which can be moved under F.

Fig. 2. The Span-triangle, to be placed upon the car B (Fig. 1). A, A′, carriages moving on rollers along the rods B and against the glass edge D ; E, a pair of rods projecting through the carriages A A′ and guided in the centre by a wire, seen near the apex ; F, a bent wire recording on the scale H (Fig. 1).

Fig. 3. For receiving by the Eye. By revolving the cylinder the lines are seen at A, through the slit B in the screen.

Fig. 4. The Motion-triangle. A, a board movable along the grooves C and C, and carrying a scale ; B B, two wooden ledges set in the form of a triangle ; D, the carriage moving along the glass slide E, and its projecting point striking against B B, seen below.

A′. *Expressing by the Eye.* Parallel to the base of a triangle (also 6 by 20 inches) were drawn a series of lines each differing in length from its neighbour by 1 mm. Each line could be referred to by a letter marked at one end; and the operation consisted in selecting a line that seemed equal to the impression received. This may be called the Sight-triangle. As this method proved to be somewhat difficult and restricted the judgment, especially in the case of short lengths, it was supplemented by marking off on ruled paper as much of the ruled line as seemed equal to the impression received. The hand did not move over the line, but indicated by a stroke the desired length.

B′. *Expressing by the Hand.* The apparatus (Fig. 2) is called the Span-triangle, and like the others is 6 by 20 inches in size. It consists of an upper part (D) and a lower part (B), joined at the apex and at the base, with an interval of about $\frac{3}{4}$ inch between the two. A pair of brass carriages (A, A′), triangular in shape and complementary to half of the large triangle, move on rollers along the rods (B) and the glass slip (D). A pair of rods (E) projecting on either side (through the interval between the two parts) is guided by a wire stretched from the apex to the middle of the base of the triangle, and keeps the carriages parallel and opposite to one another. An indicator (F) records the distance between the carriages at any point, upon a scale (H, Fig. 1). The carriages are grasped between the thumb and forefinger and adjusted by an easy motion up or down.

C′. *Expressing by the Arm.* A duplicate of the Motion-triangle above described is used, and, when the subject receives with one arm and expresses with the other, is regulated by the operator at the command of the subject. A handier method (especially applicable in successive judgments) is shown in Fig. 1′. It consists in drawing, with eyes closed, a line (E) along a straight edge (F). By moving the board upon which the paper is attached after each line, a series of lines is obtained.

Results.

In judging that a length perceived by the Eye is equal to another length perceived either by the Eye, Hand or Arm, there will be an error. The problem consists in tracing the nature and extent of this error.

I. When the receiving and expressing senses are the s a m e,

(1) *If the E y e is both receiving and expressing sense, s m a l l lengths will be u n d e r e s t i m a t e d, and l a r g e lengths e x a g g e r a t e d,* the point at which no error is made being at about 38 mm. [Fig. 5, 1-1];

(2) *If the H a n d is both receiving and expressing sense, s m a l l lengths will be e x a g g e r a t e d, and l a r g e lengths u n d e r e s t i m a t e d,* the 'indifference-point' being at about 50 mm. [Fig. 5, 2-2];

(3) *If the A r m is both receiving and expressing sense, a l l lengths* (within the limits of the experiments) *will be e x a g g e r a t e d* [Fig. 5, 3-3].

These results are expressed graphically by the three curves in the centre of Fig. 5.

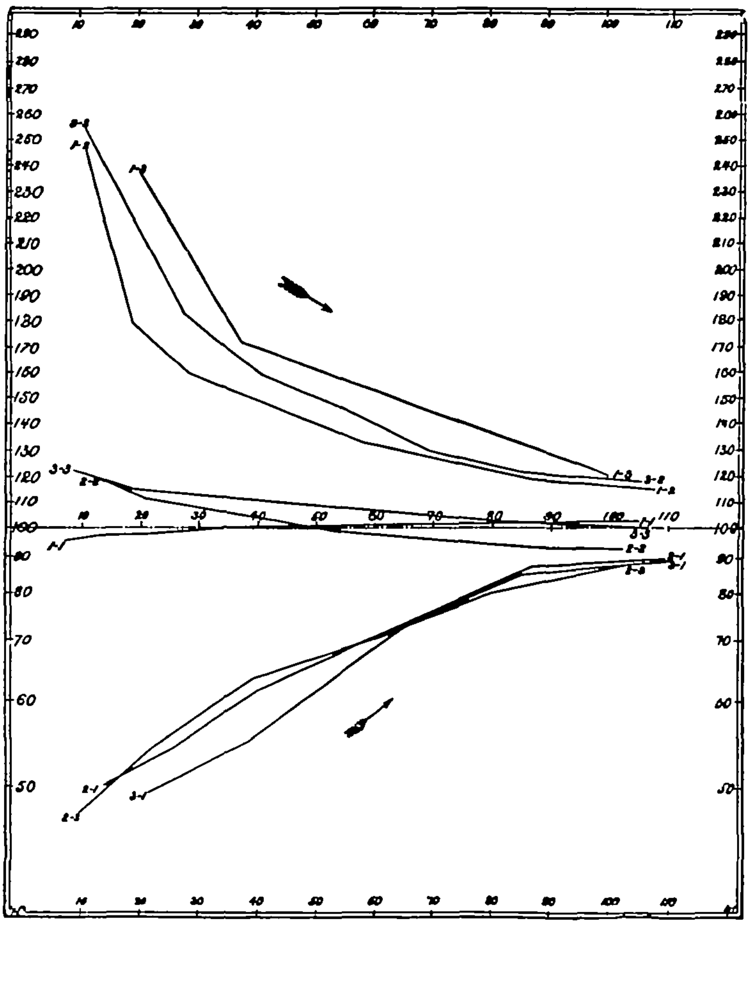


FIG. 5. CURVES SHOWING THE ERRORS IN REPRODUCING SPACE-IMPRESSIONS.

The error is measured by ordinates above or below the broken central line, in percentages as indicated at the sides of the diagram.

The abscissæ measure in millimetres the original length to be reproduced, as indicated upon the broken line as well as upon the top and bottom. The curves follow the direction of the arrows.

1 always indicates the Eye, 2 the Hand, and 3 the Arm.

1-1, the curve for receiving the impression and expressing the judgment by the Eye.

2-2, the curve for receiving the impression and expressing the judgment by the Hand.

3-3, the curve for receiving the impression and expressing the judgment by the Arm.

2-1,	the curve for receiving	by	the Hand	and expressing by	the Eye.
3-1,	"	"	the Arm	"	the Eye.
1-2,	"	"	the Eye	"	the Hand.
3-2,	"	"	the Arm	"	the Hand.
1-3,	"	"	the Eye	"	the Arm.
2-3,	"	"	the Hand	"	the Arm.

Each curve represents the average of experiments upon from three to seven individuals and the result of about 1800 observations.

The distinguishing characteristic of a curve is its direction; whether it proceeds from below the line upward, or from above the line downward. Such features as the extent of the error, or the point at which, if at all, the central line is crossed, show great individual differences. It is only when (as in the above described curves) the absolute error is small throughout, that individual differences appear as curves of opposite direction. The average error in the Eye-judgments was only 3 per cent., in the Hand-judgments 9 per cent., in the Arm-judgments 10 per cent.

When either the Hand or the Arm acted as both the receiving and expressing sense, the two sides of the body were used at once. What now would be the effect of interchanging the hands, making the receiving hand in the first case the expressing hand in the second? If it were only to alter slightly the extent of the error, it would indicate an accidental variation or a slight superiority of one hand. If, however, this change were to reverse the former result, it would indicate a lack of symmetrical correlation of the two sides of the body. In point of fact the latter is the result. When the *right* Hand is the *expressing* hand, the curve agrees with the curve 2-2 (Fig. 5); when the *left* hand is the expressing hand, the curve is *irregular* and *below* the central line. When the *left* Arm is the *expressing* arm, the curve agrees with the curve 3-3 (Fig. 5); when the *right* arm is the expressing arm, the curve is *irregular* and *below* the line. The next question is, Which of these two curves is to be preferred? It is answered thus: If instead of using both hands simultaneously, the same hand were used successively, and it were found that the little difference resulted from interchanging the hands (or arms), the curve for that hand (or arm) would be preferred which agreed with the results of the successive judgments. By this mode of reasoning, the curves for the *right hand* and the *left arm* as the expressing senses were preferred.[1] Another method of showing that the phenomenon is due to bilateral asymmetry of function, is to draw simultaneously lines with each hand, the attempt being to make the lines equal. Here as before the left arm draws the larger line, the error being slightly less when the lines are drawn towards than away from the body.

The conclusions above discussed may be summarised thus:—

When the same sense acts as the receiving and the expressing sense, the error is small (and the process easy). In operations involving the use of both sides of the body, an interchange of the function of the two sides reverses the results; when one hand alone is used in successive judgments, no such reversal takes place. The preferred Hand in span-sensations is the right; the preferred Arm in motion the left. The error of the Eye is less than that of the Hand; the error of the Hand slightly less than that of the Arm.

II. When the receiving and expressing senses are different,

(1) *If the Eye is the expressing sense, and*
(a) *the Hand the receiving sense,*

All lengths are greatly underestimated, the error decreasing as the length increases [Fig. 5, 2-1]. That is, if you attempt to mark off or select a length by the eye equal to the distance between your thumb and forefinger, the selected lengths will be too short; in case of small distances only about one-half the real length. The lines thus selected varied from about 48 per cent. to 88 per cent. of the true distance between thumb and forefinger the average being about 65 per cent.[2]

If the Eye is the expressing sense, and
(b) *the Arm the receiving sense,*

All lengths are greatly underestimated, the error decreasing as the length increases [Fig. 5, 3-1]. That is, the attempt to mark off or select by sight a line equal to the space moved over by a free arm movement will result in selecting or marking off much

[1] The successive judgments were made by the Hand, by first grasping a block between thumb and forefinger and then adjusting the carriages of the Span-triangle, to match the block felt; by the Arm, by attempting to draw (with eyes closed) the second of a pair of lines equal to the first, using the apparatus shown in Fig. 1'. In both these cases it makes little difference which hand or arm is used. All those experimented upon were right-handed.

[2] The lines were selected on the Sight-triangle or marked off on ruled paper, the impression being received by the right or the left hand. By these four methods a length of 15mm. was reproduced by lines 46 per cent., 36 per cent., 37 per cent. and 34 per cent. of the real length; of 110 mm. by lines 84 per cent., 80 per cent., 87 per cent. and 88 per cent. of the real length. The close correspondence of these numbers is an indication of the regularity of the processes involved.

too short a line. The error varies within about the same limits as when the hand acts as the receiving sense.

By combining the two conclusions we see that—

If the Eye is the expressing sense all lengths are greatly underestimated, the error decreasing as the length increases. This is expressed on Fig. 5 by the fact that the two curves 2-1 and 3-1 are close together throughout.

(2) *If the Hand is the expressing sense, and*
(a) *the Eye the receiving sense,*

All lengths are greatly exaggerated, the error decreasing as the length increases [Fig. 5, 1-2]. That is, the attempt to hold the thumb and forefinger as far apart as the length of a line seen by the eye will result in holding the thumb and forefinger too far apart, the distance being more than double the true length in case of short lines. On the average, the lines were reproduced by distances 144 per cent. of their true length.

If the Hand is the expressing sense, and
(b) *the Arm the receiving sense,*

All lengths are greatly exaggerated, the error decreasing as the length increases [Fig. 5, 3-2]. That is, the attempt to hold the thumb and forefinger as far apart as the space moved over by a free arm movement (of the other arm) will result in holding the thumb and forefinger too far apart.[1] On the average, movements were reproduced by distances 168 per cent. of their true length.

By combining the two results last obtained we see that—

If the Hand is the expressing sense, all lengths are greatly exaggerated, the error decreasing as the length increases. This is expressed on Fig. 5 by the close correspondence of the two curves 1-2 and 3-2.

(3) *If the Arm is the expressing sense, and*
(a) *the Eye the receiving sense,*

All lengths are greatly exaggerated, the error decreasing as the length increases [Fig. 5, 1-3]. That is, the attempt to move over a space equal to the length of a line seen by the eye will result in moving over much too large a space. On the average, a line will be reproduced by a space 185 per cent. of its true length.

If the Arm is the expressing sense, and
(b) *the Hand the receiving sense,*

All lengths are greatly underestimated, the error decreasing as the length increases [Fig. 5, 2-3]. That is, the attempt to move over a space equal to the distance between thumb and forefinger (of the other hand) will result in moving over much too

[1] It is to be noted that although both sides of the body are involved in this operation, it makes little difference whether the right side acts as the receiving sense and the left as the expressing sense, or *vice versâ*.

small a space.[1] On the average, the distance between thumb and forefinger will be reproduced by a movement 68 per cent. of its true length. It is not possible to combine the last two statements, for the substitution of Eye for Hand as the receiving sense changes the error from an underestimation to an exaggeration.

A comparison of the conclusions thus far reached will bring to light a few general laws applicable to all three senses.

A. The error decreases as the length (to be reproduced) increases.

This means that (within the limits of the lengths experimented upon) a larger length is reproduced more accurately than a smaller one. It is expressed in Fig 5 by the fact that the direction of all the curves is towards the central line, following one or other of the arrows.[2]

B. If reproducing one sense by another results in an exaggeration (or underestimation), then reproducing the second sense by the first will result in an underestimation (or exaggeration) to about the same extent.

In attempting to move over a space equal to the length of a line seen I move over much too large a space, and when I select by sight a line equal to a space moved over by my arm I select much too short a line. Thus the curves expressing the space-relations of the three senses are grouped in pairs [Fig. 5, 1-2 and 2-1; 1-3 and 3-1; 3-2 and 2-3], one of each pair being above the central line, the other (in which the receiving and expressing senses have changed places) below it. This law confirms one's *à priori* expectations on the assumption that the processes involved are rational and regular; for to say that the eye 'draws' a smaller line than the arm is the same as to say that the arm draws a larger line than the eye. A result of this law is that in the three pairs of operations, Eye to Hand and Hand to Eye (1-2 and 2-1), Eye to Arm and Arm to Eye (1-3 and 3-1), Arm to Hand and Hand to Arm (3-2 and 2-3), the mean proportional[3] between the exaggerated reproduction by the first and the underestimated reproduction by the second of each pair of operations will give

[1] The foot-note on page 547 is equally applicable here.

[2] The law is applicable to the curves in which the receiving and expressing senses are the same, if we measure the error by ordinates upon a horizontal line drawn through the origin of the curve.

[3] Not the 'mean' but the 'mean proportional,' because the same absolute error is a greater error as an underestimation than as an exaggeration. Doubling a length is as far from the truth as halving it; but there is an error of 100 per cent. in the first case and of 50 per cent. in the second. The two appear alike when we compare the exaggerated reproduction with the reciprocal of the underestimated reproduction. To make the curves above and below the central line (Fig. 5) absolutely comparable as they stand, the percentages below the central line are plotted in terms of their

about the real length. If (1) without looking I take a book between my thumb and forefinger and mark off by sight a length that seems equal to the thickness felt, and then (2) looking at the thickness of the book, measure the distance between thumb and forefinger that seems equal to the thickness as seen, the mean proportional between the two results will give about the true thickness of the book.

C. A third rather peculiar law remains to be noticed. The processes involved in the above-described experiments can be represented thus: A length presented to the receiving sense makes a certain impression on my brain-centre; the problem then is to reproduce the objective stimulation which shall give me an equivalent sensation. The two operations being simultaneous, the sensations can be compared and the judgment corrected until they agree. When the receiving and expressing senses are the same, the comparison is between homogeneous sensations, involving one brain-centre; the operation is easy and the error small. When the expressing sense differs from the receiving sense, heterogeneous sensations must be compared, involving two brain-centres; a difficult operation with a large error. The large error seems to be due to a looseness of association between heterogeneous space-centres; it is a path of high resistance. Why this error is in the direction in which it is, and not in the opposite direction, depends on some fundamental relation of the senses involved, still to be discovered. For the present, the fact that the same objective spacial stimulation has a different value for the several space-senses is to be emphasised. Perhaps the following method will shed some little light on the question. Which of the following changes can be made with a minimum alteration of the results: (1) Substituting one receiving sense for another, leaving the expressing sense unchanged? Or (2) substituting one expressing sense for another, leaving the receiving sense unchanged? If the first, then the error derives its characteristic more from the expressing sense; if the second, from the receiving sense. In point of fact the generalisations already formulated show that t h e e x p r e s s i n g s e n s e g i v e s t h e c h a r a c t e r i s t i c p r o p e r t i e s t o t h e c u r v e, for it was seen that with the Eye as expressing sense an underestimation, with the Hand or Arm as expressing sense an exaggeration takes place, it being immaterial whether the eye, the hand or the arm acts as receiving sense. As a peculiar exception[1]

reciprocals. The average reproductions of the exaggerating curves are 185 per cent., 168 per cent. and 144 per cent. respectively; of the underestimating curves 68 per cent., 65 per cent. and 59 per cent., whose reciprocals are 147 per cent., 154 per cent. and 170 per cent. This justifies the clause "to about the same extent" in Law B.

[1] The peculiarity of the exception is that it is a necessary one. Law B requires the curves for reproducing the arm by the hand and the hand by the arm to be on opposite sides of the central line, while Law C requires them to be on the same side; *i.e.*, whenever expressing by one sense causes the

to this rule we found that with the Arm as expressing sense and the Eye as receiving sense, an exaggeration, but with the Hand as receiving sense, an underestimation takes place.

Another mode of experimentation touches upon the problem in a somewhat different manner. The subject, instead of having an impression presented to one of his senses, attempts to express his mental recollection of some absolute measure (*e.g.*, a certain number of inches), by selecting a line, a distance between thumb and forefinger, or a space moved over by the arm, that seems equal to the mental recollection. In so doing the eye 'creates' its inches about 10 per cent. too short; the hand and arm about 20 per cent. too long in small lengths, the excess decreasing as the length increases. The smallness[1] of these errors seems best accounted for by assuming that in 'creating' inches by the Eye I use the recollection of my visual inch; by the thumb and forefinger, of my span-inch; by the arm, of my motion-inch. The operation would closely resemble that in which the receiving and expressing senses are the same; accordingly, when the sense used is the Eye we should have an underestimation, when the Hand or Arm an exaggeration, which is exactly the case. Our conclusions then are (1) *that the memory for absolute measurements is not quite accurate, the order of accuracy being Sight, Span, Motion;* (2) *that the operation probably consists in matching the reproduction with the homogeneous mental recollection;* (3) *that the Visual inch is too short, the Span- and Motion-inch too long.* These conclusions evidently favour the point of view of law C.

D. Finally, a comparison of the error in reproducing by the same and by a different sense leads to the very important conclusion that the former operation is an accurate and easy one, the latter an inaccurate and difficult one. The difficulty manifests itself as a feeling of discomforting uncertainty and lack of confidence in one's judgments, and a great susceptibility to fatigue. The connexion between two senses seems to be a loose one.

Relative Accuracy of the Senses.

Three indications of the relative accuracy of the three senses have already been given. (1) When the receiving and expressing

same kind of error as expressing by another, this contradiction between the two laws must take place. In this case Law C is violated and Law B maintained.

[1] A further indication of the regularity of these operations was obtained by requiring the subject to judge in inches the lengths of certain lines, distances and spaces by Sight, Span and Motion. If in expressing inches there is an exaggeration (or underestimation), then in judging inches there must be an underestimation (or exaggeration); and this is really the case. To show the effect of practice in one's knowledge of absolute lengths, some carpenters were tested and found to give more accurate and confident judgments than others. This superiority was confined entirely to Sight.

senses are the same, the error of the Eye is smaller than that of the Hand, and of the latter slightly smaller than that of the Arm; (2) when the receiving and expressing senses are different, the same holds true, if we regard the expressing sense as the characteristic one; (3) in expressing and judging inches, the order of accuracy is also Eye, Hand, Arm; the two last being nearly alike.

Prof. Bowditch and Mr. Southard[1] have compared Sight and the Motion-sense by placing a small disc upon a table and requiring the subject (with eyes closed) to guide a pencil to the disc. In one set of experiments the knowledge of the position of the disc was obtained by glancing at it, in another set by placing it in position with the hand. They find that the error, *i.e.*, the distance between the disc and the point upon which the pencil was placed, is least when the eye in direct vision is the sense used, and greatest when the opposite hand is used, it being intermediate if the disc and the pencil be placed by the same hand. The effect of the time-interval between placing and finding the disc is about the same in each method, the most accurate adjustments being made with an interval of two seconds.

The following experiments were designed to obtain the ratio of erroneous judgments made in deciding which of two slightly different lengths was the longer, when the decision was made by the eye, by the hand and by the arm. For testing Sight two groups of lines, with three lines in each group, were drawn and fastened to the cylinder (Fig. 3) to be viewed successively through the slit in the screen. The lengths of the first lines in the groups were 25 mm. and 100 mm. respectively, the second differing from the first by $\frac{1}{50}$ and the third by $\frac{1}{100}$ of the entire length. For testing the sense of Span two precisely similar groups of blocks were constructed and mounted on the car (B, Fig. 1), to be felt successively by thumb and forefinger. For testing the Motion-sense a delicate Motion-triangle was devised and the points recorded on the scale at which the desired differences were reached. An observation was made as follows:—For example, we are testing the eye, using the larger lengths (100 mm.) and a difference of $\frac{1}{50}$. The subject then either (1) sees a line 100 mm. long, then one 98 mm. long, and again one 100 mm. long, or (2) sees a line 98 mm. long, then one 100 mm. long, and again one 98 mm. long. The first and third lengths are always alike, the middle length is either shorter as in the first case, or longer as in the second, and the subject is to decide whether the middle length was shorter or longer. By having two changes—one an increase, the other a decrease—in each experiment, the well-known difference in sensibility for these two kinds of change is avoided; while the chance of a correct answer is increased. In addition to its correctness or falsity, the confidence felt in the judgment given was recorded on a scale of 4 degrees, in which 3 denoted

[1] *Journal of Physiology*, iii. 3.

a feeling of certainty; 0, no decided inclination for one answer over its opposite; and between the two 1 and 2 naturally found their places.[1] In the following Table, the errors in a set of 10 judgments and the average confidence are recorded for each sense and for each relative difference distinguishing the small lengths from the large ones. Experiments were made on four individuals and include about 1000 judgments.

Sense.	Absolute Length : 100 mm.				Absolute Length : 25 mm.			
	Difference of $\frac{1}{50}$.		Difference of $\frac{1}{100}$.		Difference of $\frac{1}{50}$.		Difference of $\frac{1}{100}$.	
	No. of errors in 10.	Av. confidence.	No. of errors in 10.	Av. confidence.	No. of errors in 10.	Av. confidence.	No. of errors in 10.	Av. confidence.
Eye.........	·75	1·6	2·6	·60	·7	2·1	1·8	1·1
Hand......	1.3	·58	3·5	·27	1·2	·65	3·3	·2
Arm	3·2	·19	...	...	3·8	·17	...	...

The order of differential sensibility of the three senses is Sight, Span, Motion. It is to be noted how regularly the confidence rises as the number of errors decreases. This indicates a distinct feeling of the superior sensibibility of Sight over Span,[2] of Span over Motion, as well as a distinction between differences of $\frac{1}{50}$ and of $\frac{1}{100}$. As the errors for lengths of 100 mm. differ little from those for lengths of 25 mm., Weber's law may be applicable to these kinds of sensibility.

Some experiments were made to test the accuracy of the memory for Sight- and Span-impressions. At an early stage of the experiments, when sight was reproduced by span and *vice versâ*, only two lengths were used, one 20 mm., the other 100 mm. long. The blocks were repeatedly reproduced by the eye, and the lines by the thumb and forefinger. Before and after each day's sitting, the subject was required to mark off from memory lines of the two lengths and to guide his thumb and forefinger to the accustomed distances on the Span-triangle. In both cases the memory[3] is extremely accurate and is almost as faultless after

[1] This method was developed in connexion with experiments made by Mr. C. S. Peirce and the writer on "Small Differences of Sensation" (*Memoirs of the National Academy*, vol. iii.), to which the reader is referred for details.

[2] In judging differences with the thumb and forefinger, each hand was tested separately (the mean of the two results being given in the Table), with the result that the left hand made fewer errors. Those experimented upon were right-handed. The right arm alone was tested.

[3] Reproduction by memory is evidently analogous to expressing by inches; the accuracy of these memories favours conclusion (2) on p. 549.

the lapse of a few days as of a few minutes. The Eye-memory is slightly superior to the hand-memory; the arm was not tested. The superiority of sight finds a popular expression in such a phrase as "seeing is believing". The observation of Weber that, in writing letters or imagining them set on the chest, they are naturally inverted, being placed so as to be read by the eye, shows how unconsciously sight rules the other senses. An ingenious experiment of Helmholtz (*Phys. Optik*, p. 601) shows that sight must frequently be corrected by motor judgments. Looking through prismatic spectacles he attempted to guide his finger to an object, and naturally went far off to one side of it. Having learnt to allow for this by practice or by following the finger to the object, he found that the other hand had acquired this facility at the same time, indicating that sight alone was deceived. Children, in whom the co-ordination of sight and touch is imperfect, can guide things to the mouth more readily than to a seen object.

Experiments upon the Blind.

By experimenting upon the blind, in whose education sight—the space-sense *par excellence*—has had no share, one may be able to detect to what extent their space-conceptions have suffered by this loss, and how far the other senses, by increased practice, have been able to supply the deficiency. Experiments were made upon one subject, blind almost from birth, and the results thus obtained verified upon others.

(1) In reproducing the Hand by the Hand or the Arm by the Arm, the error of the blind is slightly greater than that of seeing persons, but in the same direction.

(2) If the Hand reproduces the Arm, the error is somewhat greater, if the Arm reproduces the Hand, much greater, than that of seeing persons, the lines being drawn, on the average, less than half their real length.

(3) In expressing inches[1] by the Hand, the error is slightly larger; by the Arm much larger than that of seeing persons. The Motion-inch of the blind is really about ½ inch long.

This yields the conclusion that the error of the blind in reproducing one sense by the same or by another sense is quite like that of normal persons, excepting that in the latter case the error is somewhat larger, especially when motion is the expressing sense. It follows, too, that the blind person's notion of inches (especially of the motor inch) is much too small. The seeing person corrects this by sight.

When, however, we compare the accuracy with which small differences of length can be recognised by blind and by seeing persons, the effect of practice in the use of the hand and the arm shows a strong superiority in favour of the blind. In the follow-

[1] The knowledge of inches was acquired by feeling the intervals between pegs set upon a wooden ruler.

ing Table the number of errors in 10 judgments and the average confidence are recorded as in the former Table.

		Absolute Length: 100 mm.				Absolute Length: 25 mm.			
		Difference of $\frac{1}{30}$.		Difference of $\frac{1}{100}$.		Difference of $\frac{1}{30}$.		Difference of $\frac{1}{100}$.	
		No. of errors in 10.	Av. confidence.	No. of errors in 10.	Av. confidence.	No. of errors in 10.	Av. confidence.	No. of errors in 10.	Av. confidence.
Span (Hand)	Seeing..	1·3	·58	3·5	·27	1·2	·65	3.3	·20
	Blind...	·5	1·84	2·2	1·56	·9	1·77	2·4	1·57
Motion (Arm)	Seeing..	3·2	·19	...	...	3·8	·16	...	...
	Blind...	1·6	1·39	...	...	2·3	1·37	...	...

As in seeing persons, the sense of Span has a finer sensibility than that of Motion. *In both senses the blind show a marked superiority over the seeing.*[1] By his thumb and forefinger the blind person can appreciate quite as fine distinctions as the seeing person by sight. Moreover, the confidence of the former is unusually high, indicating a reliance on these senses unknown to the latter.

Conclusion.

A reference to the classification of the Space-senses will show how small a portion of the problem has been investigated. Only one in each of the three most disparate methods of gaining linear impressions has been experimented upon. However, the method of experimentation employed is equally applicable to the others (and with some modifications to the study of the Time-sense). Very possibly future research in this direction will greatly supplement and modify the conclusions above reached, although these are based on no less than 28,000 observations, extending over a period of eighteen months.

My thanks are due to the very many persons who in various ways kindly gave up their time to the interests of this rather extended research.

Baltimore, Jan. 1886.

[1] The fact that the discriminative sensibility of the blind is finer but their error in reproducing sensations larger than that of seeing persons, indicates that these two kinds of faculty do not go together. This is borne out by the fact that those individuals who make the greatest error in reproducing sensations are able to judge fine differences as well as or better than others.