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ON THE AFTER-EFFECT OF SEEN MOVEMENT

by

A. WOHLGEMUTH, D.Sc. (Lond.)

THESIS APPROVED FOR THE DEGREE OF DOCTOR OF SCIENCE IN THE UNIVERSITY OF LONDON

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PREFACE

THE research to which the following pages are devoted has been carried out in the PSYCHOLOGICAL LABORATORY, UNIVERSITY COLLEGE (UNIVERSITY OF LONDON), GOWER STREET, LONDON, W.C. It was begun in 1905 on the advice and with the kind assistance of Mr William McDougall, then head of the laboratory, and was continued with several interruptions to the end of the academical year 1909. In 1910 the results were presented to and accepted by the University of London as a thesis for the Doctorate of Science, of which the following pages are a reprint with but slight alterations.

The compilation of the *Historical Survey* was very protracted work owing to the literature being scattered in many places other than the ordinary psychological sources.

I avail myself of this opportunity to thank all those who at some time or other have kindly assisted me by being observers during these long and often most trying experiments, especially to Professor Carveth Read, who has submitted to them frequently at great personal inconvenience, and to Mr J. C. Flügel. My thanks are also due to Dr C. Spearman, the present head of the department, for affording me all possible facilities in his laboratory for this lengthy research, for his constant encouragement, his invaluable criticism, and his kind assistance.

A. WOHLGEMUTH.

PSYCHOLOGICAL LABORATORY,
UNIVERSITY COLLEGE,
GOWER STREET,
LONDON, W.C.
May, 1910.

CONTENTS

I. HISTORICAL SURVEY.

(The numbers in brackets refer to the Bibliographical List.)

THE illusion which forms the subject to be treated in these pages is probably to-day one of fairly common knowledge. If we look for a little while at a waterfall, fixating a point on the stationary rock behind, and then gaze upon the stationary landscape, this will appear to move upwards. After having looked at a flowing river, we experience a similar effect as stationary objects show an apparent movement in the opposite direction. From a moving carriage, receding objects grow smaller, shrink. If the carriage stop suddenly, these objects appear to grow larger, to swell, to come nearer. In the laboratory, we produce the effect by pasting a strip of paper with alternating black and white lines on a Kymograph-drum, and then fixating a stationary point close in front of it whilst the drum is rotated. If the drum is then suddenly stopped whilst we continue to fixate the point, the lines appear to move backwards. Discs with radii or alternating black and white sectors produce an analogous effect. In short, under certain conditions, a movement produces an after-effect which manifests itself as an apparent movement in the opposite direction.

Mention of this phenomenon we find as early as:

ARISTOTLE, who in his treatise on Dreams (Parva Naturalia) writes as follows: "Also, the senses are affected in this way when they turn quickly from objects in motion, *e.g.* from looking at a river and especially from looking at swiftly flowing streams. For objects at rest then seem to be in motion[1]." Aristotle does not emphasize that the direction of the movement is reversed but this is not surprising if we consider that his statements about after-images of colours in the same treatise are even inaccurate.

[1] Translated by W. A. Hammond : *Aristotle's Psychology*. London, 1902, p. 236.

No other reference to the phenomenon is known to me earlier than Purkinje's in 1825.

JOHANN PURKINJE, 1825, (36). After having looked for more than an hour at a cavalry procession, the houses appeared to Purkinje to move in the direction opposite to that of the procession. In attempting to explain the phenomenon, Purkinje states that the eye, in endeavouring to fixate each individual soldier, moves unconsciously in the same direction. This so often repeated movement becomes, for the time being, habitual and continues even after the procession has passed. The eye then wants to fixate the stationary objects in a similar manner to which it has learned to fixate the moving one; it unconsciously slides in the accustomed direction, which makes the objects appear to slip away in the opposite direction.

R. ADAMS, 1834, (1). He discovered and described the phenomenon anew. During a tour in Scotland, he noticed that, after having looked at a waterfall for a short time, and on turning the eyes to the stationary landscape this appeared to move upwards. He attributes the cause of the phenomenon, like Purkinje, to eye-movements; he states that he has also noticed it when travelling rapidly and when unrolling a piece of calico, and that he can produce it by turning the head to and fro.

JOHANNES MÜLLER, 1840, (32). He discusses the phenomenon in his *Handbuch der Physiologie* which was published in this year. He says that if a body with serially moving parts be looked at for some time, the after-images disappear in the same order as they originated, and thus present the appearance of movement in the same direction; consequently when a stationary object is looked at during this time, it will appear to move in the opposite direction.

SIR DAVID BREWSTER, 1845, (8). He noted that after looking out of a moving railway carriage at objects near the line and then quickly shutting the eyes, a motion is perceived in a direction transverse to the real impression. Brewster is therefore the first to have noted the phenomenon in the subjective field[1] of vision, but he appears to have overlooked it in the objective field. His statement that the after-effect was "transverse" to the direction of the objective movement is

[1] I follow here the practice of previous observers and intend to designate by the term "subjective field of vision" the visual experience one has with closed eyes, and by "objective field of vision" the visual experience with open eyes. In this latter case the after-effect is projected on to an external surface which by several recent investigators has been termed the "projection ground" or "projection field." These terms also have been used by me.

possibly due to his changing the position of his head when he closed his eyes. No attempt is made at explanation.

RUETE, 1845, (37). He follows Johannes Müller's view, that the "Gesichtschwindel" is due to the passing away of after-images on the retina.

J. PLATEAU, 1850, (35). He again "discovered" the phenomenon and appears to have been the first to approach the subject critically and to investigate it experimentally. He constructed the spiral known by his name, although its present form differs greatly from that used by him, viz. a thin white spiral line of wide turns drawn on a black disc. On turning such a disc, the spiral appears to draw in towards the centre or out and away from it, according to the direction in which the disc is rotated. If a face is looked at immediately afterwards, it appears to contract or expand according to the direction of rotation. This illusion Plateau found to show itself in different degrees with different persons. He found the looking at such a rotating disc very fatiguing to the eyes; he advised that the experiment should be done with great care and that if it had to be repeated with the same person, it should be done at long intervals. He saw in this phenomenon a new argument in favour of his "Principle of Oscillation of an impression," which is the foundation of his "theory of accidental (*i.e.* complementary) colours[1]."

HERMANN LOTZE, 1852, (30). In his *Medizinische Psychologie* published in this year, he considers the after-effect of motion as a symptom of giddiness. In the case of no point being fixated, he attributes the phenomenon to unconscious eye-movements. For the case, however, of a point being fixated, he has recourse to a psychical motive; he says (page 444):

"...so bildet sich die Gewohnheit, bei ruhendem Auge eine Mannigfaltigkeit von Objecten in bestimmter Richtung vorüberfliessen zu sehen. Mit dieser Erwartung wendet sich der Blick auch auf die ruhende Landschaft, und da ihm hier die Gegenstände bei unverwendeter Stellung der Augenachse nicht verschwinden, so scheinen sie dies nur durch eine der früheren Richtung entgegengesetzte Bewegung zu können. Es entsteht daher der Schein, als wären die sämmtlichen Punkte der Landschaft jeden Augenblick im Begriffe, eine Bewegung zu beginnen, obgleich es nie dazu kommt, so lange nicht das Auge

[1] "Essai d'une théorie générale comprenant l'ensemble des apparences visuelles qui succèdent à la contemplation des objets colorés." *Nouveaux Mém. de l'Acad. de Brux.* Tome VIII. 1834.

dieser Erwartung nachgehend, selbst der vorausgesetzten Flucht der Gegenstände zu folgen anfängt, und dadurch den Schein einer wirklichen entgegenkommenden Bewegung derselben sich erzeugt."

J. J. OPPEL, 1856, (33 and 34). His first paper upon this subject was published in this year. A friend of his, after having looked at the rapids of the Rhine at Schaffhausen and then on the banks of the river, noticed an apparent vivid movement of the gravel in the opposite direction. Oppel examined the phenomenon and concluded that it was of an "entoptic nature in the larger sense of the term." He describes it as a "reaction-activity of the eye with reference to moving retinal images," caused by the eye having been exposed for some time to the uniform movement of the images; this makes the stationary objects looked at immediately afterwards seem to move in the opposite direction. The phenomenon would therefore be analogous to that of after-images of complementary colours, to that of light contrast, in short, would belong to the great class of contrast phenomena.

Oppel, too, thought that he had discovered the phenomenon; it was not until later that he found that Plateau had already described it.

In order to investigate it under experimental conditions, Oppel constructed his "antirrheoscope," an apparatus which consisted essentially of five parallel cylinders, each having a line winding spirally around it. These cylinders were rotated together by means of pulleys and a movement of the lines was thus produced. Oppel considered that in this apparatus, there was only an apparent progression of the lines. In order to have a real progression, he constructed another apparatus consisting of an endless strip of paper passing over and moved by two wooden rollers. He painted the paper with green, blue and white colours, to imitate the water of the stream, and as a projection ground, he used a sheet of card-board with a blue sky and white clouds, and a little bird or a balloon as fixation-point, painted on it, as he thought it essential to reproduce the conditions met with in nature. He laid down a number of rules which, from his experimentation, he considered indispensable in the production of the after-image. Plateau's observations were verified but his theory of oscillation criticized. Oppel puts forward a view of an "impressio remanens"; the eye retains a "spectrum" moving in the same direction which, though not actually rising to full consciousness, yet causes the stationary surface to seem relatively to move in the opposite direction. He could not, however, detect the presence of such a spectrum by experiment. In a later article (34) published in 1860, he defends himself against some criticisms and rejects the attempts at explanation made by Johannes Müller (the passing-off of after-images) and Purkinje (eye-movements) and gives Zöllner's explanation (psychical factors). He refrains from passing a judgment upon the latter but states that in his opinion "the ultimate cause of the phenomenon in question must not be looked for in the mechanical nor in the optical apparatus, but that it lies beyond the obscure bridge which connects the retina with the sensorium."

F. Zöllner, 1860, (49). He published a paper in this year which is curious on account of its purely dialectical treatment of the subject and its total neglect of experiment. Having established his premises, he proceeds step by step in apparently logical fashion. The gist of his reasoning is about as follows:

"Our idea of rest or motion is only relative." It is not the immediate product of sensory perception but the result of logical conclusions which we deduce by means of the reflecting and comparing activity of our reason from the data of observation given by the eye. Only the great rapidity with which these operations of reason follow one upon another prevents their rising singly into consciousness. If we want to ascertain whether two stars move, we measure their positions repeatedly with reference to a fixed star. Suppose that after some time, we find that one of the two stars has moved, we cannot conclude that the other has not moved; for our instruments may not be delicate enough to measure its movement. Only after many observations, during a long time, can the possibility that the second star does not move, become a probability which, with the lapse of time and the number of observations made during that time, asymptotically approaches a certainty. Hence the idea of rest requires a longer time for its development than the idea of movement. Further, we conclude from a regularly and periodically recurring phenomenon that it will also take place the next time it is due. Given a regular movement of a row of equidistant points, we conclude, as we observe the passage of one point after the other, that another point will follow and so on, our certainty being the greater the oftener our expectations have been gratified, *i.e.* the longer the movement has been observed. If then the points suddenly come to rest, this changed stimulation of the retina immediately affects our consciousness, but the change is at first perceived as a changed state of motion, since for the production of the idea of rest our reflection must have been active for some time. If this be admitted, two cases are to be considered as possible, viz. either that the movement is in the same direction or in the opposite. (To assume the possibility of movement in all possible directions would be prolonging the deductions unreasonably; by the rule of sufficient reason, all these could be eliminated.) If a body moving in a straight line pass into a movement of the opposite sign, it must necessarily pass through a state of rest; and this state may either be looked upon as the end-state of the previous movement or as the beginning of the movement in the opposite direction. Since the first of these two cases is excluded as a lasting state by the already supposed mobility, only the latter remains and the body must therefore move for our consciousness in the opposite direction. Q.E.D. (*sic*).

Dr August Classen, 1863, (11). He denies that the phenomenon is due to involuntary eye-movements since he could not discover such by objective observation. He agrees with J. J. Oppel that it is not due to after-images but denies that it is caused by a process in the brain. He looks for an explanation of the phenomenon in the reflex tendency of the eyes to follow any movement and the innervation of the antagonistic eye-muscles to resist it. When the eye is turned to a stationary object, the increased innervation continues but, being no longer adequate to the visual experience, produces visual vertigo (Gesichtschwindel). As in paralysis of an eye muscle, the vertigo is not caused by the feeling of tension but by the feeling of impulse to contraction, *i.e.* the sense of innervation.

Th. W. Engelmann, 1867, (15 and 16). He published some observations remarkable for being contrary to those of all other investigators. During a railway journey, Engelmann obtained positive after-images of the carriage-window. These developed within a few seconds and the contents of the window-frame, viz. the trees, houses, etc., appeared to be moving in the *same* direction as the objects. But this apparent direction could be reversed at will by imagining the train to move in the opposite direction.

H. v. Helmholtz, 1867, (23). In his *Handbuch der physiologischen Optik*, 1st Edition 1867, he refers twice to the matter. He thinks that the "Gesichtschwindel" is due to eye-movements and that these result essentially from the eyes following the moving object. He finds, curiously enough, that rigid fixation of a point is antagonistic to the production of the phenomenon. He mentions Plateau's spiral evidently without realizing that it disproves his own theory. Later, he gives a description of Oppel's antirrheoscope; he confirms his own previous observations, in opposition to those of Oppel; but agrees with him that the illusion is prevented by the large voluntary movements of the eyes with which we consciously follow a moving object.

v. DVOŘÁK, 1870, (14). He brought out an improvement on Plateau's spiral experiment. On a large white disc with a black spiral, he placed a smaller concentric disc with a spiral running in the opposite direction, and on this again a still smaller disc, the spiral on which ran in the same direction as the first one. On the common centre, a small black disc was put, and in front of the compound disc some black threads were stretched. The after-effect was projected on a white screen, where the negative after-images of the black centre and the black threads could be clearly seen as well as the three zones, each with a streaming movement in a direction opposite to that of the original one. From this Dvořák concluded, that the after-image of motion is not due to eye-movements but is as much a local phenomenon as the after-images of light and colour. When the objective movement was observed by him with one eye only and then this eye was closed whilst the other eye looked at a resting object, the after-image was still, he found, noticeable. The mutual relation of the two retinae also obtain here, just as in other visual after-images. He also tried two spirals on the same disc, but in opposite directions and in different colours; on rotating the disc, they appeared to shrink and swell respectively, but no after-image was obtained, even if the attention was concentrated on one spiral only.

WILHELM WUNDT, 1874, (46). In the 1st Edition of his *Grundzüge*, published in 1874, he gives Helmholtz' explanation of the phenomenon. But later, in the 5th Edition of this work (47), published in 1902, he prefers the view that the phenomenon is neither due to the effects of eye-movements, nor to a "mysterious reaction of the retina," but to the effects of the after-images aided by association factors.

E. MACH, 1875, (31). He described the phenomenon and pointed out that the after-effect only passed-off on faint contours but not on well-marked ones. He is of opinion that it is a local effect in the retina just as light and colour after-images. He recalls an early hypothesis of his[1] as holding good here also: "In a sensation process, we may assume as many different physical processes as there are psychically distinguishable different sensation-qualities." Accordingly, we have to think that with the movement of a retinal image a special process is set up which is not present in the resting stage; and that in opposite movements similar processes in similar organs are excited but these processes

[1] Mach: "Über die Wirkung der räumlichen Verteilung des Lichtreizes auf die Netzhaut." *Sitzungsberichte der Wiener Akad. d. Wissenschaften*, Bd. 52.

exclude each other in such a way that with the occurrence of the one, the other is counterbalanced, and with the exhaustion of one the other occurs. "This is not a theory," he says, "but a physical expression of observed psychical facts."

SILVANUS P. THOMPSON, 1877, (41). In his first notice on the subject, he says that the various effects of "compensation" of the movement of the retinal images could be explained by supposing them to set up a "secondary wave of nervous disturbances propagated in an opposite direction to that of the primary movement of the images." In later publications (42 and 43) he abandons this view, attributing the phenomenon to "the fact of retinal fatigue and the psychological fact of association of contrasts," and formulating a "law of subjective complementary motion."

JOHN AITKEN, 1878, (2). He experimented with discs having black and white sectors as well as with endless bands with alternating black and white stripes. The after-image or "motion spectrum," as Aitken calls it, was allowed to pass-off on a mottled surface, or on the disc or band itself on being stopped. When he used a disc with black radii for the exciting movement and projected the "spectral movement" on a larger disc with much longer radii, he found that all spectral movement was destroyed. From this, he concludes that the seat of the illusion is deeper than the retina.

Experiments were also made to determine the effect of influencing the whole retina by looking closely at the moving band, but no decisive effect was noticed. Next the observer was seated in a large cylindrical box-shaped arrangement, the sides of which had black and white vertical stripes. The cylinder was rotated round the observer and then raised, but no appearance of movement was noticed in the surrounding objects. Often while surrounded by the rotating box, the observer felt as if he were rotating in the opposite direction. The most certain result was, however, a most disagreeable and sickening effect, which continued for some time after the experiment was finished.

A. KLEINERT, 1878, (29). In order to examine Helmholtz' theory, he simultaneously regarded three radiated discs, placed side by side; the two outer ones were moved in the same direction and the middle one in the opposite direction. In the after-image the direction of each was reversed, thus disproving Helmholtz' theory of eye-movements. He showed that pseudo-movements may influence the direct observation of actual movements: he fixated the centre of a rotating spiral and allowed the after-image to pass-off on a rotating radiated disc which showed flicker; round the point of fixation, the actual objective movement of the radii appeared to fuse with the after-image. A similar phenomenon is produced if a rotating radial disc is fixated at the centre, and the after-image projected on a similar disc rotating in the opposite direction, the fixation thus being half-way between the centre and the periphery.

J. I. HOPPE, 1879, (25). His is a book of much volume but little substance. Referring to Helmholtz' experiment with the rotating sectorial disc which when "suddenly stopped, appears to move in an opposite direction," Hoppe remarks: "Dem aber ist nicht ganz so... Thatsächlich aber dreht sich die ruhende Scheibe dann nicht scheinbar. Sondern man hat dann nur die Wahrnehmung, dass sich auf der hastig angeschauten kleinen Stelle der Scheibe eine schwache und undeutliche Bewegung befindet, und wahr ist nur, dass man diese vermeintliche Bewegung rückläufig, der vorangegangenen Drehung entgegengesetzt, auf die Scheibe versetzt" (*sic*). He explains the apparent backward movement thus: "Diesen rückläufigen Schein könnte man daraus erklären, dass man mit dem Stillstehen der Scheibe seine eigene Augenbewegung, mit welcher man bis dahin der gedrehten Scheibe folgte, zu hemmen sucht, und dass diese hemmende Bewegung, zumal bei einiger Anstrengung, nicht blos der früheren Drehung entgegengesetzt sein, sondern auch bis zu einem rückläufigen Grade steigen muss[1]." This is evidently absurd, for if the eyes moved, on the stopping of the disc, in a direction opposed to that of the original objective movement, the after-image should appear to continue in the same direction as the objective movement. Quite as fanciful is his explanation of the phenomenon as obtained with Plateau's spiral.

G. ZEHFUSS, 1880, (48). He repeated Plateau's and Oppel's experiments but does not consider their explanations satisfactory. His own opinion is as follows. After having looked for some time at an objective movement and then closing the eyes without covering them, chaotic masses of sparks appear in the subjective field of vision which move in a direction opposite to that of the exciting movement. The cause of the phenomenon is therefore taken to be in the retina. That not the whole of the brain is in a state of excitation as in vertigo, but that only the stimulated parts of the retina are the cause can be demonstrated, as he thinks, in the following manner. If an after-image is obtained of the window-frame of a moving railway carriage, only the contents of the window-frame appear to be a chaotic stream of sparks which nowhere goes beyond the limits of the window-frame, and whose direction is

[1] *loc. cit.* p. 118.

opposed to that of the objective visual field. Thus the apparent movement is confined to the stimulated part of the retina. Zehfuss supposes, without experiment, that the same effect would be obtained from very small windows. Consequently, he says, each single stimulated retinal element is in this excited condition: and an after-image of motion occupying a given area consists of the sum of the after-images of the separate excited retinal elements. He thought he observed that, on close examination of the phenomenon, each elementary point of the after-image possesses only a tendency to movement in the opposite direction and does not actually move. He argues that, if the stream of sparks be due to the circulation of the blood in the retina and its parallel layers, every nerve element appears to have its own blood-vessels, the flow in which follows the retinal image. As a consequence, the blood gets dammed up because it cannot flow off as easily as it is forced in the direction of the movement. If then the movement of the retinal image is stopped, the dammed-up blood begins, of necessity, to flow back again and thus give rise to the after-sensation in the opposite direction.

Bowditch and Stanley Hall, 1881, (7). Their publication is mainly a criticism of S. P. Thompson's so-called "law of subjective complementary motion." The authors state that the analogy between colours and motion in different directions in space is at best only remote and symbolic, so that the explanatory power of this "law" is extremely slight; "complementary," they think, is used with radically different connotations in the two cases. They experimented with horizontal black and white lines: "We might expect to accommodate the contradiction between sensation and judgment; the lines would seem to bend out of their strictly horizontal direction, but they do not do so for an instant; yet the impression of backward movement persists inexpugnably." With Plateau's spiral they found that, if a black stripe was laid across the turning disc just before it was stopped, the seething movement in the subjective field was also seen in the after-image of the stripe. Thus the same retinal elements give rise at the same time to the opposite impressions of motion and rest. They consider that the impression of motion either affects a different cerebral centre than that of rest, or that one is more centralized or perceptive and the other more peripheral or more purely sensory. They say: "We cannot resist raising the question whether we may not be here very near attaining the *quale* of real pure sensation, not, as we might infer from Vierordt, itself motion, but only the more primitive element from which motor effects are inferred." They found the after-effect was constant and gradual, and not intermittent or jerky as it appeared to Prof. Thompson.

TSCHERMAK, 1881, (44). He classes the phenomenon with after-images in general, and suggests calling it "inverted after-movement." The after-movement, he says, has not the same effect as an actual displacement, but appears as if a nebular coat were moving across the objects. The movement of the image on the retina occasions an irregularity in the excitation at the anterior and posterior borders of the image. This irregularity causes a difference in the phases of the after-image. Anteriorly, the positive after-image and contrast predominate; posteriorly, the negative after-image and similar colour induction. In consequence of this irregularity, the induction wave can only move backwards and this wave we project into the visual field as a movement in the opposite direction.

ERNST VON FLEISCHL, 1883, (22). He published some observations which he made incidentally. None of these call for special mention. He finishes his paper by stating: "It is evident from this, that the axioms of Logic, especially the 'Law of Contradiction,' only apply to thoughts and ideas but not to immediate sensations."

E. BUDDE, 1884, (9). This is a long investigation dealing exclusively with this subject. He suggests calling the phenomenon "metakinetic pseudo-movement" (metakinetische Scheinbewegung). Some of his observations are at variance with those of earlier as well as of later investigators.

The following are the principal results obtained by him. He finds that the metakinetic pseudo-movement corresponds to the objective movement as regards velocity, extent, and inverse direction. He points out that when the objective movement occupies a large part of the visual field (*e.g.* when looking into a stream or at an approaching steamer whilst standing on the landing stage) the "relative movement" is sometimes mistaken; the metakinetic pseudo-movement then corresponds to the impression. To ascertain the nature of the metakinetic pseudo-movement when the entire field of vision is in movement, he constructed a large cylinder of paper, 2 metres in diameter and 1·5 metres high. He sat in this cylinder in the same manner as Aitken (page 8) had already done, but he was unable to finish the experiment as he found it too trying. Distinctness of the objects in the first field of vision is necessary to obtain the phenomenon. It is immaterial whether the second field is far away or near, whether observation of the first field is made with one or both eyes; but if it is made with one eye and this eye is then closed whilst the rested eye is opened, there is no metakinetic movement in the second field. Objective movement as well as pseudo-movement is most easily observed in the lower field of vision, because, owing to the erect posture of our body, we are accustomed to attend more to the ground. If the velocity of the objective movement is increased, the strength of the pseudo-movement is likewise increased. No pseudo-movement is produced if the velocity of the objective movement is so fast that fusion takes place. The pseudo-movement is not influenced by the nature of the second field and can also be observed in the subjective field of vision. A few seconds suffice to produce the pseudo-movement; it gradually sinks below the threshold of perception, so that no absolute point can be fixed for the transition into rest; but once the apparent rest is reached, it remains. If the second field is slowly moving, the pseudo-movement is superposed on the real. With a great display of mathematical formulae, Budde attempts to calculate the "metakinetic displacement," but as the premises from which he starts have only been guessed or roughly estimated, these calculations cannot pretend to any degree of accuracy. More interesting are his two attempts at explanation. The first hypothesis assumes a displacement of the retinal elements in the direction opposed to that of the movement observed, the pseudo-movement is then produced by the return of the elements to their normal position. Budde himself objects that we know of no such mechanism and of no reason for its existence. No later investigator has attempted to disprove this hypothesis but my experiment 26 (page 75) seems to put this hypothesis out of court.

According to Budde's alternative hypothesis, the "metakinetic displacement" may be looked upon as pseudoscopy, *i.e.* in this case "a temporary falsification of the conclusions which are drawn in the central organ from correct sensations." If the eye is steadily fixating a stationary point whilst others are moving across the field of vision, then the attention jumps from the central stationary point to a peripheral moving one and back again. When it again jumps to the moving one, this has moved further. After a short time, the observer has grown so used to the process that, when the movement is suddenly stopped, the attention jumps further than the point has moved and the staying behind of the point is interpreted as a movement in the opposite direction.

Aug. Charpentier, 1886, (10). Although this note does not treat of the after-effect of movement, it ought to be mentioned here, because this author's explanation of another visual illusion has been considered by others to apply equally to the phenomenon under investigation. If a stationary luminous point is fixated in a perfectly dark room, this point appears to move at a rate of 2°—3° per sec. The whole displacement may appear as great and even greater than 30°. This illusion is not due to eye-movements since it is possible to produce it in any desired direction, *e.g.* in thinking of picking up a pin from the floor, the point appears to be displaced downwards; in thinking of a chimney-pot on the roof, the point appears to move upwards. If the eyes moved in the direction of the object thought of, the point ought to appear to move in the opposite direction. Charpentier says that in the experiment there is fixity of the retinal image without contraction of the eye-muscles, therefore the idea must be a beginning of the motor act, a motor-effort not followed by the effect; these unconscious efforts are produced in the brain and by the association of ideas.

Hermann Aubert, 1886, (3). After distinguishing between sensation of movement (Bewegungsempfindung) and perception of movement (Bewegungswahrnehmung), he says: "In the sensation of movement there is, besides the passing of the image across the retina with a certain velocity, an additional psychical factor, viz. the necessary interpretation of the retinal process. The psychical interpretation is not a purely psychical consideration but a psychical act given immediately with the sensory affection of the organ, as immediate and involuntary as the seeing of an object." Referring to previous investigations of his (*Physiologie der Netzhaut*, p. 211, and *Physiologische Optik*, p. 580), he finds that a period of $\frac{1}{7}$ sec. for a cone and about $\frac{2}{3}$ to 1 sec. for a sensation-circle of the retina is too great for a fusion of images, and too small for a complete discontinuity of the several excitations. "There remains a relation between the actual state of excitation and that of $\frac{1}{7}$ sec. earlier; and the *expression of this relation is a sensation sui generis, the sensation of movement.*" With reference to the after-effect of movement, he finds that the "metakinetic pseudo-movements of Budde" are very disturbing since these add themselves algebraically to the velocity of actually moving objects, so that this latter may become perfectly masked. In the following year, Aubert published a second paper (4) continuing his observation, but here he does not touch on the after-effect of movement.

E. Heuse, 1888, (24). He purposes proving that in the case of retinal vertigo (Netzhautschwindel), as he calls the after-effect of movement, the retina is affected. He obtained the after-effect in the subjective field of vision and noticed a streaming, opposite in direction to that of the objective movement; he found no trace of any after-image. The retinal streaming with closed eyes is still present after the apparent movement with open eyes has faded away. He suggests the following explanation: In the retina there exist centrifugal nerve fibres whose function is unknown and these may have something to do with the phenomenon. When moving objects, after they have been observed for some time, come to rest, a nerve current opposite in direction to that of the moving objects is caused in the retina which gives rise to the after-effect.

S. Exner, 1888, (18—20). The first of a number of very important publications by him appeared also in 1888. He found that there exist certain analogies between "sensations of brightness and colour" on the one hand, and "sensations of movement" on the other, as well as between their after-images, but they also show marked differences. According to Exner, both kinds of after-images are confined to the stimulated parts of the retina. With colour, there is sometimes rivalry, sometimes fusion, if identical parts of the retina are stimulated. With movement, Exner found that fusion never took place, neither in the primary image (*Vorbild*) nor in the after-image. This last statement is opposed to that of many other investigators, nor do my own observations confirm it, as far as the after-effect is concerned. The movement-sensation is immediately followed by the negative after-effect of movement, whilst with colour the negative after-image is preceded by a positive one. The after-image of motion of the one eye may be transferred to objects in the visual field of the other eye, to which, Exner says, nothing analogous exists in colour-vision. The same remarks apply to the fact that the after-image of one eye is diminished, by stimulating the other eye by an opposite movement, and also to the fact that the corresponding points of the non-stimulated eye show excitations corresponding to the negative after-image of the stimulated eye. Projections of the after-image of motion with changed position of head or eyes, or inclination of the projection-plane, demonstrate that it is not an alteration of judgment, but an alteration of physiological relations between the neighbouring retinal elements or their corresponding central parts. The sensations which underlie the perception of depth do not participate in the after-image of motion. It is not the physiological process in the nervous system upon which the judgments "upward movement," "movement to the right, towards me, etc.," are based, that is influenced by the preceding observation of a movement, but a physiological process which is set up in the nervous connection of anatomically characterized elements of the retina, or in their central stations. There is no name in ordinary language for this physiological process, since it is of no practical importance. It only occurs in combination with other excitations, and in these combinations it leads to the judgments named. There is some ground to suppose that the centripetal excitations are worked up to some extent in the subcortical centres before they reach the cerebral cortex, the organ of consciousness.

In his hypothesis advanced in explanation of the phenomenon Exner proceeds somewhat as follows. Localization in the field of vision is closely related to eye-movements, even with resting eyes; the eyes are turned reflexly towards any object in the peripheral field if that becomes an object of attention, therefore relationship may be assumed between the retinal elements and the eye-muscles; for the sake of simplicity, only four eye-muscles will be considered. Let *a, b, c, d, e, f* (Fig. 1) be the subcortical end stations of the paths leading from the retinal elements. Each station receives its excitation from one retinal element which, however, may by other paths send excitations to other centres. Let *S* be a summation cell, representing a central organ which is closely connected with the central paths of the Musculus rectus superior. Similarly *E, If, It* are closely connected with the central paths of the Musculus rectus externus, Musc. rect. inferior, and Musc. rect. internus respectively. Every point *a, b, c, ...* is connected with cells *S, E, If, It.* In the drawing, the connection between each station (*a, b, c,* etc.) and each summation cell (*E, If,* etc.) is represented, for simplicity's sake, as passing through the neighbouring stations. It is assumed that the distance of each station from each summation cell is approximately in the proportions as shown in the schema, *i.e. b* is nearer than *c* to *It* and further than it from *E.* "Nearer" and "further" have reference only to the time which an excitation requires to travel from any one of the stations to a particular summation cell. The result of the summation, within certain limits, is the less the slower the impulses follow upon one another. The cells A_1, A_2, A_3, A_4 are centres in close relation with the nuclei of the external eye-muscles or perhaps identical with them; they also have fibres *C* that go to the cortex, the organ of consciousness.

If, now, an image moves across the retina and excites successively the points *a, b, c,* etc., impulses reach *E* at somewhat shorter intervals than *S* and *If,* and at still shorter ones than *It* (it is fairly assumed that the rate of the conduction is not very great compared to the velocity of the observed movement), and, as we have seen, the shorter intervals furnish the stronger impulses. The excitation of A_3 is therefore stronger than that of any other A-cell. If the body moves in any other direction, *e.g.* a—d, a—e, f—b, etc., the relative excitations of the various A-cells are modified analogously. This appears to explain the sensation of motion through the retina, not only as regards direction

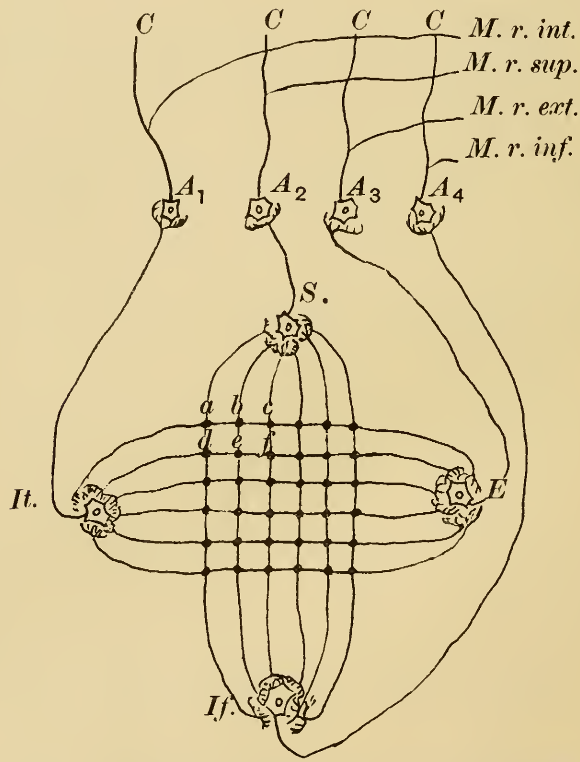

Fig. 1. Schema of a centre of optical movement-sensations.

a—f and the analogous points are the places at which the fibres from the retinal elements enter the centre.

S, E, It, If, are cells representing centres, where the excitations from each of the points mentioned arrive and where they can be summated. The time required by the excitations to reach there from any one of these points is approximately proportional to the distance given in the diagram.

A_1—A_4 are centres which are closely related to, or identical with, the nuclei of the exterior eye-muscles (only 4 are represented in the schema: M. externus, internus, superior, and inferior).

C are fibres leading to the Cortex, the organ of consciousness. (After Exner.)

but also as regards velocity; further, the fact that the sensation of movement has a lower and upper threshold. If the movement is too slow, there is no summation of stimuli in the summation-cells; if too rapid, the temporal difference of the impulses which reach the summation-cells is approximately the same for all. It also explains the phenomenon under discussion, viz. the after-image of motion. For if a constant movement is such that the points a, b, c,... are successively stimulated, the E-cell will eventually be more fatigued than the It-cell. Hence, if the eye be then turned to a stationary object, the energy of the summation-cells will be at its maximum in It, and at its minimum in E. Consequently, the excitation flowing into the A-cells will not be equal to that during continuous repose, but it will appear as if It is most strongly and E least strongly excited, *i.e.* as if the objects had a movement opposed to the original one. It might seem that on this theory, movements in opposite directions would cancel one another; for if, say, one movement is from a to c and another from f to d, the E and It-cells are affected equally; hence, there should be no "sensation[1]." But Exner gets over this difficulty by assuming a whole system of E-cells etc., and a whole system of A_3-cells etc., at the corresponding nuclei. Under this assumption, the two "sensations" would not wholly cancel one another but merely their distinctness would suffer much if two retinal images pass very close to one another in opposite directions, and after-images of motion would only be obtained from more expanded surfaces. Neither of these deductions have I been able to confirm experimentally.

If a movement, says Exner, stimulates two of the A-groups more strongly than the other A-groups, we do not see two movements, each of which corresponds to the direction-sensation of its cell group. The explanation of this is, that the movement-sensations in question can hardly be brought isolated into consciousness, because each of them is, as a rule, closely connected with a brightness-sensation and a sensation of "local sign." There is a oneness of impression in which the part-sensations cannot be analysed, based on the *principle of central confluence.* In a later paper, published in 1899, (21), Exner showed that not only real movement but also pseudo-movement gave rise to after-images of movement.

Beevor, 1889, (5). This author was evidently little acquainted with the work of previous investigators. He thinks it highly probable that the after-image of movement could be produced by "complementary

[1] By this term, Exner seems to mean what is usually called immediate perception.

sensation of movement" in the rods and cones of the retina which have become exhausted by the continued movement. While he does not deny the correctness of Helmholtz' view (eye-movements), he is unable to explain thereby how a strip only of the retina could be affected by after-movement and not the whole field of vision.

Julius Hoppe, 1894, (26). To investigate the phenomenon, he used a rotating disc covered with small geometrical figures. When a mirror was placed at right angles to the surface of the disc in the direction of the radius, the part approaching the mirror and its mirror-image moved in opposite directions. This disproved Helmholtz' theory since the eyes cannot move at the same time in both directions. To prove that only those parts of the retina which have been affected by the objective movement give the after-image, Hoppe placed a mirror close to a rotating disc in such a manner that a motionless space was between the mirror and the disc. He fixated a point within that space, and then looking on a surface with a faint pattern, he obtained two after-images, corresponding to the two movements, separated by a motionless strip. After the pseudo-movement had reached its greatest intensity, it disappeared with a sudden jerk, then there was a distinct momentary quiescent interval, to be followed by the renewal of the pseudo-movement-interval—and again a third and even a fourth pseudo-movement with diminishing amplitude (Excursionweite).

Hoppe thinks that the recurring pseudo-movements are the visible expression of a gradual recovery of the much fatigued retina and that the phenomenon belongs essentially to the class of after-images. On cessation of the primary movement, after-images are successively produced of the movement-phases just passed, those of the last phase first, their summation causing the idea of a new movement.

L. William Stern, 1894, (38). He published a paper on movement perceptions, a chapter of which is devoted to "optical illusions of movement," and among these the phenomenon under investigation is also discussed. Stern confirmed the work of previous investigators known to him, especially some of the less astonishing observations by Engelmann. Stern, seated in a moving railway carriage, fixated a point on the window-pane and observed a railing or the sleepers pass before his eyes. After 5—10 secs., he closed his eyes and at the same moment saw a distinct image of the railing or the sleepers move in the same direction. This only lasted for a short time and then made room for an indistinct flicker in which sometimes a movement in the opposite direction was distinguishable. When he fixated a point so that only the sky was visible with telegraph-posts and chimney-pots rushing by, then, on closing his eyes, he experienced practically a repetition of the scene: a shadow flitted across the field of vision, exactly as the real objects had done. By numerous repetitions, Stern obtained great practice so that he feels quite sure of the exactness of his observation. To make more exact observations, he worked with a system of vertical lines moving in a horizontal direction, both using and dispensing with a fixation-point and with shorter exposures ($\frac{1}{4}$ sec.) and longer ones (8—12 secs.). By this, he confirmed the results previously obtained and mentioned above.

The after-movement in the same direction Stern regards as nothing else but the after-image-streak in its purest form, therefore confirming the view of the "negative after-image of motion." Just as the rock behind the waterfall seems to move upwards, so, behind the veil of fading after-images, objects appear to move in the opposite direction. The fact that movement in the opposite direction can be discovered in the subjective field, *i.e.* with closed eyes, does not appear at first in accordance with this view. However, here the entoptic visions take the place of the exterior objects.

A. Borschke and L. Hescheles, 1902, (6). To measure the "velocity" of the after-image of movement, these investigators used two systems of rods (made of blackened knitting-needles) at right angles to each other; the one system with horizontal rods moving vertically and the other with vertical rods moving horizontally. These systems of rods were moving in front of a white background and behind a screen with a circular opening of 5 cm. diameter; this opening could be closed by a flap on which black lines, to represent the rods, were drawn. On this flap the after-image was projected. It was argued that each system of rods produces its own after-effect, and that the two after-effects combine in a resultant which, in magnitude and direction, is the diagonal of the parallelogram of velocities. The velocity of one system was kept constant throughout and only that of the other varied. The experimenters found it extremely difficult to fix exactly the direction of the after-effect as this seemed to fluctuate, and in their experiments they only considered the direction of the first few moments. They came to the conclusion that the velocity of the after-effect is, within certain limits, directly proportional to that of the exciting movement. They admit that the described movement of the rod-systems can only be regarded as squares, moving in an oblique direction. By removing some rods in one system and varying its velocity, they obtained results which they think showed that the direction, and with it, in general, the velocity, of every after-effect of motion increases with the number of stimuli in the unit of time. To find in which way the velocity of the after-effect is dependent on the distinctness of the *Vorbild,* they used one system of black and one system of grey rods passing in front of a black background, against which the grey rods were more easily visible than the black ones. They considered that the results proved that the velocity of the after-effect is influenced by the distinctness of the *Vorbild.* In order to investigate how the velocity of the after-effect is influenced by the duration of the observation, they had both systems equal and running with the same velocity, only one was started later than the other. The results are not very conclusive and the method of experimentation is not without objection. The same criticism applies to a similar arrangement intended to measure the duration of the after-effect.

A. v. Szily, 1905, (39 and 40). His is the most recent and comprehensive investigation of the subject. He also made an interesting historical survey which, however, is not very complete. He used spirals and also fixed systems of straight lines in front of which he moved a fixation-point. These lines were 2—3 mm. thick and so arranged as to form oblong fields. He found that slow-movement was advantageous to the production of the after-effect. He also produced an after-effect with a system of alternating black and white concentric circular bands, 2—3 mm. thick, by moving it towards the eyes or away from them, whilst the centre was steadily fixated. Other conclusions worthy of special notice are as follows: The best after-effect is produced on weak contours; strong contours weaken the effect and so does the absence of all contours; sometimes it is advisable to darken the second field. The question is not, as maintained by Hescheles, Oppel and others, one of velocity of the pseudo-movement but only a question of intensity. The pseudo-movement appears to be slower on a well-illuminated surface with strong predominant contours than on dimly-lit surfaces with slender delicate contours. The intensity of the after-effect of motion depends only in a greatly qualified sense on the velocity of the optical impression of movement. To obtain within a given time and with increasing distances between the moving contours, an after-image of approximately the same intensity, an increased velocity of the objective movement is necessary. Within equal intervals of time, equal numbers of images have to cross the retina. If the velocity is increased to distinct flicker, there will appear over the surface, during the observation of the objective movement, a nebula-like veil moving much more slowly than the surface. On increasing the velocity so that the flicker diminishes more and more, the after-effect of motion becomes fainter; but it is only abolished when the velocity becomes so great that the flicker disappears. Even very slow optic impressions of movement produce distinct after-images of motion if the duration of the action on the retina has been sufficiently prolonged.

To ascertain by an average experiment the slowest movement that produces an after-effect of motion, Szily used a disc with five concentric black spirals, 2 mm. thick and 2 mm. distant one from another. He rotated the disc at such a rate that the displacement of a point was 1 mm. per sec. along the radius; if the optic impression of such a movement is received by the eye fixating the centre at a distance of 50 cm., the angular velocity amounts to 6·8′ per sec. If such a movement is continued for 40 sec., it produces an after-effect. This velocity approaches very closely to the threshold value of immediate perception of motion in indirect vision as found by Aubert. In the peripheral field, the after-effect of motion is more intense and can be produced with shorter stimulation than in the fovea. And to this difference he attributes the apparent paradox noticed by him of an after-image of motion in the *same* direction as the exciting objective movement under the following conditions[1]. After having looked for a while into a broad river on turning the eyes to the floor of the bridge on which he was standing, Szily noticed an apparent motion in the same direction as the stream and not in the opposite as expected. The only difference of conditions between this case and the observations in the laboratory was that in the former the area of the retina acted upon was a very large one. When this condition was fulfilled in the laboratory by using large areas of striped calico, the result was also the same, viz. an apparent movement in the *same* direction. The cause of the paradoxical pseudo-movement lies, he suggests, in the fact that the reactive processes derived from the peripheral visual field are more intense than those derived from the central field. The paradoxical phenomenon is, therefore, merely caused by contrast, and Szily proves this by the following experiment: If a circular ring with a fixation point in the middle is held in front of a moving surface, the regular after-effect will be obtained all over the field except in the zone corresponding to the ring, where there is an apparent motion in the reverse direction (*i.e.* in the same direction

[1] These conditions are quite different from those under which Engelmann imagined he observed something similar, see p. 6.

as the original motion of the moving surface) which can only be due to contrast; and then suddenly the regular after-effect of the centre of the surface will disappear and even a reversal of the movement may be noticed, which can only be due to contrast with the peripheral surface.

Szily also records some observations intended to show that the seat of those sense-stimulations that manifest themselves in the after-effect of movement is to be looked for in the central parts of the visual organ. Like Dvořák, but unlike Budde, he found that if only one eye were stimulated by an objective movement the other eye was also affected. When each eye was stimulated by a separate movement, the direction of the one being opposed to that of the other, and then both eyes regarded a stationary surface, there was no after-effect, *i.e.* the two opposing after-effects neutralized each other. But if after the binocular stimulation, one eye is closed, there was an after-effect in the other one but always less intense than that resulting from binocular optical stimulation of the same direction, or from a simple monocular stimulation. In binocular mixing of movements, there was always rivalry in the objective field, but complete fusion in the after-effect. Stroboscopic pseudo-movement, he found, showed the same after-effect as an actual movement. He also made some experiments to check the older view respecting the influence of distraction. Although the observer was so absorbed by the distraction as not to be conscious of any movement going on, yet the after-effect occurred. Hence he concluded that the after-effect of motion is brought about without the mediation of consciousness. In the second paper Szily published an account of some other experiments where the observer is seated in a cylinder which is virtually a repetition of the experiments made by J. Aitken (p. 8) and Budde (p. 11). The results confirm those obtained by his previous experiments. It must however be mentioned that Szily obtained an after-effect in the same direction as the objective movement, which agrees neither with Aitken's nor Budde's observations.

Cords and v. Brücke, 1907, (12). This is an investigation on the "velocity" of the after-effect. Their experiments are based on a statement by Kleinert (*vide* p. 8) that a sufficiently fast after-effect of motion retards an objective movement in the opposite direction. The stimulating movement was produced by an endless band of alternating black and white stripes, moving behind an opening in a screen. The after-effect was allowed to pass off on a mirrored image of a strip of faintly-marked curve-paper, moving in the same direction as the stimulating movement and therefore opposed to the apparent movement of the after-effect. The authors admit that during the first experiments, after the mirror had been put in position, the judgment about the direction was wrong or uncertain; this they attribute to the fact that the fixation-point could not at once be found. From their own and Szily's experiments, they come to the following conclusions. The pseudo-movement of the after-effect can apparently retard an objective movement of the opposite direction. If this objective movement is slower than the after-effect, the contours appear to move in the direction of the after-effect. If the velocities of the objective movement and of the after-effect are equal, the contours either appear to be at rest or their movement is indistinct and variable. The velocity of the after-effect of movement varies within wide limits. The smallest measured value obtained was 0° 3′ 0″ per sec., and the largest 1° 0′ 6″ per sec. The values obtained under equal experimental conditions but on different days show sometimes marked differences, which do not lie within the limits of experimental error but must be caused by a moment, as yet unknown.

The velocity of the after-effect increases within certain limits with the velocity of the stimulating objective movement and decreases again with the beginning of flicker. The closer the moving contours of the stimulus, the faster the after-effect. It appears that the velocity of the after-effect does not depend so much upon the number of contours that pass a retinal element, as upon the closeness and number of the different simultaneously stimulated elements. Under experimental conditions otherwise equal, the velocity of the after-effect is greater in the peripheral parts of the retina than in the central ones. The velocity of the after-effect diminishes with the decrease of the difference in brightness between the contours and rises with the duration of the stimulating objective movement, in the form of a curve moving asymptotically towards a maximum.

TŌSAKU KINOSHITA, 1909, (27 and 28). He finds, as numerous previous workers have done, that the after-effect is produced, not only when an object moves before the fixating eye, but also when the object is stationary and the eye moves over it. "In the latter case, however, the after-effect differs quantitatively more or less from that of the former." "The distinctness and duration of the after-effect are less than that obtained with the old method." "Movements (? Contractions) of the exterior eye-muscles as well as changes of position and movements of the head disturb the phenomenon." Stimulating the eyes by movements, lasting variously from 5 to 30 secs., he finds that the duration of the after-effect increases with the time of stimulation. He also finds that at first it increases with the velocity of the objective movement, but decreases after a certain limit has been reached. It is, however, to be objected to in his experimentation that, whilst beginning with velocities of ·57 cm. per sec., 1·55 cm. per sec., 2·14 cm. per sec. and 6·73 cm. per sec., which show an ascending curve for the duration of the after-effect, he immediately jumps to an objective velocity of 30 cm. per sec., which shows a remarkable decrease in the duration. It is therefore impossible to construct a curve from the author's results, as there is no indication where the summit would be situated. His experiments with varying illuminations are more satisfactory. Using illuminations, varying in relative intensities from 400 : 64 : 16 : 4 : 2 : 1, he finds that the duration of the after-effect diminishes with the illumination.

II. SUMMARY AND CLASSIFICATION OF PREVIOUS WORK.

Having surveyed the work done up to the present, in its chronological order, it behoves next to make some remarks and to classify it, in order to get a general view of the subject, although a closer examination, as well as any criticism on it, may be best postponed until I have rendered an account of my own work.

Some authors have merely given a description of the phenomenon, others have attempted to explain it; some have made experiments to investigate it, others only to elucidate some particular factor or moment of the phenomenon.

To those who have made no attempt at an explanation belong Brewster, Engelmann, Kleinert, Fleischl, Aubert, Borschke and Hescheles, Cords and Brücke, and Kinoshita.

The hypotheses advanced respecting the cause of the phenomenon may be divided into three large groups, viz. those attributing it to (B) Physical processes, (C) Psychical processes, (D) Physiological processes. The hypothesis of physical processes maintains that the phenomenon is produced by unconscious eye-movements; this has been advanced by Purkinje, Adams, Lotze (in the case of non-fixation of regard), Helmholtz, Wundt (in his earlier view), and

J. I. Hoppe. The explanation by psychical factors has been proposed by Lotze (in the case of fixation), by Zöllner, and, as an alternative hypothesis, by Budde, who regards it as pseudoscopy, *i.e.* as a temporary falsification of conclusions drawn in the central organ from correct sensations.

The physiological theories are by far the most numerous. There is, first, the theory of the passage of after-images advanced by Johannes Müller, Ruete, Julius Hoppe, Stern, and by Wundt (who says it is aided by association factors), and in a modified form by Tschermak. Other kinds of local *retinal* processes have been advanced in explanation of the phenomenon by Dvořák and Mach, without definitely stating their nature beyond that they are analogous to the negative after-images of colour. Displacement of retinal elements is Budde's alternative hypothesis which is also adopted by Beevor. Zehfuss considers the cause to be the modified blood-flow in the retina; Silvanus Thompson suggests retinal fatigue *plus* association of contrast, or else secondary nervous disturbances or currents; the latter suggestion is subsequently supported by Heuse. Plateau's "principle of oscillation of a sense-organ" as explaining this phenomenon probably ought also to be classed with local retinal processes. This view was at first held by Oppel, but afterwards abandoned. The explanation adopted by Classen is based on the "feeling of innervation" to the eye-muscles antagonistic to those innervated reflexly by the movement. Bowditch and Hall probably belong to those who consider the cause of the phenomenon to reside in the central nervous system, for they think it likely that "the impression of motion has a different cerebral centre from that of rest." Here also must be mentioned Oppel's later view that the cause of the phenomenon is central, "between sense-organ and sensorium"; likewise Aitken, who says that it is "deeper than the retina"; Exner, whose hypothesis of summation-cells is most definite, and Szily, who endorses Exner's view.

In a more schematic way, the result of our classification may be given thus:

A. *No attempt at explanation.*

Brewster. Engelmann. Kleinert. Fleischl. Aubert. Borschke and Hescheles. Cords and Brücke. Kinoshita.

B. *Explanation by physical processes.*

Eye-movements.

Purkinje. Adams. Lotze (in the case of non-fixation). Helmholtz. Wundt (earlier view). J. I. Hoppe.

C. *Explanation by psychical processes.*

Lotze (in the case of fixation). Zöllner. Budde (pseudoscopy, alternative view).

D. *Explanation by physiological processes.*

(*a*) Passage of after-images across the retina.

Johannes Müller. Ruete. Tschermak. Wundt (aided by association factors. Later view). Julius Hoppe. Stern.

(*b*) Local retinal effects (analogous to negative after-images of light and colours).

Dvořák. Mach.

(*c*) Principle of oscillation in the function of sense-organ.

Plateau. Oppel (earlier view).

(*d*) Displacement of retinal elements.

Budde (alternative view). Beevor.

(*e*) Modified blood-flow in retina.

Zehfuss.

(*f*) Retinal fatigue *plus* association of contrast.

S. P. Thompson (alternative view).

(*g*) Secondary nervous impulse.

S. P. Thompson (alternative view). Heuse.

(*h*) Feeling of innervation to antagonistic eye-muscles.

Classen.

(*i*) Origin in central nervous system.

Oppel (later view). Aitken. Bowditch and Hall. Exner (Summation-cells). Szily.

III. OWN OBSERVATIONS.

In this investigation all the more important experiments of previous investigators have been repeated, or the results and conclusions drawn therefrom have been tested by other experiments. I shall not give a description of these experiments, which only corroborate other workers, but I confine myself to the following succinct statement of results.

1. The uniform passage of light stimuli over the retina in any given direction for a certain time produces the after-effect of an apparent movement in the opposite direction.

2. This after-effect is more marked if the eyes do not follow the movement but remain fixed on a stationary point, so that the same retinal elements are constantly acted upon by the moving stimuli. Although Exner, Szily and all later observers hold this view, those who advocated the theory of eye-movements in explanation of the phenomenon have contended that the eyes should follow the movements. Oppel, who considered a fixation point essential in his antirrheoscope was especially attacked on that account by Helmholtz. Some considered fixation objectionable, if not detrimental to the success of the experiment; and this may possibly be due to the fixation-point being fixed in such a way that the moving object was not in focus during stimulation.

3. The after-effect is limited to the retinal area affected by the objective movement[1].

4. The after-effect follows immediately after the stimulating objective movement.

5. The observation of the after-effect improves with practice.

6. If corresponding areas of the two retinae are stimulated by movements of opposite directions these movements do not neutralize one another; but engender "rivalry." Then if both eyes are closed or both remain open looking at a stationary surface there is no after-effect. But if only one eye is open, this eye manifests its own after-effect although more feebly than if the other eye had not been stimulated.

7. If corresponding areas of the two retinae are stimulated by movements in different, but not opposite, directions, rivalry and fusion

[1] Experiments made since the termination of this paper tend to show that this statement is true only with qualification.

of these stimulating objective movements occur. One eye alone open has predominantly its own after-effect, but both eyes open produce complete fusion.

8. The after-effect is producible by any rate of the stimulating objective movement, from the slowest which can at once be sensed as movement to the highest which is short of flicker but at which direction of movement can still be seen.

9. If one eye alone is stimulated by an objective movement, whilst the other remains closed, and if then the stimulated eye be closed and the other opened, the after-effect will appear in the corresponding part of the visual field of the not stimulated eye, but it will be somewhat feebler. Although denied by Budde, this fact is incontestable. The conclusion drawn therefrom by Exner and Szily, viz. that the seat of the cause of the after-effect was not in the retina but central, does not, however, necessarily follow, for, as there is an after-effect in the subjective field of the closed eye, the contents of this field probably fuse with that of the open eye. As the result of this, the field of the open eye is in an agitated condition.

10. Pseudo-movements, *e.g.* stroboscopic movements, produce an after-effect exactly as an actual movement does.

11. The after-effect may also be noticed in the subjective field of vision with closed eyes, although perhaps not quite so easily as with open eyes. Heuse (p. 13) is the only observer who goes further than this. He states that with closed eyes the effect lasted longer.

I have not included such statements as Szily's that "the uniform passage of systems of parallel straight lines in an oblique direction to the length of the lines produces an after-effect which is at right angles to the lines away from the direction of the movement," since they are covered by statement (1) above. It is evident that *for the retina* any movement of a straight line can only be at right angles to its length, hence the after-effect is also only at right angles to the length of the line.

Before entering on an account of my experiments, I shall describe an apparatus I have had constructed by the Cambridge Scientific Instrument Company. Fig. 2 represents the front view and Fig. 3 the back view of the "apparatus of moving fields." I was helped in the designing of it by the valuable advice of my teacher, Mr William McDougall.

An upright wooden case 64 cm. high, 50 cm. wide, and 18 cm. deep, is fixed upon a strong, heavy wooden base. The front is closed by a board with a large window in the middle, 34 cm. high and 30 cm. wide. This board is detachable and either side can be turned outwards. One of its sides is covered with alternating black and white horizontal stripes 1 cm. in width, and the other side with light grey mottled drawing paper. Through the window, two fields can be seen with alternating black and white horizontal lines, like the surrounding front board. The "fields" consist of endless bands 15 cm. wide of painted paper or other material sewn or pasted on tracing-linen, to prevent stretching and to give consistency. Each band passes over a pair of rimmed drums, the upper one of each pair being supported by, and rotating easily on, an iron rod fixed to the vertical sides of the case. The lower drums lie in the loops of the bands, stretching them

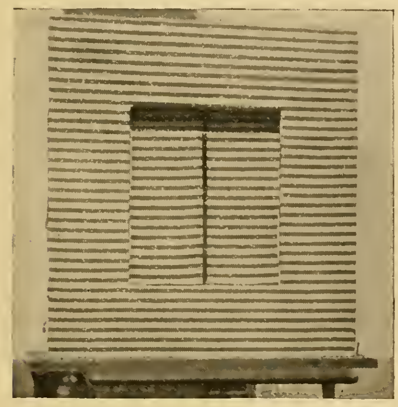

Fig. 2.

Fig. 3.

Fig. 2. "Apparatus of moving fields." Front view.
Fig. 3. "Apparatus of moving fields." Back view.

by their weight. The upper drums nearly touch each other, and each is held in position by a pair of prongs that slide along and can be fixed to a second horizontal iron rod running parallel to the other. On its outer side, each upper drum carries a set of pulleys, and by means of these, and of two other sets fixed to a horizontal rod at the bottom of the case, the drums can be rotated independently of each other and thus the striped surfaces are moved upwards or downwards in the same, or in opposite directions, and with the same, or with different velocities. Either field can also be put out of action, *i.e.* made to remain stationary while the other rotates. The apparatus is set in motion by an electric motor, the speed being regulated by a system of pulleys. A horizontal thread is stretched across the centre of the window. On this a small bead, serving as a fixation-point, slides.

All the facts stated above, except (7) and (10), can most conveniently be verified with this apparatus.

Experiment 1: *To ascertain the effect of the visual impression of stationary objects at the conclusion of the after-effect in the subjective field.*

This experiment furnishes a certain answer to the question why people who are unable to discover any after-effect in the subjective field (and these are very numerous) can yet easily experience the after-effect in the objective field.

The observer was seated at an easy distance in front of the "apparatus of moving fields," fixating the fixation-point which was in the centre of the window. Both fields were moving in the same direction. The stimulation time was 30 secs. These conditions remained unaltered during the experiment. At the end of the 30 secs. the apparatus was suddenly stopped and a stop-watch was set going. The observer continued to look steadily at the fixation-point and watched the after-effect. At its conclusion, he gave a signal. The watch was stopped and the duration of the after-effect noted. Five of these preliminary observations were made. The test experiment was then performed under exactly the same conditions. The observer closed his eyes immediately the stimulating movement ceased and kept them closed for a longer period than the maximum duration of the after-effect in the preliminary experiments. In obedience to a signal from the operator he then opened his eyes and looked at the fixation-point, noting the effect. Mr Shearman kindly assisted me in this experiment which gave the following results.

Observer S. In the preliminary experiments, the after-effect lasted 14, 25, 18, 26, and 19 seconds respectively. The longest duration of the after-effect was 26 seconds. In the test experiment the eyes were closed for 28 seconds. The observer noticed, on opening them, a faint, though distinct, after-effect lasting 11 seconds.

Observer W. In the preliminary experiments, the durations of the after-effect were respectively 21, 17, 20, 19, and 18 seconds. In the test experiment the eyes were closed for 23 seconds. The after-effect was faint but distinct and lasted for 10 seconds. In a second experiment it lasted nine seconds and was also faint but quite distinct.

Observer W, while his eyes were closed, had a vivid after-effect in the subjective field of vision. This, however, seemed to die away long before the eyes were opened. Observer S was unable to discover any after-effect in the subjective field of vision.

Hence it might be concluded that *it is far more difficult to discover the after-effect in the subjective field of vision than in the objective* (*i.e.* with open eyes). In other words *the after-effect is more easily discovered if the field of vision is filled.* Such stimulation of the retina, however, shortens the after-effect. The after-effect in the objective field of vision can, however, hardly be regarded as a fusion or a mere addition of the after-effect in the subjective field of vision to the stationary contents of the objective field. At no time does there appear to be such a rapid or tumultuous streaming in the objective field as in the subjective; nor does it seem to be either the sum or the average of the two "velocities." But the correctness of the above conclusion is open to doubt. There is another possible view of the results of the experiments, and certain observations tend to confirm it.

I have noticed, and all who have been kind enough to assist me in this investigation have confirmed my opinion, that when an after-effect has passed off in an objective field of vision, it can be caused to recur momentarily several times by winking with the eyes. That is to say a peripheral stimulus restores an after-effect already passed from consciousness. From this it may be argued that *the after-effect is much more noticeable in the objective field of vision because here it receives a reinforcement by a peripheral visual stimulus*; but that at the same time its force is more quickly spent and it is consequently of shorter duration. Here then would be another resemblance of the after-effect to the negative after-images of light.

If the theory that the after-effect is reinforced by a peripheral stimulus is correct, the better illuminated the projection-field is the more vivid should be the after-effect. This would be in direct contradiction to the statements of those previous observers who have pronounced an opinion on this point. Szily especially is emphatic. He writes: "Die dem Bewegungsnachbilde entsprechende Scheinbewegung äussert sich am kräftigsten und dauert am längsten auf mässig beleuchteten Flächen mit schwach hervortretenden Konturen. Je heller die Projektionsfläche ist, je stärker die Konturen sich auf ihr abzeichnen, um so stärkere Widerstände erwachsen der Entfaltung des Bewegungsnachbildes." (No. 39, *loc. cit.* p. 147.) The experiment upon which he bases this judgment does not, however, warrant the drawing of such a conclusion. He describes it (*loc. cit.* p. 112) as follows: "Man beschränkt die Ausdehnung des objectiven Bewegungsbildes dadurch, dass man ein Diaphragma aus schwarzem Karton mit centralem rundem Ausschnitt von etwa 8 cm. Durchmesser hart an die Strahlenscheibe hält. Nach einiger Betrachtung entfernt man sich plötzlich, mit Beibehaltung der Fixation des Zentrums, um 10—15 cm. von der Scheibe, indem man dieselbe zugleich stillstehen lässt. Man sieht dann sofort die rückläufige Scheinbewegung nicht bloss in dem sichtbaren Teil der Scheibe selbst, sondern auch darüber hinaus auf dem schwarzen Karton in einer den Ausschnitt umgebenden ringförmigen Zone, deren Ausdehnung genau den veränderten Projektionsverhältnissen entspricht. Hierbei kann man nun aus dem Unterschiede der Intensität der Scheinbewegung auf dem sichtbaren Teil der Scheibe selbst und in der sie umgebenden Zone den behindernden Einfluss der Konturen kennen lernen. Während die plötzlich angehaltene Sectorenscheibe sich nur träg zurückzudrehen scheint, vollzieht sich die Scheinbewegung in ihrer Umgebung mit geradezu sturmischem Anlauf. Was aber hier an der Bewegung eigentlich teilnimmt, das sind nicht so sehr die feinen Pünktchen und Fäserchen des Papiers, als vielmehr wiederum jener obenerwähnte subjective Nebelstrom." Szily projected the after-effect on a uniform black surface, hence he is not discussing the effect of weak contours but of their entire absence. Although the eyes remain open the field becomes practically equivalent to a subjective one.

Therefore I made

Experiments 2, 3 and 4: *To ascertain the influence of the illumination of the exciting field as well as that of the projection field on the after-effect.*

For this purpose I had some lantern-slides made on the principle of the so-called "chromotropes" sold for magic lanterns, as represented in Fig. 4. Two circular glass plates are held in a wooden frame and each is fitted with a peripheral rack. The teeth of these racks face each other. Between them there is a cogwheel fixed on a spindle passed through the wooden frame. This can be turned by a handle. By this means the two plates are rotated in opposite directions, *i.e.* clockwise and anti-clockwise. The glass plates are painted with curves which form a pattern by transmitted light. When the handle is turned a centrifugal or centripetal movement is given to this pattern. Slide A has only one pattern (Fig. 5). Slide B has three concentric fields (Fig. 6), the central and the peripheral ones are red and move in the same direction, whilst the field between them is green and moves in the opposite direction.

In Experiment 2 one of these slides was put before a demonstration lantern and the light of a 200 candle power arc lamp sent through. As the observer looked into the slide the contours were very distinct and definite, and the light was dazzling. Yet there was a marked after-effect when the slide was stopped.

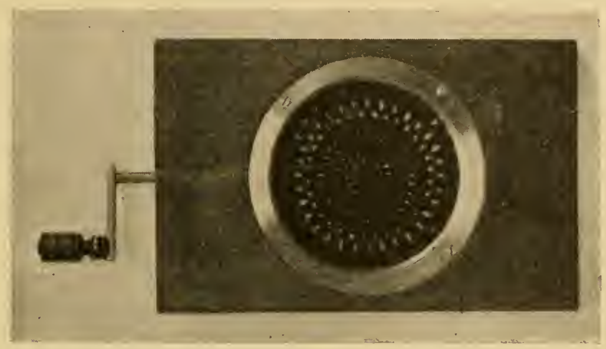

Fig. 4.

Fig. 5. Rosette A.

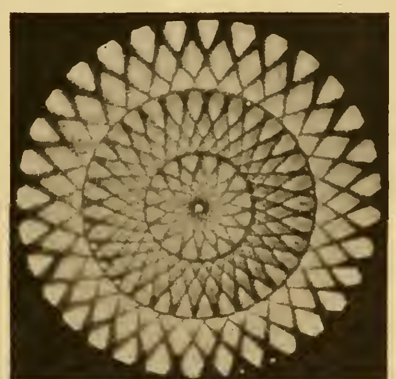

Fig. 6. Rosette B.

In Experiment 3 two cylinders with alternating black and white stripes parallel to the axis of the cylinder, so that on rotation the stripes moved at right angles to their length, were placed side by side in the dark room. The light from a 50 candle power lamp was concentrated by a lens on one of the cylinders. The other was shaded by a piece of

Projection field darkened by:	Duration of after-effect	Intensity of after-effect and Remarks
Observer: Mr Swan		
0 Ground glasses	16 seconds	Very marked at beginning.
0 ,, ,,	17 ,,	,, ,, ,,
0 ,, ,,	17 ,,	,, ,, ,,
1 ,, ,,	15 ,,	Marked, not quite as much as before.
1 ,, ,,	15 ,,	,, ,, ,, ,,
1 ,, ,,	15 ,,	,, ,, ,, ,,
2 ,, ,,	5 ,,	Very slight.
2 ,, ,,	5 ,,	,, ,,
2 ,, ,,	5 ,,	,, ,,
0 ,, ,,	12 ,,	Very strong.
1 ,, ,,	10 ,,	Less marked.
2 ,, ,,	9 ,,	,, ,,
2 ,, ,,	4 ,,	,, ,,
Observer: Prof. Read		
0 Smoked glasses	11 ,,	Very marked.
0 ,, ,,	13 ,,	Very marked, not quite so much.
0 ,, ,,	17 ,,	Very marked.
1 ,, ,,	25 ,,	Quite as distinct, much the same.
1 ,, ,,	19 ,,	,, ,, ,, ,,
1 ,, ,,	18 ,,	,, ,, ,, ,,
2 ,, ,,	17 ,,	,, ,, ,, ,,
2 ,, ,,	17 ,,	,, ,, ,, ,,
2 ,, ,,	16 ,,	,, ,, ,, ,,
0 ,, ,,	16 ,,	Very definite.
1 ,, ,,	17 ,,	,, ,,
2 ,, ,,	15 ,,	Very distinct (green zone turning red).
3 ,, ,,	17 ,,	Very marked as before (green turning red).
4 ,, ,,	15 ,,	Very marked, possibly a little less (green turning red).
5 ,, ,,	19 ,,	Quite marked (negative after-image of colour very marked).
6 ,, ,,	16 ,,	Not quite so marked.
6 ,, ,,	18 ,,	Certainly not so marked; negative after-image of colour seemed to interfere.
5 ,, ,,	18 ,,	Quite recognizable; contours first blurred by negative after-image of colour. As this passed off, and contours were restored, illusion of movement became greater.
4 ,, ,,	22 ,,	Quite distinct, better than previous at beginning. Colour contrast not quite so marked, contours not so much effaced.
3 ,, ,,	15 ,,	Illusion of movement well marked, possibly a little more than before, colour contrast less.
2 ,, ,,	18 ,,	Illusion of movement very distinct.
1 ,, ,,	15 ,,	Very marked.
0 ,, ,,	16 ,,	,, ,,
Observer: Dr Spearman		
0 Smoked glasses	12 ,,	After-effect marked. Green zone coming towards observer.
1 ,, ,,	11 ,,	Effect distinctly less.
2 ,, ,,	12 ,,	Still possibly a shade slower and less vivid.
3 ,, ,,	10 ,,	Again possibly less marked.
0 ,, ,,	11 ,,	Very marked; began slowly, went towards observer. Movement towards observer in objective movement as well as in after-effect predominates over movement away from him.
4 ,, ,,	15 ,,	Less marked. Again gradually increased in speed, but not in vividness.
0 ,, ,,	14 ,,	Distinctly more vivid (in objective movement green zone predominantly moving inwards, whilst other zone advanced).
6 ,, ,,		Colour contrast disturbing, no illusion of movement.
6 ,, ,,		Colour contrast too strong, disturbing.

cardboard so that the black and white lines could only just be distinguished. The observer was seated at a convenient distance (2 m.) in front of the cylinders, fixating a point midway between them. Both cylinders were rotated with the same velocity for 30—60 seconds. They were then suddenly stopped and the after-effect allowed to pass off on them. Neither Mr Shearman nor myself could discover any difference in the two after-effects.

In Experiment 4 I used one of the lantern slides. Its image was thrown on a transparent screen of ground glass from behind. The observer sat in front, fixating the centre. The stimulating movement was continued for a given time at a certain rate and then stopped. The observer watched the after-effect of movement passing off on the now stationary image. He announced the moment when the after-effect appeared to cease. The duration of the after-effect was measured by a stop watch. Except in a few final experiments the field of the stimulating movement was kept at full brightness; but that of the after-effect was darkened by the insertion of slides of ground or smoked glass in the path of the light; I soon discontinued the use of the ground glass, as the contours were too much blurred by it. A transcript from my laboratory note-book appears on page 34 opposite and continues as follows:

The duration of the stimulating movement was 20 seconds, and the number of revolutions during this time 12.

Next the objective movement took place in a field darkened by three smoked glasses, and the after-effect in a field of full brightness: after-effect lasted 12 seconds: more vivid. Observer can distinguish between velocity and vividness.

Objective movement in bright field, and after-effect in field darkened by three smoked glasses: after-effect lasted 13 seconds: less vivid, and a little slower.

Objective movement in field darkened by four glasses, and after-effect in field of full brightness: after-effect lasted 11 seconds: distinctly more vivid.

These experiments prove beyond cavil that *the after-effect of movement is more marked in a brightly illuminated objective field with distinct contours than in a darker one with less distinct contours.*

In almost all the experiments hitherto conducted by any investigators, black and white fields have been used to excite the retina. These fields have been either discs with black and white sectors, planes with black and white stripes, white discs with black radii, or white discs with a black spiral. (Plateau was exceptional in using a black disc with a white spiral.) But no one, except Exner, has inquired which is the stimulus—the black or the white part? Exner, who regards black as a sensation, looks upon it also as a stimulus in this case; and those who used a black spiral or black radii on a white background, and Borschke and Hescheles who used blackened rods on a lighted background, probably have done the same. Other investigators who employed alternating black and white stripes or sectors might, however, have regarded the difference of brightness as the exciting stimulus. This is closely connected with the reasons which led me to the last set of experiments, for the inquiry, whether a light stimulus reinforces the after-effect, is related to the question as to which is the stimulus that gives rise to the after-effect.

I was led to these considerations whilst making experiments to check Borschke and Hescheles' results. As these observations are important I shall first describe them. I shall not stop to criticize the experiments of Borschke and Hescheles as the errors of their experimentation have already been pointed out by Szily and others. I therefore proceed with

EXPERIMENT 5: *To check Borschke and Hescheles' statement that under the same conditions the magnitude of the after-effect depends upon the distinctness of the stimulating moving objects.*

Here these experimenters used two similar systems of rods moving in the same plane at right angles to each other before a black surface. One system consisted of rods painted black, and the other of rods painted grey. For the purpose of my investigation, I varied the conditions of the experiment in the following manner. On a slip of paper for a kymograph-drum I painted two systems of lines, both at an angle of 45° to the length of the slip and at right angles to each other. The background was white. One system consisted of black, and the other of light grey lines. The width of the lines was 4 mm., and the distance between them 8 mm. A screen with a square opening and fixation-point, as shown in the illustration, was placed close to the drum, in front of it (Fig. 7). The time of stimulation was 45 secs.

The after-effect always began in a direction opposite to that of the actual objective movement. But it soon changed in direction by jumps and jerks, and always ended by a pure after-effect of the grey system only. Dr Spearman and myself always obtained this result; Professor Read and Mrs Spearman, though frequently, not always.

There is probably rivalry here between the after-effect of the grey and that of the black system; the former being the stronger and lasting longer than the latter. But the result is opposed to that of

Borschke and Hescheles. These authors chose a black and grey system on a black background; the grey, which was the more distinct of the two, proved the more effective; from this particular instance they induced the general proposition that the greater the distinctness of the stimulating field, the stronger its effect. But I used a black and a grey system on a white background, so that my black system was

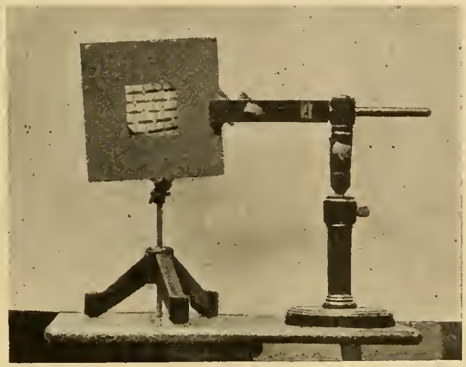

Fig. 7. Apparatus for Experiment 5. System of horizontal black lines moving in a vertical direction, and system of vertical grey lines moving in a horizontal direction.

the more distinct; but yet its effect was less marked. It follows from this that it is not the black that is a stimulus, nor the *difference* in brightness, but the white. The number of white interstices that affect the retina in a given time is here equal in both systems; but in the case of the grey system the grey lines form additional, though weaker, stimuli, while in the case of the black system the black lines do not form stimuli.

If these inductions are correct they should be capable of confirmation. I therefore devised

EXPERIMENT 6: *To ascertain whether the difference of brightness* (*i.e. the distinctness of moving contours*) *is essential for the production of the after-effect of movement.*

I used my "apparatus of moving fields" for this purpose. The front board was turned with its grey side outwards. The *left* field consisted of alternating *white and black* stripes, and the *right* field of *white and grey* stripes, 1 cm. wide. The fixation was in the centre of the window between the two fields. As projection-field I used either the exciting-field, stopping the apparatus, or, in order to have both halves equal, a reproduction of its front to scale, but having both fields the same, viz. alternating grey and white, like the right field of the apparatus. The apparatus was set in motion by an electric motor and stopped by breaking the current. Both parts of the field moved at the same rate. With the usual time of excitation of about 30

Duration of excitation	Projection field	Observations
Observer: A. W.		
1 minute	A	Left more vivid than right.
30 seconds	,,	Uncertain.
1 minute	,,	Left slightly "faster" at first; uncertain whether right lasted longer.
1 ,,	,,	Left decidedly faster at beginning.
1 ,,	,,	Left decidedly faster at beginning, but right seemed to last somewhat longer.
1 ,,	B	Both same intensity.
30 seconds	,,	,, ,, ,,
1 minute	,,	,, ,, ,,
1 ,,	A	Left decidedly faster and lasted much longer.
20 seconds	B	Both sides equal.
40 ,,	,,	,, ,, ,,
60 ,,	,,	,, ,, ,,
60 ,,	A	Left first "faster," then a little later right for a short time faster, but left finished later.
80 ,,	B	Both started equal, then left gained on right and finished later.
100 ,,	,,	As last, though possibly not quite so marked as before.
120 ,,	,,	Left decidedly "faster"; finished together.
60 ,,	,,	Left started "faster," especially its outer portion; finished together.
Observer: Dr Spearman		
60 seconds	A	Left more intense at beginning.
60 ,,	B	Short duration, equal vividness.
60 ,,	,,	,, ,, ,, ,,
60 ,,	,,	,, ,, ,, ,,
80 ,,	A	Left more vivid at beginning, end equal.
120 ,,	B	Both equally vivid at first, then right more, then left more, then again right.
120 ,,	,,	Left more vivid at beginning.
60 ,,	A	Left longer and "faster."
60 ,,	,,	Left started faster, then there was possibly a very short period when the right was faster.
Observer: Prof. Read		
60 seconds	B	Left side certainly more vivid, especially on outer part, also lasted longer.
30 ,,	A	Left much greater effect and lasted much longer.
45 ,,	,,	Left lasted 11 seconds, right 9 seconds. Observer attended more to end and could not say which was the more vivid.

seconds, to my disappointment I did not obtain the anticipated results. I was, however, glad to find that with a longer excitation the result was quite unmistakeable. I may mention that, as I could not in my own case be absolutely sure of having been free from suggestion, I was careful to keep Professor Read and Dr Spearman, who acted subsequently as observers, in ignorance about the result expected. I simply told them to attend to relative "velocities," or vividness in the after-effect. With stimulations of 1 min. or more, the after-effect of the system of alternating white and grey stripes was, as a rule, decidedly better than that of the system of alternating white and black stripes. It was either faster, or more vivid, or lasted longer. The details will be found in the transcript from my laboratory notebook as on page 38 opposite.

Exciting-field : *left* part grey and white.
right part black and white.
Projection-field : *either* A the same as the exciting-field.
or B both parts grey and white.

From the results of this last experiment and the previous one leading up to it, we may draw the following inferences:

1. *Distinctness of contours is not the essential factor in the production of the after-effect of movement.*

2. *If in the production of the passage of images over the retina, a stimulus, of given intensity, alternates with one of less intensity, the after-effect of movement produced is more vivid than if such stimulus alternates with a complete cessation of stimulus.*

I next performed

EXPERIMENT 7: *To check Borschke and Hescheles' statement, that the velocity, of every after-effect of motion, increases with the number of stimuli in the unit of time*[1].

As in the experiment mentioned above (p. 36), Borschke and Hescheles used systems of blackened rods passing in front of a lighted surface. I achieved the same object by painting, on a slip of white paper for a kymograph-drum, two systems of black lines at an angle of

[1] It does not appear to have struck these investigators that there are two distinct factors here at work. First, in these two systems different numbers of stimuli pass given retinal points in the unit of time; secondly, different numbers of stimuli affect equal retinal areas at the same time. The first factor involves merely time and is known as "frequency," which must be distinctly distinguished from "velocity," which involves not only time but also space. The results of this experiment are then due to both these factors.

45° to the length of the slip and at right angles to each other. The thickness of the lines was 4 mm. In one system, the distance between the lines was 4 mm., and in the other 12 mm. The slip of paper was fixed on the drum and the axle of the latter inclined at an angle of 45° so that one system consisted of horizontal and the other of vertical lines. On one side of the drum the narrow system was horizontal and the wide system vertical. On the other side this was, of course, reversed. A screen with a square opening, as large as the width of the kymograph-drum would permit, was placed in front of the drum and a thread was fixed across the opening. A knot in the middle of the thread indicated the centre of the opening and served as a fixation-point (*vide* Fig. 7, Expt. 5). The movement of the drum was, of course, in the direction of one of the diagonals of the square. The horizontal lines, however, appeared to move upwards or downwards, and the vertical lines towards the left or the right, according to the movement of the drum. After fixation of the moving field for about 45 seconds, the drum was stopped and the after-effect watched passing off on it, special attention being paid to the direction.

The after-effect began in the direction opposite to that of the actual objective movement. It did not, however, pass off smoothly; but occurred in jerks of indefinite direction, sometimes to the left, sometimes to the right of the diagonal of the square, *i.e.* sometimes more vertically, sometimes more horizontally. But the last phase was always an after-effect of the movement of the narrow system alone. The whole phenomenon appears to be a rivalry between the two after-effects, viz. that of the narrow system and that of the wide, the former finally prevailing. Dr Spearman, as well as myself, acted as observer in this experiment.

In this experiment of Borschke and Hescheles the two systems of lines moved over the same retinal field in different directions. These conditions are complicated and the results, as we have seen, uncertain. It appeared therefore worth while to simplify the experimental conditions and I devised

EXPERIMENTS 8 and 9: *To ascertain the influence of the width of the moving bands, which is really equivalent to the joint influence upon the after-effect of the number of stimuli affecting a given area of the retina at the same time, and the frequency with which these stimuli pass given retinal elements.*

EXPERIMENT 8. Using again "the apparatus of moving fields," I had one of the fields, as before, consisting of alternating black and white lines 10 mm. wide, whilst the other consisted of alternating black and white lines 5 mm. wide, *i.e.* in this field the number of stimuli for the same area of the retina at the same time was twice the number of stimuli in the other field. Both fields moved in the same direction, with the same velocity, viz. 4·5 cm. sec.$^{-1}$. The time of stimulation varied from 30 secs. to 3 minutes. As projection-fields I used either the stopped apparatus, *i.e.* the same fields which gave rise to the excitation, or the reproduction of the front view of the apparatus, but with both fields consisting of white and grey stripes, 1 cm. wide.

With longer stimulation I could distinguish frequently, although not always, a greater vividness in the after-effect of the narrower lines than in that of the wider ones on the stopped fields of the apparatus, but not on the projection-field of white and grey lines. Mr Kerr, who acted as observer, obtained no difference in the vividness of the two after-effects, but that of the narrower lines lasted distinctly longer than that of the wider ones when the apparatus was stopped (in one instance the duration of the after-effect of the former being 26 and that of the latter 19 seconds). There was, however, no difference in intensity or duration of the after-effect on the projection-field of white and grey lines. Professor Read and Dr Spearman were unable to discover any difference in vividness or duration under any conditions. As I mistrusted my own observations in this particular instance, on account of my expectation, and as Mr Kerr's observations were not numerous enough to be of any value, I decided to modify my experiment. In the experiment just described the two fields move side by side. There is therefore the possibility of the two respective areas of the retinae reciprocally influencing each other, that is to say, the absence of any difference in the two after-effects under the given experimental conditions may be due to the principle of *associative Angleichung.* This principle was first enunciated by Wundt[1], and has since been elaborated by Spearman[2] and Krueger[3]. As we shall, however, presently see, this principle of *Angleichung* is only potent within limits. To eliminate it I resorted to what may be called "*paired direct successive comparison*" and

Experiment 9 was arranged as follows. Only one of the two fields was exposed at one time, the other being covered. The observer fixated

[1] Wundt: *Grundzüge der Phys. Psychologie*, 1902, 2te Bd. S. 564.

[2] C. Spearman: "Die Normaltäuschungen in der Lagewahrnehmung" in Wundt's *Psych. Studien*, Bd. 1, S. 484.

[3] Felix Krueger: "Die Theorie der Konsonanz" in Wundt's *Psych. Studien*, Bd. 1, S. 351.

a point in the centre of the moving field for 30 seconds. At the end of this time a signal was given, the apparatus was stopped simultaneously, and the observer turned to the projection-field at his side, so that turning through an angle of 90° he faced it. This projection-field was the same for all experiments, and consisted of alternating white and grey stripes 1 cm. wide. As the observer turned towards the projection-field, on hearing the signal, a stop watch was set going. This was stopped when the after-effect ended. The same experiment was then repeated with the other stimulating field, and the two constituted a pair, the vividness and speed in the second observation being compared with those of the first. Then a rest of about two minutes was allowed and another pair of observations was made, but this time in the reverse order, *i.e.* if in the first pair the narrower preceded the wider system, in the second pair the wider system preceded the narrower. The objective velocity was $4{\cdot}5$ cm. sec.$^{-1}$. Prof. Read, Dr Spearman and myself acted as observers. The following are the results, the numbers in brackets being the order of the experiments.

System of wider lines.				*System of narrower lines.*			
Observer: A. W.							
(2)	9	sec.	Less marked than 1.	(1)	12	sec.	Marked.
(3)	14	„	Marked.	(4)	12	„	More marked than 2.
(6)	10	„	As marked as 5.	(5)	13	„	Very marked.
(7)	11	„	Marked.	(8)	11	„	Marked.
(10)	11	„	Marked.	(9)	11	„	Marked.
(11)	12	„	Faint.	(12)	13	„	Very marked.
(14)	11	„	Not so marked as 13.	(13)	14	„	Very marked.
(15)	10	„	Fairly marked.	(16)	14	„	Very marked indeed.
(18)	11	„	Marked.	(17)	15	„	Very marked.
(19)	10	„	Marked.	(20)	10	„	More marked than 19.
Observer: Dr Spearman.							
(2)	8	sec.	Just as vivid.	(1)	10	sec.	Very distinct.
(3)	6·5	„	Perhaps not so vivid.	(4)	11	„	Distinctly faster than 3.
(6)	8·5	„	As vivid as 5.	(5)	9·5	„	Less marked than 4.
(7)	8·5	„	Uncertain.	(8)	10·5	„	Much faster, especially rushing at beginning.
(10)	5·5	„	Distinctly slower than 9.	(9)	8·5	„	Not so fast as 8.
(11)	5·5	„	Vivid but slow.	(12)	8·5	„	Quicker than 11.
(14)	6·2	„	Not certain.	(13)	8·4	„	Quite fast.
(15)	6	„	As before.	(16)	12	„	Possibly faster.
(18)	5	„	Less vigorous.	(17)	8	„	As before.
(19)	7	„	The same.	(20)	8·4	„	Not more vivid.
Observer: Prof. Read.							
(2)	14	sec.	Possibly rather slower.	(1)	14	„	Very vivid, initial velocity greater than ever.
(3)	12	„	Uncertain.	(4)	12·5	„	Faster than before, especially at beginning.

System of wider lines.			*System of narrower lines.*		
Observer: Prof. Read.					
(6)	12 sec.	Not as vivid as 5, yet much the same speed.	(5)	11 sec.	Not as vivid as 4.
(7)	14 „	Very vivid.	(8)	14 „	Very vivid, quicker than before.
(10)	12 „	Very vivid, quick.	(9)	15 „	Very vivid and as fast as 8.
(11)	13·5 „	Faint and slow.	(12)	11·5 „	A little more vivid and faster.
(14)	11·2 „	A little less vivid and a little slower.	(13)	14·2 „	Medium vividness.
(15)	12 „	Very vivid, quickness not as great as usual.	(16)	15 „	(About) medium vividness, a little faster.
(18)	12·5 „	Vivid and rapid, about same as 17.	(17)	10 „	Very vivid and quick.
(19)	9 „	Medium vividness and speed.	(20)	10·2 „	Uncertain.

During the last two pairs of observations, the subject complained of being very tired and sleepy.

(2)	12·2 sec.	Less vivid, slower.	(1)	12·4 sec.	*Very* vivid, moderate speed.
(3)	14 „	Vivid, speed like objective movement.	(4)	15 „	As before, for both.
(6)	13·2 „	Not so vivid, speed similar.	(5)	14 „	Vivid, gradually slowed down.
(7)	17 „	Not very vivid or fast.	(8)	11 „	Much the same.
(10)	11 „	Less vivid and slower.	(9)	9·2 „	Very vivid, very fast at beginning, intermittent.
(11)	12 „	Vivid and fair speed.	(12)	11 „	Same vividness, faster.
(14)	12 „	Not quite so vivid, not so fast.	(13)	14 „	Very vivid and fast.
(15)	10 „	Vivid and fast.	(16)	11 „	Not so vivid or fast.
(18)	12 „	More vivid and fast.	(17)	7 „	Very poor.
(19)	11 „	Not 1st degree of vividness or speed.	(20)	12·4 „	Also good, much the same.

During the last three pairs of observations, the subject asked repeatedly for rest, complaining of being fatigued.

If we examine these results and tabulate them, we obtain the following:

Subject: A. W.

Duration.

In 6 cases after-effect of narrow line system lasted longer.
„ 3 „ „ „ „ both were equal.
„ 1 case „ „ „ wide line system lasted longer.
Average duration of after-effect of narrow line system 12·5 sec.
„ „ „ „ „ „ wide „ „ 10·9 „

Vividness and/or Speed.

In 7 cases after-effect of narrow line system more vivid.
„ 3 „ „ „ „ both were equal.
„ 0 „ „ „ „ wide line system more vivid.

Subject: Dr Spearman.

Duration.

In 10 cases after-effect of narrow line system lasted longer.
„ 0 „ „ „ „ both equal.
„ 0 „ „ „ „ wide line system lasted longer.
Average duration of after-effect of narrow line system 9·5 sec.
„ „ „ „ „ „ wide „ „ 6·7 „

Vividness.

(6 cases no statement.)
In 1 case after-effect of narrow line system more vivid.
„ 3 cases „ „ „ both equal.
„ 0 „ „ „ „ wide line system more vivid.

Speed.

(5 cases no statement.)
In 5 cases after-effect of narrow line system faster.
„ 0 „ „ „ „ wide „ „ „

Vividness and/or Speed.

In 6 cases after-effect of narrow line system more vivid, or faster, or both.
„ 3 „ „ „ „ both equal.
„ 1 case „ „ uncertain.

Subject: Prof. Read.

If we reject five pairs of observations where the subject complained of fatigue and sleepiness we get:

Duration.

In 8 cases after-effect of narrow line system lasted longer.
„ 2 „ „ „ „ both equal.
„ 5 „ „ „ „ wide lines lasted longer.
Average duration of after-effect of narrow line system 12·9 sec.
„ „ „ „ „ „ wide „ „ 12·8 „

Vividness.

(In 1 case no statement.)
In 8 cases after-effect of narrow line system more vivid.
„ 5 „ „ „ „ both equal.
„ 1 case „ „ „ wide line system more vivid.

Speed.

In 10 cases after-effect of narrow line system faster.
„ 5 „ „ „ „ both equal.
„ 0 „ „ „ „ wide lines faster.

Vividness and/or Speed.

In 12 cases after-effect of narrow line system more vivid, or faster or vivid alone.
„ 2 „ „ „ „ both equal.
„ 1 case „ „ „ wide lines faster.

The three factors of the after-effect: duration, vividness, and speed, vary differently with different persons, but the results show distinctly *that the after-effect is increased in one or several ways, within limits, with the number of stimuli affecting a given area of the retina at the same time, and/or with the frequency with which the stimuli pass given retinal elements.*

In the remarks leading up to the last two experiments, we distinguished between "frequency" and "velocity." We had two systems of lines moving with the same velocity, but in one system the width of the lines was half that of the lines of the other system; consequently in the narrower system, the frequency with which the stimuli impounded upon given retinal elements was twice that of the wider system. The same result can be obtained with systems of lines of equal width but of varying velocities: here the frequency with which the stimuli impound upon given retinal elements varies directly with the velocity. Further, the factor which complicated the last experiment, viz. difference in the number of stimuli affecting a given retinal area at the same time, is here absent.

It has been recognized by several observers that the velocity of the objective movement has a great influence upon the velocity or intensity of the after-effect. Budde, *e.g.*, states that the after-effect is increased with the velocity of the objective movement; but if the objective movement becomes so fast that fusion takes place, no after-effect is produced. Szily's observations are much to the same purpose.

More systematic investigations upon this particular aspect of the after-effect were made by the following observers. Borschke and Hescheles obtained results which, for reasons stated above, are not very conclusive. Objections of a different kind have been raised against the experimentation of Cords and Brücke. These investigators find, however, that, within limits, the velocity of the after-effect increases with the velocity of the stimulating objective movement, and decreases again with the beginning of flicker. Tōsaku Kinoshita found that the after-effect first increased with the velocity of the objective movement, but decreased after a certain limit had been reached. The velocities investigated are, however, not numerous enough to construct a curve.

I think I have been working under less objectionable conditions and obtained more numerous results, when making

Experiments 10—13: *To ascertain the influence of the velocity of the stimulating movement upon the after-effect.*

Experiment 10. I arranged my "apparatus of moving fields" so that one of the fields was moving much faster than the other, *e.g.* when the slow one was moving at a rate of 4·5 cm. sec.$^{-1}$, the rates of the fast one varied from 11 to 16 cm. sec.$^{-1}$. To make sure that no difference of illumination obtained, the velocities of the fields were frequently reversed. The times of stimulation varied from 20 seconds to 2½ minutes. As projection-field either the stopped apparatus was used or a reproduction of the front board with window and contents. In this reproduction, the surrounding field was grey and the central field consisted of alternating white and grey lines. Under all these varying conditions, I was unable to notice any appreciable difference in the magnitude of the two after-effects. Five other observers, among whom were Dr McDougall, Professor Read, and Dr Spearman, all obtained the same effect as myself.

The absence of any difference in the two after-effects under these experimental conditions may again be due to the principle of *associative Angleichung*, as in Expt. 8.

In order to eliminate this possible psychical factor, I made the following modifications in

EXPERIMENT 11. The two fields were exposed singly, *e.g.* the faster one was exposed while the slower was covered. The stimulation lasted for 30 seconds. The after-effect was projected by the observer on a field at his side, which he faced by turning through an angle of 90°. This projection-field was a cardboard reproduction of the apparatus made to scale. When the signal was given, a stop watch was set going which was stopped as soon as the observer signified that the after-effect had passed off. The duration of the after-effect was thus measured and noted, together with the statement of the observer about its vividness and velocity. The experiment was then repeated with the faster field covered and the slower one exposed. These two experiments formed a pair, and the observer in making his statement about the vividness and velocity of the second after-effect compared it with the first one. After a rest of 1—2 minutes the next pair of experiments was made in the reverse order; that is to say, the slower movement first and the faster last, and so on, in order to eliminate any time error. The position of the two fields was also occasionally reversed in order to eliminate any possible space-error or error due to difference in illumination.

I made two series of experiments: the first series with respective velocities of 12 and 4·7 cm. sec.$^{-1}$, and the second with 8 and 3 cm. sec.$^{-1}$ respectively.

The following are the results:

1*st or Fast Series.*

Observer: Prof. Read.

Fast. 12 cm. sec.$^{-1}$			*Slow.* 4·7 cm. sec.$^{-1}$		
(1)	13	sec. Not very vivid, rather slow.	(2)	12	sec. A little more vivid, a little faster.
(4)	21	,, Very vivid, cannot say whether faster.	(3)	13·2	,, Fairly vivid and quick.
(5)	19	,, Fairly vivid and quick.	(6)	15·8	,, Much the same as 5.

1*st or Fast Series.*

Observer: Prof. Read.

Fast. 12 cm. sec.$^{-1}$			*Slow.* 4·7 cm. sec.$^{-1}$		
(7)	23 sec.	Fairly vivid, no noticeable increase in speed.	(8)	15 sec.	Unusually vivid and quick.
(10)	15 „	Nearly as vivid, not so fast.	(9)	15·6 „	Vivid and quick.

Observer: Dr Spearman.

Fast. 12 cm. sec.$^{-1}$			*Slow.* 4·7 cm. sec.$^{-1}$		
(1)	7 sec.	Vivid.	(2)	13 sec.	More intense and faster.
(4)	12 „	Less vivid and slower.	(3)	12·6 „	Marked and quick.
(5)	14 „	As 4.	(6)	13 „	More vivid and faster.
(8)	10 „	Less vivid and slower.	(7)	11 „	Fast and vivid.
(9)	8 „	Much the same as 8.	(10)	10 „	Slower and less vivid than 9.
(12)	11 „	Faster and more vivid.	(11)	9 „	Medium.
(14)	10 „	Somewhat less on the whole than 13.	(13)	13 „	Pretty vivid and fast.

Observer: A. W.

Fast. 12 cm. sec.$^{-1}$			*Slow.* 4·7 cm. sec.$^{-1}$		
(1)	9 sec.	Marked.	(2)	9 sec.	More marked than 1.
(4)	9 „	Less marked than 3.	(3)	11 „	Marked.
(5)	11 „	Very marked.	(6)	10 „	Slightly less than 5.
(8)	10 „	Less marked than 7.	(7)	11·4 „	Very marked.
(9)	9 „	Rather faint.	(10)	10·5 „	Faint, though a little better.
(12)	9·8 „	Much the same as 11.	(11)	11·2 „	Marked.
(13)	7 „	Rather faint.	(14)	8 „	Possibly a trifle fainter than 13.
(16)	9 „	Less vivid though as fast as 15.	(15)	12·8 „	Vivid, but slow.
(17)	9 „	Fairly vivid and slow.	(18)	11 „	More vivid and faster than 17.
(20)	13 „	Much more vivid and faster.	(19)	7·2 „	Fairly vivid.

2*nd or Slow Series.*

Observer: Prof. Read.

Fast. 8 cm. sec.$^{-1}$			*Slow.* 3 cm. sec.$^{-1}$		
(1)	13 sec.	Pretty vivid, moderately rapid.	(2)	11 sec.	Effect more vivid and quicker.
(4)	18 „	Not so quick or vivid.	(3)	13 „	Vivid and fairly quick.
(5)	13·2 „	Vivid and quicker at first, rapidly decreasing.	(6)	12 „	Vivid and steadily quick, on whole better effect as to vividness.
(8)	18 „	Very vivid and quick, unusually good.	(7)	10 „	Not very vivid or rapid, poor affair.
(9)	11 „	Very feeble effect all round.	(10)	11 „	Moderate vividness and speed, better than last.
(12)	8·4 „	Feeble in every way.	(11)	17 „	Very good, vivid and quick.

2nd or Slow Series.

Observer: A. W.

Fast. 8 cm. sec.$^{-1}$			*Slow.* 3 cm. sec.$^{-1}$		
(1)	7 sec.	Fairly fast and vivid.	(2)	9 sec.	Faster and more vivid.
(4)	8 ,,	Much the same as 3.	(3)	7 ,,	Fast and vivid.
(5)	6 ,,	Vivid and fast.	(6)	7 ,,	Slightly fainter all round.
(8)	7 ,,	Much the same as 7.	(7)	8 ,,	Very fast and vivid.
(9)	8 ,,	Fast and vivid.	(10)	8 ,,	Slightly more marked all round.

If we examine these results more closely we find

(A). In the *faster series* (respective velocities 12 and 4·7 cm. sec.$^{-1}$).

For Prof. Read.

Duration.

In 4 cases after-effect of FAST system lasted longer. Average 18·2 sec.
,, 1 case ,, ,, ,, SLOW ,, ,, ,, ,, 14·3 ,,

Speed.

In 0 case after-effect of FAST system was faster.
,, 3 cases ,, ,, ,, SLOW ,, ,, ,,
,, 1 case ,, ,, ,, both equal.

Vividness.

In 1 case after-effect of FAST system was more vivid.
,, 3 cases ,, ,, ,, SLOW ,, ,, ,, ,,
,, 1 case ,, ,, ,, both equal.

For Dr Spearman.

Duration.

In 2 cases after-effect of FAST system lasted longer. Average 10·3 sec.
,, 9 ,, ,, ,, ,, SLOW ,, ,, ,, ,, 11·7 ,,

Speed.

In 2 cases after-effect of FAST system was faster.
,, 5 ,, ,, ,, ,, SLOW ,, ,, ,,

Vividness.

In 2 cases after-effect of FAST system was more vivid.
,, 5 ,, ,, ,, ,, SLOW ,, ,, ,, ,,

For A. W.

Duration.

In 2 cases after-effect of FAST system lasted longer. Average 9·6 sec.
,, 7 ,, ,, ,, ,, SLOW ,, ,, ,, ,, 10·2 ,,
,, 1 case ,, ,, ,, both equal.

Speed.

In 1 case after-effect of FAST system was faster.
,, 1 ,, ,, ,, ,, SLOW ,, ,, ,,
,, 2 cases ,, ,, ,, both equal.
,, 6 ,, there was no statement.

Vividness.

In 3 cases after-effect of FAST system was more vivid
,, 6 ,, ,, ,, ,, SLOW ,, ,, ,, ,,
,, 1 case ,, ,, ,, both equal.

(B). In the *slower series* (respective velocities 8 and 3 cm. sec.$^{-1}$).

For Prof. Read.

Duration.

In 4 cases after-effect of FAST system lasted longer. Average 13·6 sec.
„ 1 case „ „ „ SLOW „ „ „ „ 12·3 „
„ 1 „ „ „ „ both equal.

Speed.

In 2 cases after-effect of FAST system was faster.
„ 4 „ „ „ „ SLOW „ „ „

Vividness.

In 2 cases after-effect of FAST system was more vivid.
„ 4 „ „ „ „ SLOW „ „ „ „

For A. W.

Duration.

In 1 case after-effect of FAST system lasted longer. Average 7·2 sec.
„ 3 cases „ „ „ SLOW „ „ „ „ 7·8 „
„ 1 case „ „ „ both equal.

Speed.

In 1 case after-effect of FAST system was faster.
„ 2 cases „ „ „ SLOW „ „ „
„ 2 „ „ „ „ both equal.

Vividness.

In 1 case after-effect of FAST system was more vivid.
„ 2 cases „ „ „ SLOW „ „ „ „
„ 2 „ „ „ „ both equal.

We have through all these experiments a general predominance of the after-effect of the "slow" systems, a result which is opposed to those of previous observers.

Although in Prof. Read's case the durations of the after-effect of the "fast" systems lasted in both series of experiments longer than that of the "slow" systems, yet in each case the vividness and speed of the "slow" systems were superior to that of the fast ones. This is even somewhat more marked in the second series where the speed of the objective movement was reduced by $\frac{1}{3}$.

With Dr Spearman the after-effect of the "slow" system is in both series superior to that of the "fast" one, not only in vividness and speed but also in duration.

In my own case the results of both series show a predominance of the after-effect of the slower system not only in duration but also in vividness (resp. speed), yet the difference is no longer so marked in the second (slower) series, thus indicating a tendency towards a reversal.

This induced me to make

EXPERIMENT 12. The apparatus was arranged as in Experiment 8, *i.e.* both planes were visible and moving in the same direction, the fixation-point being between them. The velocities were, however, greatly reduced. I began with 2·5 and ·7 cm. sec.$^{-1}$, and found, after a stimulation of 30 seconds and allowing the after-effect to pass off on the stopped fields, that that of the faster field was far more vivid and quicker and in general also lasted longer. This, I think, tends to show that there is a summit in the after-effect curve. To ascertain the approximate position of this summit I made further experiments with the following pairs of slower velocities and obtained the following results:

2·5	cm.	sec.$^{-1}$	and	·7	cm.	sec.$^{-1}$.	Faster movement gave better result.		
2·75	"	"	"	·75	"	"	Do.		
3·0	"	"	"	·8	"	"	Do.		
3·8	"	"	"	1·1	"	"	Do.		
3·8	"	"	"	1·5	"	"	Do.		
2·3	"	"	"	·6	"	"	Do.		
1·7	"	"	"	·6	"	"	Do.		
1·4	"	"	"	·6	"	"	Do.	} Though less than before.	
1·0	"	"	"	·6	"	"	Do.		

These experiments, in conjunction with the previous ones, suggest that the *after-effect at first increases very rapidly with the objective velocity, but soon reaches a maximum and then gradually diminishes with further increase in speed.* This last experiment (12) shows further that the principle of *associative Angleichung*, as far as it obtains here, is overcome when the difference between two simultaneous after-effects is great enough.

EXPERIMENT 13. I have attempted to show the above result more clearly, and to obtain some more data for the formation of an idea as to the shape of the curve of the after-effect. I used again the "apparatus of moving fields." One field was moving more slowly and the other faster, the velocities being always as nearly as possible in the ratio of 1 : 2 to each other. The two surfaces were observed simultaneously, the fixation-point being between them. Unless the after-effect was extremely pronounced, the observations were repeated successively, as in Experiment 9, in order to eliminate any error due to the principle of *Angleichung*. The table on p. 51 shows the results of the experiment.

From these data a curve of the following form may be constructed (Fig. 8).

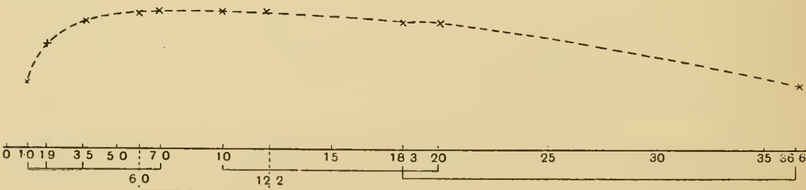

Fig. 8.

Observer: A. W. Velocities of Objective Movements	After-effect of Faster Movement: Observed simultaneously	After-effect of Faster Movement: Observed successively to avoid *Angleichung*
1 cm. sec.$^{-1}$ and 1·9 cm. sec.$^{-1}$	(1) Faster. (2) Slightly faster. (3) ,, ,,	(4) Faster and more vivid. (5) Decidedly more vivid and faster. (6) Faster and more vivid.
1·9 ,, ,, 3·5 ,,	(1) Both nearly equal. (2) Slightly faster. (3) No difference.	(4) Slightly faster, more vivid, longer. (5) Possibly slightly less vivid. (6) More vivid and faster.
3·5 ,, ,, 7·0 ,,	(1) Slightly faster. (2) ,, ,, (3) ,, ,,	(4) More marked, faster and longer (12 sec. against 7 sec.) (5) Less marked, slower and shorter (12 sec. against 14 sec.). (6) Equal speed and vividness, shorter (13 sec. against 15 sec.).
6·0 ,, ,, 12·2 ,,	(1) ,, ,, (2) Apparently equal. (3) No difference.	(4) Less marked, slower and shorter (9 sec. against 14 sec.). (5) More marked, faster, equally long (12 sec.). (6) More marked, faster, longer (12 sec. against 10 sec.).
10·0 ,, ,, 20·0 ,,	(1) Both equal, possibly a little slower. (2) ,, ,, (3) ,, ,,	(4) More vivid, faster, longer (10 sec. against 7 sec.). (5) A little less vivid, slower, longer (15 sec. against 13 sec.). (6) A little less vivid, slower, shorter (10 sec. against 17 sec.).
18·3 ,, ,, 36·6 ,,	(1) Decidedly slower. (2) ,, ,, (3) ,, ,,	

The objective velocities to which the after-effects are due are marked off on the abscissa, and the ordinates represent the intensities of the respective after-effects. The figures below the abscissa indicate the actual velocities investigated, and the lines linking them together mark the pairs observed together. The position of the first × is chosen arbitrarily. The first pair 1·0 and 1·9 show a marked difference in the after-effect, and consequently the × to 1·9 is inscribed much higher. 3·5 gives a more marked after-effect than 1·9, but the difference is not quite so great as that between 1·0 and 1·9, hence its × is inscribed accordingly. 7·0 is found similarly from 3·5. 6·0 is interpolated, its position being given by 3·5 and 7·0; 10 also is interpolated, 20 gives a slightly less marked after-effect than 10, hence it is marked lower, and so on.

At the beginning the curve rises rapidly, but soon reaches its summit somewhere between 7 and 10 cm. sec.$^{-1}$, under the given experimental conditions, then it gradually but steadily declines. This position of the summit is close to, and a little in advance of, that deducible from Experiment 11. It is far short of the flicker-point, in the neighbourhood of which previous observers have assumed it must lie.

In Experiments 8 and 9 we investigated the influence of the width of the moving stripes upon the after-effect, and found that we could not alter this without altering the frequency of the stimulus, unless the velocity was also altered accordingly. In Experiments 10—13 we kept the width of the moving stripes constant and altered the frequency by altering the velocity. Another possible experimental modification is to vary the relative width of the stripes (but not the total width of a pair), whilst keeping the velocity, and hence the frequency, constant. Therefore I performed

EXPERIMENT 14: *To examine the influence upon the after-effect of the relative width of the moving stripes, the number of stripes per unit area and the velocity remaining constant.*

I employed three different systems of stripes, viz. (*a*) alternating black and white stripes of 10 mm. width each, which I shall designate by "*equal*" stripes; (*b*) black stripes 15 mm. wide alternating with white ones 5 mm. wide, which I shall call in short *wide "black"* stripes; (*c*) black stripes 5 mm. wide alternating with white stripes 15 mm. wide, named shortly *wide "white"* stripes. Hence there were three sets of comparisons to be made, viz. I. *wide "white"* and *"equal"* stripes; II. *wide "black"* and *"equal"* stripes; III. *wide "black"* and *wide "white"* stripes.

I again used the "apparatus of moving fields." On trying "direct simultaneous comparison," the after-effect from the three different systems appeared quite equal. But suspecting *Angleichung*, I then tried the method of "*paired direct successive comparison*," as described in Experiment 9 (page 41). The objective velocity chosen was 10 cm. sec.$^{-1}$, and the time of stimulation 30 secs. The following is a transcript from my laboratory note-book, giving the duration and nature of the after-effect.

Observer: Mr Flügel.

I.

Left: "equal" stripes.			*Right: wide "white" stripes.*		
(1)	9·4 sec.	Fairly vivid; rather slow.	(2)	10·0 sec.	Faster to begin, afterwards no difference; vividness same degree.
(4)	10·4 „	Slightly more fast and vivid, especially at beginning.	(3)	7·6 „	Fairly fast and vivid.
(5)	10·6 „	Fast and vivid.	(6)	7·0 „	Very slightly less fast and vivid.
(8)	6·4 „	No difference.	(7)	7·6 „	Fairly fast and vivid.
(9)	7·2 „	Fairly fast and vivid.	(10)	6·0 „	Slightly slower, less vivid.

Left: wide "white" stripes.			*Right: "equal" stripes.*		
(1)	10·6 sec.	Fast and vivid.	(2)	9·4 sec.	Same vividness; possibly a little quicker at beginning.
(4)	10·0 „	Slightly less fast and vivid.	(3)	10·0 „	Very fast at beginning; fairly vivid.
(5)	10·0 „	Fairly fast and vivid.	(6)	10·0 „	No difference.
(8)	10·0 „	Same speed; less vivid.	(7)	9·6 „	Fairly vivid; not very fast.
(9)	6·0 „	Slow, not very vivid.	(10)	8·2 „	Faster and more vivid.

II.

Left: "equal" stripes.			*Right: wide "black" stripes.*		
(1)	6·8 sec.	Fairly fast and vivid.	(2)	8·0 sec.	Very slightly less vivid; same speed.
(4)	7·6 „	No difference.	(3)	7·0 „	Fairly fast and vivid.
(5)	8·5 „	Vivid; not fast.	(6)	6·8 „	More vivid; same speed.
(8)	7·6 „	Slightly more vivid; same speed.	(7)	6·2 „	Slow; not vivid.
(9)	8·4 „	Fairly fast and vivid.	(10)	6·0 „	Very slightly less fast and vivid.

Left: wide "black" stripes.			*Right: "equal" stripes.*		
(1)	6·6 sec.	Rather slow, not very vivid.	(2)	8·4 sec.	Very slightly faster; more vivid.
(4)	8·8 „	No difference.	(3)	7·4 „	Fairly fast and vivid.
(5)	8·0 „	Fairly fast and vivid.	(6)	8·4 „	Faster; more vivid.
(8)	7·6 „	Less fast and vivid.	(7)	9·0 „	Vivid, not very fast.
(9)	8·0 „	Slow; but fairly vivid.	(10)	9·2 „	Slightly faster, same vividness.

III.

Left: wide "black" stripes.			*Right: wide "white" stripes.*		
(1)	6·8 sec.	Slow, not vivid.	(2)	8·2 sec.	Slightly faster and more vivid.
(4)	8·6 „	Slightly faster, same vividness.	(3)	9·2 „	Slow, but fairly vivid.
(5)	8·6 „	Fairly fast and vivid.	(6)	8·6 „	Same speed, more vivid.
(8)	8·0 „	Slightly less fast and vivid.	(7)	8·6 „	Fairly fast and vivid.
(9)	7·0 „	Fairly fast, but not very vivid.	(10)	5·4 „	Slow, not vivid.

Left: wide "white" stripes.			*Right: wide "black" stripes.*		
(1)	5·0 sec.	Very slow and faint.	(2)	6·0 sec.	Slightly faster; more vivid.
(4)	5·0 „	Slow; not vivid.	(3)	6·4 „	Fairly fast and vivid.
(5)	6·2 „	Slow; not vivid.	(6)	5·0 „	Slightly faster; more vivid.
(8)	7·2 „	No difference.	(7)	5·8 „	Slow; fairly vivid.
(9)	6·0 „	Fairly fast and vivid.	(10)	7·0 „	No difference.

Observer: Mr Sully.

I.

Left: "equal" stripes.			*Right: wide "white" stripes.*		
(1)	10·0 sec.	Fairly vivid; rather slow.	(2)	7·2 sec.	Less vivid and fast.
(4)	13·0 „	Much more vivid and fast.	(3)	8·0 „	Fairly vivid.
(5)	11·2 „	Vivid and fast.	(6)	10·0 „	Less vivid and fast.
(8)	11·8 „	Stronger.	(7)	8·6 „	Faint and slow.
(9)	15·0 „	Vivid and fast.	(10)	9·8 „	Fainter.

Left: wide "white" stripes.			*Right: "equal" stripes.*		
(1)	8·0 sec.	Fairly vivid; slow.	(2)	11·0 sec.	About the same.
(4)	10·8 „	More vivid.	(3)	9·4 „	Fairly vivid and fast.
(5)	8·0 „	Faint all round.	(6)	10·0 „	Distinctly more vivid and fast.
(8)	9·0 „	The same.	(7)	9·0 „	Fairly vivid and fast.
(9)	7·0 „	Faint all round.	(10)	9·8 „	Stronger all round.

II.

Left: "equal" stripes.			*Right: wide "black" stripes.*		
(1)	9·0 sec.	Faint.	(2)	11·0 sec.	A little more marked.
(4)	10·2 „	Better marked; perhaps a little quicker.	(3)	9·4 „	Faint.
(5)	9·4 „	Faint.	(6)	9·0 „	Less distinct; slower.
(8)	9·0 „	Faint, yet stronger than 7.	(7)	9·0 „	Very faint.
(9)	11·0 „	Very faint.	(10)	8·4 „	Still faint, but stronger than 9.

Left: wide "black" stripes.			*Right: "equal" stripes.*		
(1)	8·4 sec.	Faint.	(2)	9·4 sec.	Still faint; slightly stronger.
(4)	8·0 „	No difference.	(3)	10·2 „	Faint.
(5)	8·0 „	Still faint.	(6)	8·0 „	Possibly a little stronger.
(8)	7·6 „	No difference.	(7)	8·0 „	Fair.
(9)	8·4 „	Fair.	(10)	8·4 „	Stronger than 9.

III.

Left: wide "black" stripes.			*Right: wide "white" stripes.*		
(1)	10·4 sec.	Faint all round.	(2)	8·2 sec.	No difference.
(4)	11·6 „	Not much difference; possibly a little stronger.	(3)	10·0 „	Faint.
(5)	11·0 „	Faint.	(6)	8·2 „	Less strong than 5.
(8)	11·8 „	Stronger and faster.	(7)	10·0 „	Faint.
(9)	11·0 „	Fairly vivid and fast.	(10)	9·4 „	Fainter and slower.

Left: wide "white" stripes.			*Right: wide "black" stripes.*		
(1)	9·4 sec.	Faint.	(2)	10·0 sec.	Slightly stronger.
(4)	9·4 „	No difference.	(3)	10·2 „	Faint.
(5)	9·4 „	Fairly vivid and fast.	(6)	9·4 „	Slightly stronger all round.
(8)	9·4 „	Rather less strong.	(7)	9·4 „	Fairly vivid.
(9)	10·0 „	Faint.	(10)	10·0 „	Slightly stronger, not much.

N.B. Observer cannot generally distinguish between vividness and speed.

Observer: A. W.

I.

Left: "equal" stripes.			*Right: wide "white" stripes.*		
(1)	13·6 sec.	Fairly vivid and fast.	(2)	13·6 sec.	More vivid, less fast.
(4)	11·0 „	No difference.	(3)	12·6 „	Vivid, fairly fast.
(5)	12·0 „	Fairly vivid; slow.	(6)	15·0 „	More vivid; a little faster.
(8)	14·2 „	Quite as vivid; a little slower.	(7)	15·0 „	Very vivid, fairly fast.
(9)	12·2 „	Vivid, but slow.	(10)	14·0 „	A little more vivid and faster.

Observer: A. W.

Left: wide "white" stripes.			*Right: "equal" stripes.*		
(1)	13·0 sec.	Slow but very vivid.	(2)	10·2 sec.	Slower and much less vivid.
(4)	14·0 „	Decidedly faster and more vivid.	(3)	11·8 „	Slow; fairly vivid.
(5)	15·8 „	Vivid and fast.	(6)	14·0 „	No difference.
(8)	12·0 „	No difference.	(7)	14·0 „	Fairly vivid and fast.
(9)	14·0 „	Very vivid and fast.	(10)	12·6 „	Not quite so vivid and fast.

II.

Left: "equal" stripes.			*Right: wide "black" stripes.*		
(1)	12·0 sec.	Fairly vivid and fast.	(2)	9·0 sec.	No difference.
(4)	9·0 „	A little faster, more vivid.	(3)	9·4 „	Not very fast or vivid.
(5)	9·8 „	Fairly vivid and fast.	(6)	8·6 „	Less vivid and fast.
(8)	11·0 „	A little faster and more vivid.	(7)	9·8 „	Not very fast or vivid.
(9)	12·0 „	Vivid and fast.	(10)	7·2 „	Less vivid and fast.

Left: wide "black" stripes.			*Right: "equal" stripes.*		
(1)	12·0 sec.	Speed and vividness fair.	(2)	11·0 sec.	Not so good all round.
(4)	10·6 „	No difference.	(3)	11·0 „	Fair vividness and speed.
(5)	11·0 „	Not very vivid or fast.	(6)	12·0 „	Both a trifle better.
(8)	11·0 „	Both a little better.	(7)	9·8 „	Not very vivid or fast.
(9)	8·0 „	Fairly vivid and fast.	(10)	11·0 „	No difference.

III.

Left: wide "black" stripes.			*Right: wide "white" stripes.*		
(1)	10·8 sec.	Vivid, fairly fast.	(2)	13·0 sec.	More vivid and fast.
(4)	12·4 „	No difference.	(3)	11·0 „	Fairly vivid and fast.
(5)	11·6 „	Vivid and fast.	(6)	15·4 „	No difference.
(8)	12·0 „	More vivid, perhaps not so fast.	(7)	11·0 „	Vivid and fast.
(9)	11·0 „	Fairly vivid, not very fast.	(10)	10·4 „	Much the same as before.

Left: wide "white" stripes.			*Right: wide "black" stripes.*		
(1)	9·2 sec.	Fairly vivid and fast.	(2)	11·0 sec.	Same vividness, a little faster.
(4)	11·2 „	More vivid and faster.	(3)	8·0 „	Fairly vivid and fast.
(5)	11·8 „	Vivid and fast.	(6)	12·2 „	Quite as vivid and fast, if not more.
(8)	11·4 „	More vivid and faster.	(7)	10·6 „	Fairly vivid and fast.
(9)	14·0 „	Fairly vivid and fast.	(10)	11·0 „	More vivid but slower.

If we analyse these three sets of observations, we get:

Observer: Mr Flügel.

I. *Wide "white" and "equal" stripes.*

Duration:	4 times	"white" lasted longer.	
	4 „	"equal" „ „	
	2 „	no difference.	
Average:	"white" 8·5 sec.		
	"equal" 9·1 „		
Vividness:	0 times	"white" more vivid.	
	6 „	"equal" „ „	
	4 „	no difference.	
Speed:	1 times	"white" faster.	
	6 „	"equal" „	
	3 „	no difference.	

Observer: Mr Flügel.

II. *Wide "black" and "equal" stripes.*

Duration: 2 times "black" lasted longer.
8 ,, "equal" ,, ,,
0 ,, no difference.

Average: "black" 7·3 sec.
"equal" 8·1 ,,

Vividness: 1 times "black" more vivid.
6 ,, "equal" ,, ,,
3 ,, no difference.

Speed: 0 times "black" faster.
5 ,, "equal" ,,
5 ,, no difference.

III. *Wide "black" and wide "white" stripes.*

Duration: 4 times "black" lasted longer.
5 ,, "white" ,, ,,
1 ,, no difference.

Average: "black" 6·9 sec.
"white" 6·9 ,,

Vividness: 3 times "black" more vivid.
3 ,, "white" ,, ,,
4 ,, no difference.

Speed: 5 times "black" faster.
2 ,, "white" ,,
3 ,, no difference.

Observer: Mr Sully.

I. *Wide "white" and "equal" stripes.*

Duration: 1 times "white" lasted longer.
8 ,, "equal" ,, ,,
1 ,, no difference.

Average: "white" 8·6 sec.
"equal" 11·0 ,,

Vividness: 1 times "white" more vivid and/or faster.
and/or 7 ,, "equal" ,, ,, ,, ,, ,,
Speed: 2 ,, no difference.

II. *Wide "black" and "equal" stripes.*

Duration: 1 times "black" lasted longer.
6 ,, "equal" ,, ,,
3 ,, no difference.

Average: "black" 8·7 sec.
"equal" 9·3 ,,

Vividness: 2 times "black" more vivid and/or faster.
and/or 6 ,, "equal" ,, ,, ,, ,, ,,
Speed: 2 ,, no difference.

III. *Wide "black" and wide "white" stripes.*

Duration: 7 times "black" lasted longer.
0 ,, "white" ,, ,,
3 ,, no difference.

Average: "black" 10·5 sec.
"white" 9·3 ,,

Vividness: 8 times "black" more vivid and/or faster.
and/or 0 ,, "white" ,, ,, ,, ,, ,,
Speed: 2 ,, no difference.

Observer: A. W.

I. *Wide "white" and "equal" stripes.*

Duration:	8 times	"white" lasted longer.	
	1 ,,	"equal" ,, ,,	
	1 ,,	no difference.	
	Average:	"white" 13·9 sec.	
		"equal" 12·6 ,,	
Vividness:	6 times	"white" more vivid.	
	0 ,,	"equal" ,, ,,	
	4 ,,	no difference.	
Speed:	6 times	"white" faster.	
	1 ,,	"equal" ,,	
	3 ,,	no difference.	

II. *Wide "black" and "equal" stripes.*

Duration:	3 times	"black" lasted longer.	
	7 ,,	"equal" ,, ,,	
	0 ,,	no difference.	
	Average:	"black" 9·7 sec.	
		"equal" 10·9 ,,	
Vividness:	2 times	"black" more vivid.	
	5 ,,	"equal" ,, ,,	
	3 ,,	no difference.	
Speed:	2 times	"black" faster.	
	5 ,,	"equal" ,,	
	3 ,,	no difference.	

III. *Wide "black" and wide "white" stripes.*

Duration:	5 times	"black" lasted longer.	
	5 ,,	"white" ,, ,,	
	0 ,,	no difference.	
	Average:	"black" 11·1 sec.	
		"white" 11·8 ,,	
Vividness:	3 times	"black" more vivid.	
	3 ,,	"white" ,, ,,	
	4 ,,	no difference.	
Speed:	2 times	"black" faster.	
	5 ,,	"white" ,,	
	3 ,,	no difference.	

These results we may summarize thus:

Observer: F.	Duration	W = E,	B < E,	B = W.
	Vividness	W < E,	B < E,	B = W.
	Speed	W < E,	B < E,	B = W.
Observer: S.	Duration	W < E,	B < E,	B > W.
	Vividness and Speed	W < E,	B < E,	B > W.
Observer: W.	Duration	W > E,	B < E,	B = W.
	Vividness	W > E,	B < E,	B = W.
	Speed	W > E,	B < E,	B = W.

Where B = wide "black" stripes.
,, W = ,, "white" ,,
,, E = "equal" ,,

Thus the results of these experiments are not very decisive, but the general tendency seems to be as follows: *If a moving series of alternating dark and light stripes excite the retina, a slightly better after-effect seems to be obtained if the width of the stripes is equal; but if the relative width is not equal, it seems indifferent which stripes are increased and which decreased in width.*

Another point upon which there appear to be no systematic experiments I approached in

EXPERIMENT 15: *To determine the influence of an after-effect upon an objective movement, or vice versâ.*

I again used the "apparatus of moving fields," but now that side of the front which was covered with black and white stripes was turned outwards. The parts of this front board above and below the level of the window were covered with strips of paper running right across the

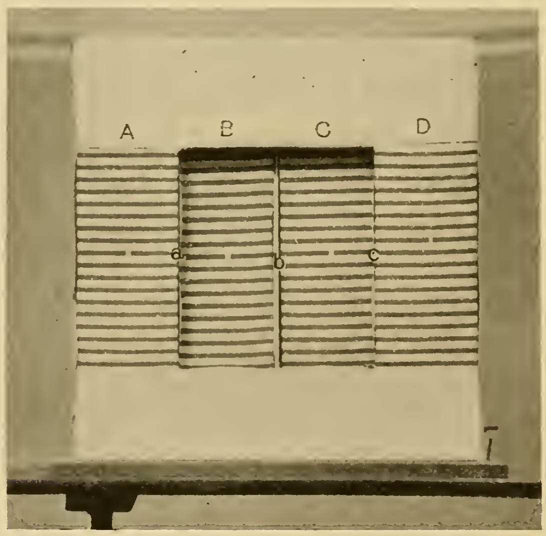

Fig. 9.

board so that the observer had four fields facing him, the outer or marginal ones stationary and the inner or central ones moving. Figure 9 represents the arrangement.

A and *D* are the stationary fields, whilst *B* and *C* were moving with uniform velocity (about 5—7 cm. $sec.^{-1}$) in the same direction. Either *A* and *B* were covered, whilst *C* and *D* were exposed or *vice versâ*;

a and *c* were the respective fixation points. To take the case when *C* and *D* were covered: then after a stimulation of about 30 seconds with *a* as fixation point, the cover was removed and *b* fixated. The result of this was that during the first exposure one field beside the fixation mark was in motion and the other one was stationary, while during the second exposure both the fields beside the fixation mark were moving with the same velocity, and it was found that the after-effect of the first exposure appeared to retard the objective movement of the second one. The effect was, of course, analogous when *A* and *B* were covered at first. We may conclude from this that *the after-effect adds itself to an objective movement.* But I consider it very doubtful whether the amount of the joint effect is just equal to the sum of the two separate effects.

The next point to be considered is one that has given rise to much controversy, viz. the *velocity* of the after-effect. Exner and Szily hold that there is no *velocity* in the after-effect, but only *intensity.* I was myself at one time of that opinion; led to it not only from theoretical considerations, of which I shall speak later, but also from experimental observations. Experiments under varied conditions have, however, modified my views on this subject.

Attempts to measure the *velocity* of the after-effect have been made by Budde, Borschke and Hescheles, and Cords and Brücke. Budde, as pointed out in the historical survey, made a great show of mathematical formulae, but he started from wrong and arbitrary premises. Borschke and Hescheles, like Cords and Brücke, had recourse to experiment. The experimentation of the former is, however, vitiated because the systems of black rods which they used are not the stimuli for the retina. The bright squares between them are the stimuli; and, as these always move in the direction of the diagonal of the parallelogram of velocities, the after-image is bound to correspond to this direction of movement. Cords and Brücke's experiments for the quantitative determination of the velocity of the after-effect are unsatisfactory for four reasons. First, because, as they admit, it was very difficult to notice the real movement of the projection-field, even in the absence of any pseudo-movement and therefore it must have been doubly difficult to determine the point when the real and the pseudo-movement just balanced each other. Secondly, as these authors also recognize, the results were very divergent. Thirdly, their experiments rest upon the assumption that the after-effect and the objective movements add together as algebraic quantities which is not proved and which I personally consider very doubtful. (Also *vide* Expt. 15, p. 58.) Last, but not least, no "puzzle experiments" were introduced to make sure of the absence of suggestion.

I therefore made

Experiment 16: *On the velocity of the after-effect.*

I discarded such complicating and vitiating conditions as were adopted by Cords and Brücke and resorted to simple direct comparison. If we take a disc with alternating black and white sectors and rotate it at a moderate rate, fixating the centre for about 30 seconds, then stop it and allow the after-effect to pass off on the stopped disc, we can compare the after-effect with an objective movement in the same direction. If we rotate the disc in the same direction as the after-effect and about the same rate as the stimulating movement, the observer will declare at once and emphatically that the comparison-movement is much faster than the after-effect. If we give as comparison-movement a very slow rate of movement, say one rotation in 3—4 minutes, we are told equally immediately and emphatically that the comparison-movement is much too slow. From this it is evident that comparison *is* possible. If we begin with a comparison-movement "decidedly too fast" and gradually go down until it is "decidedly too slow," and then work up in the reverse way, we are able to arrive at a determination of the upper and lower limen of the apparent velocity of an after-effect for a given subject and under given experimental conditions, but such determination must be expected to fluctuate largely.

My arrangements consisted of two similar discs of 20 cm. diameter and bearing 12 alternating black and white sectors; these discs were mounted in such a way that they were visible in front of a uniform background of cardboard. The distance between the two discs was about one metre. The axles on which the discs were mounted passed through openings in the cardboard background behind which the driving apparatus was standing. The observer was seated in front of the arrangement, half-way between the two discs. The disc on the left-hand side of the observer was rotated by hand and with this disc the stimulus-movement (12 revolutions in 30 seconds) was given. The observer fixated the centre of this disc during the 30 seconds of the objective movement. The disc was then stopped and the observer continued his fixation of the stationary disc, on which he allowed the after-effect to pass off. During all this time the right-hand disc was hidden from the observer by a screen. When the after-effect was finished, the screen was removed from the right-hand, or comparison-disc, and placed before the left-hand, or stimulation-disc. The comparison-disc was rotated uniformly in the same direction as the after-effect at various slow rates, moved by an electric motor and a speed-reducing set of pulleys. The subject had to compare the slow objective movement of the comparison-disc with the after-effect that had passed on the stopped stimulus-disc.

Very exact and methodical results could not be aimed at by this apparatus. First the graduation of the velocity was only possible in big jumps, and it also varied at different hours of the day, probably owing to variation in the pressure of the electric current driving the motor, so that exactly the same rate of rotation could not always be obtained again. The greatest difficulty was, however, that any change in the velocity required a rearrangement of the apparatus. A great amount of time was thus wasted and I could not get many observers for such a lengthy experiment.

The stimulus movement was of a uniform rate and uniform duration, viz. 12 revolutions in 30 seconds (*i.e.* the disc had an angular velocity of 144° per sec.).

Observer: Dr Spearman. Comparison Movement		Judgment (3 experiments each)
Duration of 1 revolution	Angular movement of disc in 1 sec.	(With reference to comparison movement)
70 seconds	5° 8′ 34″	Too fast; do.; do.
110 „	3° 16′ 22″	Slightly faster; faster; faster.
200 „	1° 48′ 0″	Very nearly the same; very nearly the same or slightly faster; slightly faster.
624 „	0° 34′ 39″	A little too slow; too slow; distinctly too slow.
372 „	0° 58′ 4″	Undecided; slightly slower; do.
228 „	1° 34′ 39″	Very slightly faster; nearly the same; do.

The velocity of the after-effect is thus equal to one revolution between 228 and 372 seconds, or an angular movement of the disc between 0° 58′ 4″ and 1° 34′ 39″.

Observer: Miss Broughton. Comparison Movement		Judgment
Duration of 1 revolution	Angular movement of disc in 1 sec.	(With reference to comparison movement)
720 seconds	0° 30′ 0″	Much too slow; do.
420 "	0° 51′ 26″	Still too slow; very nearly the same.
240 "	1° 30′ 0″	Slightly too fast; about the same.
180 "	2° 0′ 0″	A little too fast; not certain; a little too fast.
132 "	2° 43′ 38″	Very near, if anything a little too fast; very near it; very little too fast.
114 "	3° 9′ 28″	Still a little too fast; about the same.
90 "	4° 0′ 0″	About the same; do.; a little too fast.
54 "	6° 40′ 0″	Too fast; a little too fast.
42 "	8° 51′ 26″	Decidedly too fast.

In this case the judgments do not seem very decided over a considerable area; but the limen appears to lie between 420 and 240 seconds, or an angular movement of the disc between 0° 51′ 26″ and 1° 30′ 0″.

Having investigated all the chief points respecting the velocity, vividness and duration of the after-effect, we may now turn to the question answered by

Experiment 17: *To ascertain whether all colours produce an after-effect.*

The results of this experiment show that they do. I prepared four black discs and painted a differently coloured spiral on each of them. One had a red spiral, one a yellow, one a green, and the fourth a blue. I then rotated these discs around their centres. *All of the colours produced an after-effect.*

Experiment 18: *To determine whether any of the elementary colours produces a more marked effect than another one.*

I attempted to solve this problem by using black discs, on each of which I painted two spirals, of different colours, taking care to choose colours of nearly the same brightness. One spiral was clockwise and the other anticlockwise; and, on turning the disc, one appeared to move centripetally and the other centrifugally. The result was always the same, viz. that although an apparent backwards movement of the disc could often be detected, yet no inward or outward movement of any spiral was observed even when the observer's attention had been fixed on one spiral alone during the stimulation. Hence we may conclude that *all colours, if of the same brightness, produce the same after-effect.*

These experiments raised a very interesting and important point which I approached in

Experiment 19: *To ascertain whether alternating different colours of the same brightness produce an after-effect, or whether difference of brightness is essential.*

The solution of this problem offered some difficulty. I experimented first with a disc having alternating blue and red sectors (10° each). With the bright illumination of a 100 c.p. Osram lamp the red was distinctly brighter, whilst in dim light the blue was the brighter colour. I thought that if I gradually diminished the illumination, introducing a resistance in the lamp-circuit by means of a rheostat, I could arrive at a point where the two colours were of equal brightness. The Purkinje effect was, however, so disturbing a factor that I was never able to get a satisfactory equation.

I therefore abandoned this experimentation and tried to satisfy the necessary conditions by using transmitted as well as reflected light. I took the frame of a chromotrope (see description p. 32). Into this frame I fixed a disc of dark blue glass with a piece of white paper pasted on the back so that by reflected light the disc appeared dark blue. On the front I pasted six sectors, of 30°, of light yellow glazed paper alternating with equally large sectors of the blue glass. The front of this was covered by a disc of plain glass, so as to give the whole a uniform surface. The chromotrope frame was fixed into a screen of stout cardboard, rigidly held in position by clamps and supports. The sectorial glass disc was illuminated from behind by a 200 c.p. Osram lamp placed in a box only open towards the disc. The intensity of the light of the lamp could be varied by a rheostat. The light passed through a filter of blue gelatine. The front of the disc was illuminated by a 16 c.p. carbon-filament lamp, placed at a distance of about six metres at such a height and in such a position that the observer, seated in front of the apparatus, did not cast a shadow on the disc. In front of this 16 c.p. lamp, two sheets of ground glass were placed, and the intensity of its light could also be regulated by a rheostat.

During these experiments I found that great differences in brightness were sensed immediately. The "more" or "less," the "brighter" or "darker" were given immediately with the perception. But with smaller differences in brightness, much deliberation and weighing was necessary, and in hardly any case could the judgment be given with absolute certainty. To overcome this difficulty, I made use of the episkotister; but then I found that an equation made when looking through the episkotister no longer held good when looking at the disc directly. With the episkotister the blue always appeared brighter than if viewed directly and the yellow less bright. Therefore a judgment of equality arrived at when looking directly at the disc showed a distinctly greater luminosity of the blue when viewed through the episkotister; conversely, after an equation had been made whilst looking through the episkotister, a direct view of the disc gave at once the impression of "yellow brighter." I also found that the relative luminosity of the two colours varied with the distance from which the disc was viewed. The blue became brighter when the observer approached the disc, whilst the luminosity of the yellow increased with the distance. In the experiments all four modes of viewing the disc were employed and all the observations were made in two series, one beginning with the "yellow decidedly brighter than the blue," and the other in the opposite direction. Prof. Read and myself acted as observers. The tables on pp. 65 and 66 give the results. In the first column are given the respective illuminations by indicating the resistances in ohms introduced in the circuit for the blue transmitted and the yellow reflected lights. The illumination decreases, of course, as the resistance increases. The second and fourth columns give the judgments about the relative brightness, and the third and fifth columns the duration and nature of the after-effect. The four methods of viewing are indicated by the letters *A*—*D*, viz. *A* close and directly; *B* close through episkotister; *C* from distance and directly; *D* from distance and through episkotister. The experiments in the second and third columns were in the descending order in the table, and those of the fourth and fifth in the ascending one, as indicated by the arrows.

To meet the objections that blue and yellow were complementary colours, or that blue was a cold and yellow a warm colour, I constructed another disc, replacing the yellow sectors of the previous one by green sectors. I made equations of the two colours as before, not only when looking at them directly, but also when looking at them through the episkotister. The results obtained by Professor Read as well as by myself were essentially the same as before.

We see that in these experiments there was no cessation of the after-effect and no diminution that could in any way be attributed to

Observer: A. W.

Illumination regulated by resistances: yellow	blue	Judgment about relative brightness and method of viewing	Duration and Nature of After-effect	Judgment about relative brightness and method of viewing	Duration and Nature of After-effect
0 ohms	150	*A.* Yellow much brighter. *B.* Yellow distinctly brighter. *C.* *D.*	Very marked. 13, 13, 16, 15, 13 sec. Average 14 sec.	*A.* Yellow much brighter. *B.* Do. *C.* Do. *D.* Do.	Very marked. 13, 14, 14, 14, 15 sec. Average 14 sec.
25 ,,	125	*A.* Yellow still brighter. *B.* Nearly equal. *C.* *D.* Yellow brighter.	Very marked. 14, 14, 15, 16 sec. Marked 13 sec. Average 14·4 sec.	*A.* Yellow much brighter. *B.* Good match. *C.* Yellow much brighter. *D.* Good match.	Marked. 12, 13, 17 sec. Well marked. 14, 17 sec. Average 14·6 sec.
50 ,,	100	*A.* Good match. *B.* Do. *C.* Do. *D.*	Very marked. 17, 14, 16, 16, 18 sec. Average 16·2 sec.	*A.* Yellow brighter. *B.* Blue slightly brighter. *C.* Yellow distinctly brighter. *D.* Equally bright.	Marked. 16, 19, 17, 14, 14 sec. Average 16 sec.
75 ,,	75	*A.* Good match. *B.* Yellow slightly darker. *C.* *D.*	Very marked. 17, 17, 17, 14, 18 sec. Average 16·6 sec.	*A.* Yellow slightly brighter. *B.* Blue brighter. *C.* Yellow brighter. *D.* Blue a trifle brighter.	Very marked. 20, 20, 17, 18, 18 sec. Average 18·6 sec.
100 ,,	50	*A.* Blue a little brighter. *B.* Blue distinctly brighter. *C.* *D.*	Very marked. 16, 15, 19, 17 sec. Marked only. 14 sec. Average 16·2 sec.	*A.* Good match. *B.* Yellow possibly a little brighter. *C.* Blue distinctly brighter. *D.* Do.	Very marked. 18, 18, 20, 18, 18 sec. Average 18·4 sec.
125 ,,	25	*A.* Blue brighter. *B.* Blue much brighter. *C.* *D.*	Very marked. 18, 21, 19, 19 sec. Marked 17 sec. Average 18·8 sec.	*A.* Blue brighter. *B.* Blue much brighter. *C.* Blue a little brighter. *D.* Blue much brighter.	Very marked. 20, 20, 19, 24 sec. Marked 17 sec. Average 20 sec.
150 ,,	0	*A.* Blue distinctly brighter. *B.* Do. *C.* *D.*	Very marked. 16, 23, 23, 24, 19 sec. Average 21 sec.	*A.* Blue distinctly brighter. *B.* Do. *C.* Do. *D.* Do.	Very marked. 18, 18, 16, 20, 18 sec. Average 18 sec.

Observer: Prof. Read.

Illumination regulated by resistances: yellow / blue	Judgment about relative brightness and method of viewing ↓	Duration and Nature of After-effect	Judgment about relative brightness and method of viewing ↑	Duration and Nature of After-effect
0 ohms 150	*A.* Yellow distinctly brighter. *B.* Yellow brighter.	Good 18 sec. Not quite so good 16 sec. Fair 14 sec. Average 16 sec.	*A.* Yellow much brighter. *B.* Do.	Only fair 13 sec. Much weaker 11 sec. Not so well marked 14 sec. Average 12·7 sec.
25 ,, 125	*A.* Yellow brighter. *B.* Still yellow brighter.	Fair 18 sec. ,, 16 ,, Hardly as good as before but persistent 20 sec. Average 18 sec.	*A.* Yellow much brighter. *B.* Yellow markedly brighter.	Well marked 21 sec. Fair only 20 sec. Fair to well 13 sec. Average 18 sec.
50 ,, 100	*A.* Yellow not much brighter. *B.* Both equal.	Good 22 sec. Not quite so good 22 sec. Fair 16 sec. Average 20 sec.	*A.* Yellow much brighter. *B.* Yellow a little more luminous.	Well marked 20 sec. Not so strong. Fair 15 sec. Fair 14 sec. Average 16·3 sec.
75 ,, 75	*A.* Yellow a little brighter. *B.* Yellow darker.	Not very strong, below medium 12 sec. Also below medium 12 sec. Fair 14 sec. Average 12·7 sec.	*A.* Yellow decidedly brighter. *B.* Blue still a little brighter.	Well marked 18 sec. Good, well marked 22 sec. Not quite so good. Fair 23 sec. Average 21 sec.
100 ,, 50	*A.* A very near match. *B.* Blue brighter.	Rather feeble 11 sec. Feeble 9 sec. ,, 8 ,, Average 9·3 sec.	*A.* Yellow brighter. *B.* Blue brighter.	Much better 21 sec. Well marked 18 sec. Not quite so marked 17 sec. Average 18·7 sec.
125 ,, 25	*A.* Blue brighter. *B.* Blue decidedly brighter.	Well at beginning 9 sec. Distinctly feeble 8 sec. Feeble 10 sec. Average 9 sec.	*A.* Very nearly a match. *B.* Blue brighter.	About the same 15 sec. Not very strong 13 sec. A little better 12 sec. Average 13·3 sec.
150 ,, 0	*A.* Blue brighter. *B.* Do.	Medium 15 sec. Medium 13 sec. Feeble 10 sec. Average 12·7 sec.	*A.* Blue brighter. *B.* Do.	Fair 15 sec. ,, 17 ,, Not quite so strong 15 sec. Average 15·7 sec.

N.B. Towards the close of each sitting the observer complained of being tired, nearly falling asleep.

the equality of brightness of the two colours. It follows then, that *in the case of different colours difference of brightness is not essential for the production of the after-effect; colours of the same brightness will produce it also.*

The question I attempted to solve by

Experiment 20 was: *Does movement perceived by means of the rods, as well as that perceived by the cones, give rise to an after-effect?*

If we accept v. Kries' theory that the rods are the apparatus for vision in dim light and the cones for vision in bright light, the question resolves itself into this: Is the after-effect produced with dark-adapted eyes and low illumination as well as with light-adapted eyes? After four hours sleep in a dark room I experimented with black discs, on each of which were drawn spirals in red, yellow, green and blue colours respectively. The yellow and green spirals could be distinguished in the very dim light of the bye-pass of an incandescent gas-burner as being somewhat brighter than the black background, but colour not perceptible. The movement of these spirals was perceptible when the discs were rotated by means of a small colour-wheel, and an after-effect was produced in each instance. This after-effect was marked enough, but of very short duration. The red and blue spirals did not show sufficient relief from the black background—the red none at all and the blue too slight—to produce a clear inward or outward movement of the spirals, hence the after-effect was also absent in these two instances. No special experiments were needed to show an after-effect with light-adapted eyes. Hence we may conclude that *vision by rods as well as by cones is receptive to the after-effect.*

This latter point might also have been attacked by observation in peripheral vision, but I treat of this in the next experiment.

Experiment 21 (A and B): *Comparison of the after-effects in central, paracentral, and peripheral fields of vision, and of their influence on non-stimulated parts of the retina.*

A. I threw the image of slide B (Fig. 6, p. 33) on the screen by means of a lantern. In front of the slide I fitted an arrangement into which I could drop screens to shut out one or more of the three fields. I stimulated with any one of the three fields for 30 seconds, and observed the after-effect in the same field alone or together with one or both of the other fields.

I. *Central field alone stimulated.*

(*a*) After-effect observed on *Central* field alone.

Marked	12 sec.
„	13 „
„	12 „
„	14 „
„	14 „

(*b*) After-effect on *Central and Paracentral* fields.

Central marked 11 sec.	Paracentral faint, movement in opposite direction to central for about 3 sec.
„ „ 12 „	Do. Do. 3 „
„ „ 10 „	Do. Do. 2–3 „
„ „ 11 „	Do. Do. 2–3 „
„ „ 12 „	Do. Do. 4 „

(*c*) After-effect on *Central and Peripheral* fields.

Central faint 7 sec.	Peripheral no appreciable effect.
„ a little better 9·5 „	Do. Do.
„ marked 9 „	Peripheral a faint movement for about 1 sec. opposed to central in direction.
„ „ 13 „	Do. Do.
„ „ 13 „	Do. Do.

(*d*) After-effect on *Central and Paracentral and Peripheral* fields together.

Central marked 13 sec.	Paracentral faint opposite movement.	Peripheral no effect.
„ „ 12 „	Do. Do.	„ „
„ „ 11·5 „	Do. Do.	„ „
„ „ 13 „	Do. Do.	„ „
„ „ 14 „	Do. Do.	„ „

II. *Paracentral field alone stimulated.*

(*a*) After-effect on *Paracentral* field alone.

Marked	11·5 sec.
„	11 „
„	11 „
„	12 „
„	12 „

(*b*) After-effect on *Paracentral and Central* fields.

Paracentral.	*Central.*
Marked 8 sec.	A little effect, opposed to that on paracentral field.
„ 12 „	Very little, but later seemed to be pulled with paracentral.
„ 11 „	Do. Do. Do.
„ 14 „	Afterwards seemed to move with paracentral.
„ 11 „	Afterwards seemed to move with paracentral. A little more, yet still very faint.

(*c*) After-effect on *Paracentral and Peripheral* fields.

Paracentral.	*Peripheral.*
Fairly marked 7·5 sec.	No after-effect.
„ „ 10 „	Do.
Very „ 12 „	Do.
„ „ 13 „	Do.
„ „ 13 „	Do.

(*d*) After-effect on *Paracentral, Central and Peripheral* fields together.

Paracentral.		*Central.*			*Peripheral.*
Very marked	13 sec.	Fairly marked, not so long, direction opposed to paracentral.			No effect.
Do.	14 ,,	Well marked, in same way.			Do.
Do.	12 ,,	Fairly	Do.	Do.	Do.
Do.	13 ,,	Faintly	Do.	Do.	Do.
Do.	15 ,,	Do.	Do.	Do.	Do.

III. *Peripheral field alone stimulated.*

(*a*) After-effect on *Peripheral* alone.

Very marked at beginning,	rapidly diminishing, total	8 sec.
Do.	Do.	9 ,,
Do.	Do.	8 ,,
Do.	Do.	7 ,,
Do.	Do.	9 ,,

(*b*) After-effect on *Peripheral and Paracentral* fields.

Peripheral.		*Paracentral.*
Marked	7·5 sec.	More marked, in opposite direction and appeared to last longer.
Do.	10 ,,	Equally well marked, in opposite direction, lasted equally long.
Very marked	9·5 ,,	Nearly as well marked, in opposite direction, not quite so long duration.
Do.	9 ,,	Do.
Do.	8·5 ,,	Not quite so well marked, and not quite so long.

(*c*) After-effect on *Peripheral and Central* fields together.

Peripheral.		*Central.*
Marked	8·5 sec.	Very faint and short, in opposite direction.
,,	9·5 ,,	Do. Do.
,,	9·5 ,,	Very faint and short, in opposite direction. Black paracentral field also seemed to move in opposite direction to peripheral, and more so than central.
,,	9·5 ,,	Very faint and short, in opposite direction.
,,	8·5 ,,	Do. Do.

(*d*) After-effect on *Peripheral and Paracentral and Central* fields together.

Peripheral.		*Paracentral and Central.*	
Very marked indeed	10 sec.	Less marked, in opposite direction to peripheral, lasted not quite so long.	
Do.	10 ,,	Do.	Do.
Do.	10 ,,	Do.	Do.
Do.	11 ,,	Do.	Do.
Do.	12 ,,	Do.	Do.

Comparing the after-effects in the central, the paracentral and the peripheral fields due to the stimulation of the respective fields, we find that *the duration of the after-effect diminishes as we move from the centre towards the periphery.* But there is another remarkable difference which, although not explicitly expressed in the above tables, I have no hesitation in affirming, since the results of numerous frequently repeated observations bear me out, viz. *In the central field, the after-effect is very marked and distinct, and gradually and evenly diminishes. In the peripheral field, it sets in with more vigour, appears to be rushing more powerfully during the first moment, but very rapidly diminishes and vanishes below the threshold.* It is, so to speak, as if the same "quantity" of after-effect was got rid of in a shorter period and more abruptly. In this too *the after-effect in the peripheral field greatly resembles the after-effect with dark-adapted eyes.* I have made this observation not only when carrying out Experiment 20, but also during the preliminary trials for Experiment 19. When working with the disc with alternating red and blue sectors, I diminished the light in order to arrive at an equation of brightness between the red and the blue. The after-effects of the stimulations in dim light were distinctly different from those in bright light. This was invariably the case, and there could be no mistake about the wholly different character of the two after-effects. We may draw from these facts the further conclusion, viz. that *the after-effect due to the stimulation of the rods is different in character from that obtained by the stimulation of the cones. The former sets in more powerfully, but diminishes more rapidly than the latter which, however, is more distinct and diminishes more gradually, and lasts longer.*

As to the influence of stimulated on non-stimulated areas, I found that *the after-effect in a non-stimulated area is of opposite direction to that of the stimulated area.* When the central field is stimulated the paracentral is more influenced than the peripheral, so that we may say that *the influence of a more central on a more peripheral area decreases towards the periphery.* I found also that the stimulation of the paracentral area affects the central, but not the peripheral area, and that both paracentral and central fields are influenced by a stimulus of the peripheral field, the former of course more powerfully on account of its greater proximity. These facts are comprised in the following statements:

(1) *If a retinal area is stimulated by movement, the more central adjacent area is more affected in the after-effect than the more peripheral adjacent one.*

(2) *The more peripheral a stimulated area is, the more powerfully it affects the centrally adjacent area; the latter area is more affected than the still more central one.*

B. I may mention here an observation which I made at an early stage of this investigation. I used my "apparatus of moving fields." Both fields moved in the same direction with uniform velocity. The surrounding field consisted of black and white stripes like the moving fields. In the centre of the window was a fixation-point. The time of stimulation was 30 seconds. After stimulation, the eyes were closed and shaded by the hand or turned towards a neutral surface such as the wall or ceiling of the laboratory. The after-effect of the objective movement was indicated by a "molecular streaming" in the opposite direction, which appeared to have died away by the time the negative after-image of the surrounding field had developed. This negative after-image consisted of alternating dark and bright lines surrounding the empty window. No "molecular movement" could be detected any longer in the space of the window, yet the dark and bright lines of the surrounding field seemed to move at a rapid rate in an opposite direction to the foregoing molecular streaming. This can hardly be regarded as a case of contrast, since no streaming or movement could be discovered in the centre of the visual field. It must, however, be borne in mind that, as we have seen in Experiment 1, the after-effect is better perceived in an objective field than in a subjective one, and perhaps the after-image of the dark and bright lines may be considered more of the nature of an objective field than of a subjective one.

I may record here an observation which appears to me of sufficient interest. I used a kymograph-drum with alternating black and white stripes 1 cm. wide. After a stimulation of 30—60 seconds the eyes were closed and shaded by the hands. As I became conscious of the "Eigenlicht" I noticed the after-effect as a streaming in the opposite direction to the objective movement across the centre of the visual field, and on both sides a lateral streaming in a direction opposed to the central streaming. The length of the central streaming was evidently determined by the portion of the retina stimulated. This central stream broadened out towards the end and appeared to divide, each half swerving round outwards on to its side and flowing back as the lateral streams. They appeared to turn again inwards at the other end and run back into the central stream. Mr McDougall made exactly the same observation.

These results, especially those of Experiment 21, confirm Szily's theory, advanced in explanation of the after-effect observed by him when the whole visual field was filled by an objective movement (*vide*

p. 21). As Szily's observation is opposed to Aitken's (p. 8), I made a point of examining the question also in

Experiment 22 (A and B): *To ascertain how the after-effect is affected if the whole visual field is filled by an objective movement.*

A. I used a large piece of printed calico with alternating black and white lines, 5 mm. wide. The ends were sewn together so as to form an endless band. This hung over a wooden roller fitted to the wall of the laboratory and was pulled down by another heavy wooden roller, lying in the lower loop. In this way a large surface was formed, 180 cm. broad and 110 cm. high, covered with horizontal lines. A piece of wire was bent over the top and ended in front at the centre of the field, where it served as a fixation-point. The observer was standing close in front of the apparatus fixating the end-point of the wire, whilst the field was moved by the operator upwards or downwards. Numerous experiments were made, the time of stimulation varying from 30 to 60 seconds. A few were made with 2—3 minutes stimulation. Dr Spearman, Prof. Read and myself acted as observers. In all cases there was a total absence of any after-effect.

It must, however, be admitted that the observation of any after-effect was rendered somewhat difficult by the fact that, owing to the very large surface, the material could not be kept evenly stretched, and when the apparatus was stopped, there was frequently some movement of the surface.

B. To overcome this difficulty, I used a screen of ground glass 80 cm. square. On this I threw from behind, by means of a lantern, an image of vertical rods which could be made to move from right to left or *vice versâ*. The shadow of these rods on the screen was each 2 cm. wide and the bright interstices 1 cm. wide. In the centre of the field a small piece of paper was pasted to serve as a fixation-point. The observer stood in front of the screen, with his face close to it, fixating the mark. The stimulation lasted from 30 seconds to 3 minutes. Professor Read, Dr Spearman and myself again acted as observers. *Generally there was a total absence of an after-effect.* Sometimes a very feeble and transient after-effect, opposed in direction to the objective movement, was noticed, especially in the periphery; but never an after-effect in the same direction as the objective movement. These observations agree with Aitken's and Budde's rather than with Szily's; but still they are quite in harmony with the latter's theory.

Having examined the after-effect of a very large moving field, we may investigate in

EXPERIMENT 23 (A—C): *The after-effect of movements confined to very small areas.*

These experiments were undertaken for the purpose of examining Exner's statement, that an after-effect is only produced by moving surfaces of some size.

A. A spiral disc was so arranged behind a small bi-convex lens in front of the observer that, looking with one eye only, the inverted image of the disc exactly filled the small lens. The spiral was then turned for 30 seconds and it was found that there was a very marked after-effect which, however, lasted only for a very short period. The distance of the lens from the eye was 45 cm. and the diameter of the image 15 mm., *i.e.* the image subtended an angle of less than 2°.

B. I repeated the above experiment without the lens, looking at the disc directly from a distance of 6 m. The diameter of the disc was 20 cm., *i.e.*, as before, the image subtended an angle of nearly 2°. The result was exactly the same as in the previous experiment.

C. A thin white thread about 50 cm. long and tied into an endless band passed over two horizontal pulleys. When one of these was turned by hand, the thread moved upwards or downwards. With black paint I marked off on the thread alternating black and white segments about 2 mm. long. Into the loop I passed a screen of cardboard so that one part of the thread was in front of the screen and the other part moving in the opposite direction was hidden by it. A pencil-mark on the screen behind the thread serves as a fixation-point. The length of thread visible was about 25 cm.; its thickness, measured under the microscope, ·175 mm.; distance of observer 60 cm.; period of stimulation 30 sec. Under these conditions the after-effect was very marked indeed and lasted over 5 sec. When another screen with a small window was put in front, so that only a length of 1 cm. of the thread was visible, the after-effect was still marked, although less than before. The angle subtending the thickness of the thread was only 0° 1′.

These results contradict Exner's statement, since they show clearly that *movements of small stripes whose breadth subtends an angle of about 1′ also produce an after-effect.*

This induced me to examine another statement made by Professor Exner, viz. that the after-effects of movements in opposite directions, if confined to small closely adjacent areas, neutralize each other.

EXPERIMENT 24 (A and B): *To ascertain how the after-effects of opposite movements which are confined to small closely adjacent areas influence one another.*

A. I placed before the "apparatus of moving fields" a screen with a slit 1·5 cm. wide, so that a strip of ·5 cm. of each field was visible, the gap between the two fields being also ·5 cm. One field was moving upwards and the other downwards with the same velocity. A stimulation of 20 seconds produced a marked after-effect.

B. The arrangement used was similar to that described in Expt. 23 C, but two threads passed over the two pulleys and one of the threads was crossed. The crossing-point of this thread was kept close to one of the pulleys by means of another pulley, so that the two threads moved in opposite directions in front of the screen. A point between the two threads was fixated. When the distance between them was 2 mm. the after-effect was very marked and lasted about 3—4 sec. When the distance was reduced to 1 mm. the after-effect was still quite distinct, though less than before and lasted for 1—2 sec.

The results of these experiments show that with *small areas the width of which are subtended by an angle of about 1′, even if the movements in such areas are of opposite directions and the areas be close together, the after-effects do not neutralize one another; they coexist, but they are weaker and of shorter duration than if the movements were in the same direction.*

Having completed the consideration of the spatial characters and influences of the after-effect, we may now turn to its temporal characters.

A problem of this nature is examined in

EXPERIMENT 25: *To determine whether all influence of an objective movement has passed off with the termination of the visible after-effect.*

I experimented with the chromotrope slide A, the image of which was thrown on the screen. With considerable intervals of rest I noted the duration of the after-effect on long exposures of 120 seconds, and of short exposures of 20 seconds.

Exposure of	120 sec.	yielded an average after-effect of	20 sec.
„	20 „	„ „	16 „

After these preliminary experiments were finished, I performed the main experiment. This consisted in a long exposure to a centripetal movement (which we may designate by +), observation of its after-effect, followed by a rest and then by a short exposure to a centrifugal movement (which we may call −). The following are the results:

120 sec. exposure to + movement	yields	20 sec. −	after-effect.
60 „ rest			
20 „ exposure to −	„	7 „ +	„
10 „ rest			
20 „ exposure to −	„	8 „ +	„

A repetition of this experiment with the direction of the respective movements reversed yielded analogous results.

Thus we see that even after two minutes the after-effect of the first long exposure, in spite of having been counteracted by movements in the opposite direction, still manifests itself, although it has long ceased to exist for consciousness. It may therefore be stated that *when the after-effect of a stimulation has passed away for consciousness a disposition remains for some time that makes itself felt by shortening subsequent after-effects of opposite sign.*

I referred on page 27 to the fact that if each eye was stimulated separately, the movements being in opposite directions, the two after-effects tend to neutralize each other. We have just seen the influence of a preceding longer movement upon the after-effect of succeeding shorter ones. I examined in

Experiment 26: *The influence of an immediately succeeding shorter movement upon the after-effect of a preceding longer one.*

I again used chromotrope slide A. By preliminary experiments, made at intervals, I obtained the following average durations of the after-effect.

Stimulation for	20 sec.	yielded	an after-effect of	17 sec.
„	10 „	„	„	7 „
„	5 „	„	„	2—3 „
„	2 „	„	no appreciable after-effect.	

The main experiments were as follows. I stimulated by a movement in one direction and succeeded this immediately by a shorter movement in the opposite direction, noting the effect.

(1) Stimulation by + movement for 20 sec. followed immediately by
„ − „ 10 „
After-effect nil.

(2) Stimulation by + movement for 20 sec. followed immediately by
„ − „ 5 „

There was no after-effect for two seconds. Then a – after-effect, *i.e.* one due to the first and longer stimulus, set in and lasted for 10 seconds.

The two after-effects seem to be superposed, in fact there appears to be an *interference*, analogous to the physical principle of interference, as met with in light and sound. If sound-waves of equal amplitude, proceeding from two different sources, meet in such a way that a condensation of the one coincides with a rarefaction of the other, then both neutralize one another, and the air at that point is at average density, and, according to Lord Rayleigh's definition, we have interference and no sound. The same thing occurs when two pencils of similar monochromatic light cross one another under certain conditions. Then in certain parts where the undulations are in opposite phases, they neutralize one another and the result is a dark band. We may represent the experiment and its results graphically as in the accompanying diagram (Fig. 10).

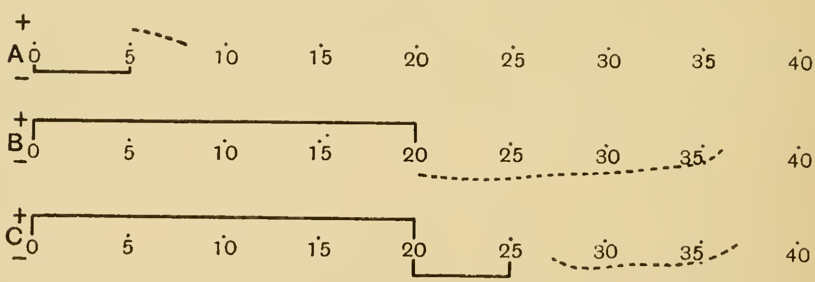

Fig. 10.

The time is marked off in seconds, in a straight line. Movement in one given direction we may call positive, and allocate to it the position above the line. Then movement in the opposite direction would be negative and represented by a curve below the line. A drawn-out curve represents objective movement, while apparent movement is denoted by a dotted curve.

A shows a stimulation of 5 seconds duration, and *B* one of 20 seconds duration, constituting the preliminary experiments. *C* represents a stimulation in the + direction of 20 seconds, immediately followed by a stimulation in the opposite or – direction lasting 5 seconds. There is a quiescent period of about 2 seconds and then an apparent movement in the – direction sets in and lasts for about 10 seconds.

From the considerations already stated which induced me to perform this experiment and from the results thereby obtained, we may conclude that *when several objective movements stimulate the same retinal area simultaneously or successively, an effect is produced which is the resultant of the after-effects of the various movements.* Besides this conclusion several very important theoretical inferences can be drawn from this experiment; but we will treat of these later.

A kindred question is examined by

EXPERIMENT 27: *To ascertain how the after-effect behaves in a continuous series of alternating movements of opposite sign.*

I used the chromotrope slide A (*vide* p. 33) which was thrown on the screen. The time of stimulation was 20 seconds. A metronome was beating seconds, serving both to count the time of the stimulation and to regulate the rate of the stimulating movement, one turn of the handle of the chromotrope being completed each second. A centripetal (+) movement was given first and the duration of the after-effect measured by means of a stop-watch; then followed a centrifugal (−) movement and again the duration of the after-effect was noted and so on, + and − alternating with one another. The following are the results of the experiment, the figures representing the duration of the after-effects in seconds.

−16, +12, −12, +12, −12, +12, −10, +10, −10, +9, −12, +10, −9, +10, −10, +9, −9, +8, −7, +7, −7, +7, −7, +8, −7, +7, −6, +6, −6, +5, −4, +6, −5, +5, −5, +5, −5, +5, −5, +5, −4, +6, −4, +4, −3, +6, −4, +5, −5, +4, −4, +5, −4, +5, −4, +4, −4, +5, −4, +4, −3, +4, −4, +4, −4, +4, −3, +4, −3, +3, −4, +4, −3, +3, −3, +5, −4, +3, −3, +4, −3, +3, −3, +3, −2, +3, −3, +3, −3, +3, −3, +4.

This experiment shows that *the duration of the after-effect is rapidly decreased by successive stimulations of alternating opposite sign, i.e. that fatigue is set up.* However even after about 50 such pairs of stimulations the after-effect is not annihilated, but only reduced to a quarter of its original duration. As there is hardly any diminution during the last 20 stimulations this probably indicates that the minimum of the duration of the after-effect has been reached[1].

[1] Later experiments show that if the series is continued long enough, say $1\frac{1}{2}$ to 2 hours, the after-effect frequently becomes zero.

This last experiment suggested immediately the following

Experiment 28: *If fatigue is set up by a continuous series of alternating movements of opposite sign in any given direction, how does it influence the after-effect of a movement at right angles to that of the fatigue-producing-series?*

I used a projection-lantern by the reflecting method. With this method, the lantern is fitted with a condenser consisting of two lenses, one (a) of which remains perpendicular in front of the source of light, whilst the other (b) can be lifted into a horizontal position and kept there by a mirror (c) forming an angle of 45° with each condenser-lens (Fig. 11). By this means the rays passing through the perpendicular condenser-lens fall on the mirror, are reflected upwards, and pass through the horizontal lens, issuing as parallel vertical rays. The

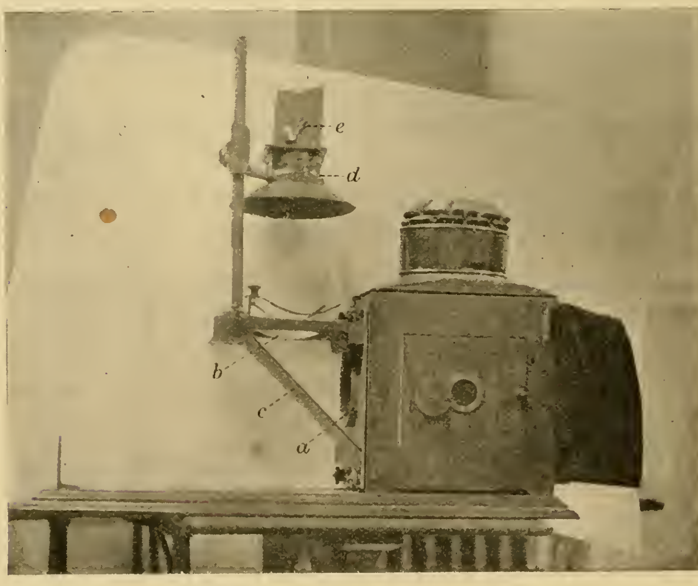

Fig. 11. Demonstration Lantern arranged for Expt. 28

projection-lens (d) is vertically above this arrangement and is fitted with a reflecting prism (e) which turns the rays again into a horizontal position on to a screen. The slide to be projected on to the screen is simply laid on the horizontal condenser-lens (b). I cut a strip from a French sun-blind, 1 metre long and 10 cm. wide, consisting of thin cylindrical wooden rods, 2 mm. thick. Their length formed the width of the strip. The distance between the rods was 1 mm. This strip I formed into an endless band, and supported it by two drums so that one side passed closely over the horizontal condenser-lens. It could be moved by turning one of the drums slowly by hand. The experiment was performed in the dark room. The whole apparatus just described was placed on a low table and in such a position that the projecting lens of the lantern was at an equal distance from two adjacent walls at right angles to each other. One screen was fixed straight in front of the lantern and another on the adjacent wall opposite the projection-lens. Thus the image of the system of rods thrown on the screen in front of the lantern consisted of alternating dark and bright *vertical stripes that moved in a horizontal direction.* When the reflecting prism fixed to the projection-lens was turned through an angle of 90° the image of the system of rods was thrown on the other screen and consisted of *horizontal stripes that moved in a vertical direction.* In the centre of each screen a small circular disc of coloured paper was pasted to serve as a fixation-point. A metronome, beating seconds, was used to measure the duration of the stimulation and also to facilitate the regular movement of the hand turning the drum. The time of stimulation lasted 20 seconds. The movement was alternately from left to right and from right to left. A stop-watch was used to measure the duration of the after-effect. Now and then a series of such alternating movements, each 20 seconds, were inserted without allowing the after-effect to develop. This was done in order to shorten the whole experiment. These series are indicated in the report. Objective movement from left to right is called +, and from right to left −. The figures give the duration of the after-effect in seconds.

(Horizontal movement.) + 8, − 10, + 8, − 7, + 8, − 7, + 10, − 8, + 7, − 7, + 7, − ?, + 6, − 8, + 7, − 8, + 7, − 10, + 9, − 7, (10 alternating movements), + 6, − 6, + 6, − 5, + 5, − 6, + 4, − 7, + 4, − 6, + 5, − 5, + 5, − 6, + 4, − 5, + 4, − 5, + 4, (10 alternating movements), − 4, + 4, − 4, + 5, − ?, + 6, − ?, + 6, − 5, + 3, − 4, + 5, − 4, + 4, − 4, + 3, − 4, + 3, − 3, + 3, − 2, + 3, − 4, + 3, − 4, (10 alternating movements), + 2, − 2, + 2·5, − 2, + 2, − 2, + 1·5, − 2, + 3, − 3, + 3, − 4, + 2·5, − 2, + 3, − 4, + 1·5, − 0, + 2, − 1.

Change to second screen (vertical movement). Up 6, down 5; up 9, down ?; up 6, down 5; up 6, down 5.

Professor Read and Mr Flügel confirmed this experiment in every detail, also corroborating the result of the previous experiment, namely that the duration of successive opposite after-effects gradually diminishes. It was further noticed in the present experiment that the intensity or vividness of the after-effect also suffered. When we turned to the second screen and observed the after-effects of upward and downward movements, the duration of the after-effects at once increased, and also became more vivid.

This experiment then, besides confirming the result of the previous one, also shows that *the after-effects of movements at right angles to the previous ones are only very slightly affected if at all.*

The facts established experimentally by the last two demonstrations I had already anticipated, from the result of Experiment 25 (p. 74).

Another point of great theoretical interest is examined in

Experiment 29: *To ascertain whether the fatigue produced by a continuous series of movements, alternating in sign and of a given colour, is maintained with similar movements of other colours.*

The experimental arrangements were essentially the same as described in Experiments 25—27. I used the chromotrope slide B, thrown on the screen by means of a demonstration lantern. The light, however, passed through a filter. For blue, I could not make use of ordinary coloured glass or gelatine, because they transmit so much light from the lower end of the spectrum. I therefore took a 5 % copper ammonium sulphate solution, which, according to Busck[1], does not allow any waves exceeding 511 $\mu\mu$ in length to pass. The solution was contained in a trough placed in front of the chromotrope and the condenser. As a red-light filter, I used a piece of ruby-glass, which, according to my own examination, allowed very little light to pass beyond the F line (*i.e.* shorter than 486 $\mu\mu$).

Stimulation 20 seconds.
\+ = centripetal movement.
\- = centrifugal „

(*Observer:* Professor Read.)

Fatigue produced in red light.

+18, −19, +12, −16, +15, −14, +13·5, −16·5, +14, −?, +12·5, −13, +11·5, −12·5, +10·5, −13·5, +10, −?, +10·5, −17, +14, −15, +7·5, −15·5, +9, −11·5, +9, −15, (10 alternating movements of

[1] Gunni Busck: "Über farbige Lichtfilter." *Zeitschrift für Psychologie und Physiologie der Sinnesorgane*, 1904, Bd. 37, S. 104—111.

20 seconds), + 8, – 14, (20 alternating movements of 10 seconds), + 6, – 13·5, + 9, – 11, (10 alternating movements of 20 seconds), + 9, – 11·5, + 5, – 9.

Effect in blue light.

+ 9, – 16, + 10, – 14, + 8, – 11.

(*Observer:* A. W.)

A. Fatigue produced in red light.

+ 17, – 17, + 13, – 15, + 13, – 13, + 12, – 13, + ?, – 15, + 10, – 11, + 10, – ?, + 10, – 10, + ?, – 11, + 10, – ?, + 10, – 10, + 8, – 10, + 9, – 11, + 9, – 12, (10 alternating movements of 20 seconds each), + 7, – 8, (20 alternating movements of 10 seconds each), + 5, –13, + 6, – 10, (10 alternating movements of 20 seconds each), + 5, – 8.

Effect in blue light.

+ 6, – 9, + 6, – 10, + 7, – 8.

Continued stimulation in red light.

(10 alternating movements of 20 seconds each), + 4, – 9, + 5, – ?, + 6, – 10, + 6, – 9, (10 alternating movements of 20 seconds each), + 4, – 5, + 5, – 9, + 8, – 9, + 5, – 8, + 5, – 9, + 5, – 7, + 4, – 8, + 5, – 7, + 5, – 6, + 4, – 7, + 6, – 7, + 7, – 7, + 4, – 9, + 4, – 8.

Effect in blue light.

+ 8, – 9, + 4, – 8, + 6, – 8, + 4, – 8.

B. Fatigue produced in blue light.

– 13, + 14, – 12, + 12, – 14, + 13, – 12, + 11, – 12, + 10, – 14, + 10, – 12, + 12, – 11, + 9, – 14, + 9, – 12, + 12, – 13, + 11, – 13, + 8, – 10, + 9, – 9, + 7, – 11, + 11, – 10, + 8, – 9, + 8, – 10, + 7, – 8, + 8, – 8, + 7, – 9, + 7, – 9, + 7, – 11, + 12, – 7, + 6, – 10, + 8, – 10, + 7, – 7, + 6, – 8, + 8, – 10, + 7, – 11, + 8, – 9, + 6, – 9, + 6, – 7, + 5, – 7, + 6, – 7, + 4, – 6, + 4, – 5, + 7, – 9, + 5, – 10, + 5, – 11, + 7, – 8, + 7, – 7, + 5, – 10, + 5, – 8, + 6, – 9, + 5, – 6, + 5, – 8, + 7, – 8, + 6, – 9.

Effect in red light.

+ 10, – 7, + 6, – 9, + 7, – 4, + 5, – 4, + 4, – 4.

I also tried the effect with *red* light and with *green* light, with similar result, *i.e.* no increase in the duration or vividness of the after-effect.

The result of this experiment may be thus stated: *Fatigue produced by alternating movements of opposite sign is independent of the colour of the light producing it, i.e. the fatigue is maintained in light of different colour.*

Looking at the figures of the experiment given above, a very curious fact is noticeable, viz. that the average duration of the centrifugal after-effect is decidedly longer (average 2·2 sec.) than that of the centripetal one. This curious fact obtained, in Professor Read's figures as well as in my own, with red as well as blue light. It appears to admit of an easy explanation. During the long continued fixation of the centre of the slide on the screen, the eyes become fatigued, accommodation and convergence cease. In consequence of this want of accommodation the rays are not brought to a focus on the retina, and the image becomes blurred and somewhat enlarged; and, owing to divergence of the visual axes, definite parts of the image fall on disparate parts of the retina, *i.e.* two images of the slide are produced whose inner parts overlap, and these together occupy horizontally a greater portion of the field than the single image when properly focussed. The relaxation is gradual and unconscious, but produces an enlargement of the image which is mistaken for an apparent centrifugal movement. Self-observation, during the experiment, reveals the facts just stated. These tend to intensify or lengthen an apparent centrifugal movement and to counteract or shorten a centripetal one. I confirmed this theory by experiment, throwing the slide on the screen without movement, and fixating the centre as before; in a few seconds an apparent enlargement took place.

N.B. On the termination of this investigation I performed the following experiment to elucidate a question raised by Mr McDougall, viz. "How does the 'Fatigue' obtained in one eye by successive alternating movements of opposite sign affect the other eye?" I proceeded similarly as in Expt. 27 (p. 77), stimulating the right eye whilst the left one was bandaged. Observers were Mr Flügel and myself; time of stimulation 30″. At the beginning the after-effect was very marked and lasted about 8 to 10 sec.; after about one hour's experimentation it had practically vanished. When then the rested eye was tested, the fatigued one being closed, the after-effect was again as marked as at the beginning and lasted nearly as long. Continuing with the experiment on the rested eye it was, however, noticed that the after-effect declined in duration as well as in intensity more rapidly than at the beginning. As the bandaged eye had become dark-adapted during the experiment I repeated the experiment with the following modification. The resting eye was kept open and was screened from the stimulating movement by a circular piece of milk-glass held in position by a spectacle-frame and the experiment was performed in a well-lighted room. The result was exactly the same as in the first experiment.

EXPERIMENT 30 (A—C): *To examine the influence of attention on the after-effect.*

Szily has also worked at this subject (p. 22). He used a complex spiral, described on p. 21. This procedure is open to the objection that by merely looking at any such pattern of very narrow alternating black and white lines, the visual field appears agitated. There is a flagella-like movement at right angles to the length of these lines which obscures any after-effect of movement, or may even be taken, I think, for a faint after-effect when such is looked for. I therefore give a description of my experiments which confirm the result obtained by Szily, and are at the same time free from this objection.

A. I experimented with the "apparatus of moving fields." The observer had to listen to some reading or to perform some mental arithmetic. The experimenter read or called out numbers in quick succession and the observer listened, adding the figures together, whilst he fixated a point in front of the moving surface. The after-effect was as marked and lasted as long during such a mental operation as without it.

B. I used Ranschburg's memory apparatus with a card on which proper names were written. The apparatus was mounted behind a screen of white cardboard with an opening in the middle, so that the window of the memory apparatus was just behind the opening in the screen and the names as they appeared could be read off by the observer sitting in front and somewhat sideways. Ranschburg's memory apparatus was connected with a key handled by the observer. At each closing and opening of the key, the disc in the apparatus was turned, exposing a fresh name. The observer was instructed to handle the key so that the names in the window succeeded each other at the quickest possible rate at which he could read them off. He was to concentrate his attention upon this and not to pay any to the surrounding fields of the screen. Upon this the chromotrope slide B was thrown by means of a lantern. The observer set to work manipulating the key and reading aloud the names as fast as he was able. When he was well started the slide was turned, first very slowly, but gradually a little faster. After 20 seconds of this stimulation, the slide was suddenly stopped, a signal being given simultaneously to the observer who continued to look at the window but now paid attention to the surrounding field. Dr Spearman as well as myself acted as observers, and we were unable to detect any diminution in the after-effect.

C. A circular disc of 20 cm. diameter, having six pairs of white and grey sectors, was fixed in a circular frame. This frame ran on a peripheral ball bearing in a wooden board 40 cm. square. Thus the disc required no axle, and was driven by means of an endless band from a motor, the endless band moving round the frame of the disc, which had a groove. In the centre of the disc was a circular window, of 2 cm. diameter, through which numbers could be seen. The numbers were written on a slip of paper fixed round a kymograph-drum, driven by

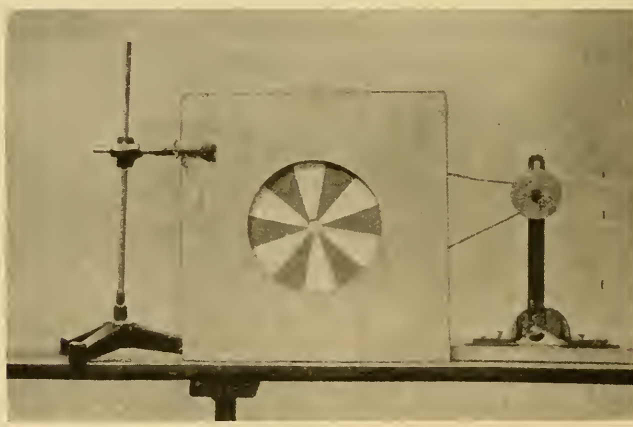

Fig. 12.

clockwork at so fast a rate that the observer had difficulty in adding the numbers together as they passed behind the window (Fig. 12). Experiments were made both with the attention of the observer occupied by the addition of the numbers and with the attention concentrated on the movement of the disc, without any other mental occupation. There appeared to be no difference between the after-effects in the two cases.

Result: *The after-effect of movement is produced although the mind does not attend to the objective movement, but is closely occupied by some other activity.*

L. William Stern who, as we have seen, advocated the "passages of after-images across the retina" as the explanation of the phenomenon, reports that immediately after a *short* stimulation he had been able to observe an after-image travelling in the same direction as the objective movement. He covered his head with a black cloth and temporarily lifted this to look at a moving object. This statement induced me to perform

EXPERIMENT 31: *To examine the effect of short exposures of movements.*

I worked in the dark room. A disc with six pairs of black and white sectors was mounted on a colour-wheel and rotated by hand. A 50 c.p. electric lamp was enclosed in a black, light-tight box. This box had an opening on the side opposite the disc, which was closed by a Thornton-Pickard photographic shutter. For exposures shorter than a second the shutter was set for "instantaneous" and the exposure regulated by the adjustment of a spring. For exposures of a second and more, the shutter was set for "time" and the exposure measured by the beats of a metronome. The durations of the exposures were 1/60, 1/30, 1/10, 1, 2, 3, and 4 seconds respectively.

Even during the shortest exposures the objective movement could be distinctly discerned. But in all these exposures, from the shortest to the longest, *no after-image of the sectors moving in the same direction as the objective movement could at any time be discovered.* With the short exposures a *positive* after-image of the disc developed after the lapse of nearly a second. This *positive* after-image was always stationary and the contours of the sectors were more definite the shorter the exposure. When the exposure was 1/10 second or more, the contours appeared blurred. After the exposures of 1 second and longer no sectors could be distinguished, the after-image of the disc being of a uniform grey as if complete fusion were observed on a fast rotating disc. This after-image required the same time to develop as that of the shorter exposures. To make doubly sure, however, that we had still to deal with the *positive* after-image, a narrow slip of white paper was stretched in front of the disc. In the after-image it appeared as a white strip. Dr Spearman and Professor Read confirmed these observations.

We have now, I think, exhausted the study of the more important characteristics of the after-effect, but we have not attempted to give an adequate description of the phenomenon. Most observers have been content to describe it merely by the name of pseudo-movement (Scheinbewegung), or apparent movement. A few have gone further. Tschermak attempted to picture the after-effect by describing it "as if a nebular coat were moving across the objects." Although introspective evidence did not sanction this description, I endeavoured to reproduce such conditions objectively in order to see whether the description was correct.

I made therefore in

EXPERIMENT 32 (A and B): *An attempt to produce a "pseudo-after-effect."*

A. I cut out a piece from a French sun-blind consisting of thin wooden cylinders 2 mm. thick and 1 mm. apart, fitted it in front of the condenser of a lantern and threw its image on a screen consisting of a large sheet of ground glass. The image presented alternating brightly illuminated and dark horizontal bands. The observer was seated in front of the transparent screen fixating a central point. The experimenter held in front of the objective of the lantern a long strip of thin meshed material (some surgical bandage). As the image of this material was not in focus on the screen, it could not be detected and only somewhat impaired the brightness. On moving the material upwards or downwards, a kind of cloud seemed to pass across the image on the screen, but the experience was *totally different* from that of an after-effect of movement. Prof. Read and Dr Spearman acted as observers and were quite ignorant of the conditions and the purpose of the experiment.

B. I replaced the system of wooden rods by a grill-pattern, made of black paper pasted on a piece of glass: width of bars and of interstices 1 mm. each. The image was thrown on a reflecting screen and I used a very much finer material to produce the moving shadow. The result was exactly the same as before, the unanimous verdict being: "Quite different from an after-effect of motion."

Having thus failed to imitate the after-effect of movement and shown Tschermak's description to be inaccurate, I endeavoured to get some results from trained observers by arranging in

EXPERIMENT 33: *A direct comparison of after-effect of movement and of objective movement.*

I used the apparatus of moving fields, the front-board being turned with its black and white stripes outward. The whole of the part above the level of the upper edge of the window and the whole of the part below the level of the lower edge were covered by grey paper. There were thus visible four fields, each 14 cm. wide and 33 cm. long; the two outer ones were stationary and the two inner ones were moving in opposite directions, similar to the arrangement in Experiment 15, Fig. 9. The right-hand field of the inner ones was moving upwards and faster, viz. 3·3 cm. sec.$^{-1}$, and the left downwards and slower, viz. ·7 cm. sec.$^{-1}$ or ·47 cm. sec.$^{-1}$ or ·35 cm. sec.$^{-1}$ respectively. A strip of paper, 2·5 cm. wide, separated each stationary field from the adjacent moving one. In the centre of each of these separating strips of paper, a pencil mark was made to serve as a fixation-point. A median vertical line thus divided the four fields into two pairs; a right-hand pair of which the right field was stationary and the left one moving moderately fast, and a left-hand pair of which the right field moved very slowly and the left one was stationary. In the experiment, the observer was seated in front of the middle of the apparatus; the left-hand pair of the fields was covered by a screen and the right-hand pair exposed. The observer fixated the fixation-mark of the right-hand pair for periods varying from 20—60 sec. The screen was then quickly shifted, hiding the right-hand pair and exposing the left-hand one whilst the observer now fixated the fixation-point of the left-hand pair.

During the first or "stimulation" exposure, the left half of the visual field was excited by a moderately fast upward movement whilst the right half remained stationary. The screen was then shifted, and during the second or "observation" exposure the downward after-effect in the left half of the visual field could be compared with a very slow objective movement of the same direction in the right half of the visual field, *i.e.* the after-effect and the objective movement were simultaneously side by side and in the same direction.

Prof. Read found that a comparison was possible between the after-effect and the objective movement, one being either faster or slower. He concurred that the after-effect had a hollow, ghost-like appearance as compared with the objective movement. The lines of the surface on which the after-effect passed off were moving faster on the inner side and seemed to bend down towards the inner edge.

Dr Spearman had similar experiences in this experiment. In his case, speaking generally, he finds that the after-effect may have all degrees, from reality to evanescence and ghostliness. I have myself sometimes found observers to take the after-effect for a real objective movement and be unwilling to believe the contrary.

As for myself, the after-effect is an experience *sui generis*. I have never found it approaching to the appearance of real objective movement. It is, so to speak, the remainder of an actual movement after everything "solid" and "real" has been taken out; what renders the movement "solid" and "real" is the change of position in space. How far this attitude is due to my continual observation during several years I am unable to say. I do not wish to forestall the theoretical considerations of this question to which I shall refer in the next part of this paper.

In conclusion, I mention another experiment. The two senses which give us the most information about space, viz. sight and touch, have several points in common, and it has been shown[1] that even some of the visual illusions have their parallel in tactile illusions. I enquired in

EXPERIMENT 34: *Is there an analogous after-effect of movement in the case of the sense of touch?*

I used an endless band of a moderately thin silk cord with knots at regular intervals of about 4—5 cm. This cord was driven round the bare fore-arm over the same place at such a rate that the succession of the knots could be distinctly felt. Various rates were used and the experiments lasted from 1—3 minutes. The cord was then allowed to drop off, or the movement stopped whilst the cord remained on the arm. The result was negative. Therefore, under the given experimental conditions, *no analogous after-effect of movement exists in the case of touch*[2].

The experimental part of this investigation being finished, we may now turn to theoretical considerations.

[1] Sobeski: *Über Täuschungen des Tastsinnes.* Dissertation, Breslau, 1903. Reference by Dr Spearman: "Fortschritte auf dem Gebiete der Psycho-physik der räumlichen Vorstellungen." *Archiv für die ges. Psychologie*, 1906, Bd. 8, Literaturbericht, p. 1.

[2] Cp. however my remarks on p. 109.

IV. THEORETICAL.

"Die Wichtigste (wenn) um nicht zu sagen einzige Regel für die ächte Naturforschung ist die, eingedenkt zu bleiben, dass es unsere Aufgabe ist, die Erscheinungen kennen zu lernen, bevor wir nach Erklärungen suchen oder nach höheren Ursachen fragen mögen. Ist einmal eine Thatsache nach allen ihren Seiten hin bekannt, so ist sie eben damit erklärt, und die Aufgabe der Wissenschaft ist beendigt[1]." These words were written nearly sixty years ago by J. R. Mayer, the originator of the epoch-making "Principle of the Conservation of Energy." They are quoted by Ostwald, who deprecates the use of hypotheses in science, and then continues: "Bis auf den heutigen Tag wird eine Unsumme von Zeit und Arbeit verschwendet, um über die grössere oder geringere Wahrscheinlichkeit dieser oder jener Hypothese zu diskutiren, ohne dass es dabei den Streitenden einfällt zu sagen, worin der thatsächliche oder experimentell aufzeigbare Unterschied der gegen einander ausgespielten Hypothesen denn eigentlich besteht[2]." It must be admitted that there are numerous instances of the abuse of hypotheses, as *e.g.* by Descartes and Leibnitz; but to deny their necessity, nay even utility, is as much an excess in the other direction. To forbid their use would be to relegate us to the Baconian method which, although valuable in itself, is unable to take their place. The benefit modern scientific investigation has derived from the use of hypotheses is too overwhelming to require their apology here. As I can personally testify to their great heuristic value in the present investigation, I may at once begin to examine those advanced here.

In Part II, "Summary and Classification of previous work," pages 24 *seq.*, I placed all previous workers in four large classes, viz.

A. Those who merely described the phenomenon or some special feature of it *without attempting any explanation* as to its cause.

B. Those who attributed the cause to *physical processes.*

C. Those who attributed the cause to *psychical processes.*

D. Those who attributed the cause to *physiological processes.*

The first class (A) need not, of course, be considered. To the second class (B) belong those who attribute the phenomenon to eye-movements.

[1] J. R. Mayer: *Bemerkungen über das Äquivalent der Wärme*, 1850. (Quoted from Ostwald's *Vorlesungen über Naturphilosophie*, 2te Aufl., Leipzig, 1902, p. 205.)

[2] Wilhelm Ostwald: *Vorlesungen über Naturphilosophie* (2te, Leipzig, 1902, p. 206).

The hypothesis states that when a serial movement passes before the eyes, these, by reflex-action, follow the movement slowly for some distance, and then suddenly and quickly jump back to the point from which they started. These movements are unconscious, become habitual and continue for some time after the movement has ceased. For these reasons the relative movement of eyes and stationary objects is attributed to the latter, *i.e.* the objects appear to move in the opposite direction to the original movement. This hypothesis is at once put out of court by the experiment with Plateau's spiral (p. 3), for the eyes cannot move in all directions at once. The objection is made still more striking by Dvořák's modification of Plateau's spiral (p. 7), Kleinert's experiment with three discs (p. 8) and Julius Hoppe's experiment with disc and mirror (p. 18). I need not, therefore, refer to any of my own experiments which would also incidentally disprove the theory, *e.g.* Experiments 21, 24, 26, etc.

Class (C) contains those hypotheses that consider some psychical process to be the cause of the phenomenon. It is often very difficult to disprove such theories experimentally, but, I think, in this instance we are more fortunate.

Taking first Budde's psychological theory, we remember that he recommended considering the after-effect of movement as an instance of "pseudoscopy," *i.e.* in this case "a temporary falsification of the conclusions drawn in the central organ from correct sensation." An outline of his theory has been given on p. 12, so that it need not be repeated here, and I quote only his concluding sentences. "The whole phenomenon of the metakinetic displacement can therefore be interpreted as pseudoscopy, if we admit the fundamental supposition, viz. the jump of attention in the visual field....We cannot dispense with these jumps without getting into conflict with the psychological principle that the soul can only concentrate its activity at any one moment on one action....If we observe a surface...we become cognisant of its configuration, because the optical axes pass over it, although these eye-movements only exceptionally become factors in consciousness. It is similar when we examine a surface in indirect vision; here also something passes over the surface and this is the attention. I therefore consider the above-described jumps of attention as something really existing."

Some simple experiments suffice to disprove the theory. If we take a disc with a spiral, radii, or sectors, and rotate it whilst fixating the centre, we can do so and allow the movement of the disc to be in the focus of attention; or we may concentrate our attention upon the centre itself, which may be made to remain stationary by covering it with a small piece of cardboard or paper held in position by a piece of wire. There will be no difference in the after-effect. Experiment 18 (p. 62) may also be used to disprove this hypothesis; for if the attention be concentrated upon the movement of one of the two spirals, that spiral ought to show an after-effect, which, as we have seen, is not the case. The same result is also indicated by Experiment 30, pp. 83 *seq.*, which shows that the after-effect is produced equally well whether the mind be closely occupied during the objective movement or not.

Lotze's theory in explanation of the after-effect with fixed eyes is, as we have seen (p. 3), that the mind has grown accustomed to the movement and that such habitual state of movement is, for the time being, normal; so that, if we look at stationary objects, rest is equivalent to an equal rate of movement in the opposite direction (psychological contrast). Therefore, stationary objects appear to us as if they were on the point of starting on such movement without ever really doing so. The error of the hypothesis may be demonstrated in the following way. Fixate a stationary point at one, say the left, side of a moving surface, *e.g.* of a rotating drum. Then stop the movement and fixate a corresponding point at the other, *i.e.* the right side of the surface. We have grown habituated to the movement of the surface, yet the surface does not seem to move backwards. There appears, however, a movement on some unexpected object whose image on the retina happens to occupy the same position as the image of the moving surface had occupied during the stimulating movement. Further, from this hypothesis, we ought to expect a greatly increased after-effect when the whole visual field is filled by a movement, as described in Experiment 22 (p. 72), but there, we have seen, the reverse is the case. Perhaps still more decisive is the result of Experiment 26 (p. 75). Two movements of opposite direction succeed one another immediately. According to Lotze's hypothesis we should most certainly expect the after-effect of the second movement. This is, however, not the case; in particular the quiescent period succeeding the second movement remains quite inexplicable.

The third and last of the psychological theories is that of Zöllner, which is given shortly on p. 5. His treatment of the subject, as before mentioned, is wholly dialectical.

When hoping to establish his premises, he says: "The ideas...of rest or motion of a body...are not immediate products of sensory perception but the results of logical conclusions, etc." And, after having discussed this idea with reference to two stars, as given above, he concludes: "Hence the idea of rest requires a longer time for its development than the idea of movement of a body." What Zöllner here calls the "*idea* of rest or motion" corresponds to what Aubert terms the "Bewegungswahrnehmung" or "perception of movement," as distinguished from the "Bewegungsempfindung" or "sensation of movement." Porterfield[1], Schmidt[2], Valentin[3] and others have shown that an object has to move with an angular velocity of at least 1′—2′ per second in an open field of vision in order to appear at once as moving. At a slower angular velocity, it appears in motion only after several seconds, and as resting when the angular velocity is still less. An after-effect, however, is not produced by the slow movements, but only by such as are experienced at once as movement. In the establishment of his premises, Zöllner only considers the slower movements which would not produce an after-effect, *i.e.* he speaks of "perceptions of movements," whilst he draws his conclusions concerning "sensations of movements." This is a fallacy of equivocation.

If Zöllner's argument were correct, there would be nothing to prevent our getting an after-effect where movements of opposite sign stimulate the same retinal area, but, as a matter of fact, we do not get one. Neither is Experiment 27 (p. 77) explicable by Zöllner's hypothesis. There we obtained fatigue by a continuous series of alternating movements of opposite sign. If, however, Zöllner would attribute this result to *general* fatigue, then such fatigue ought also to be brought about by a series of movements, not alternating, but all in the same direction. Here, however, there is a continuous tendency towards increasing the after-effect.

We now come to the largest and most important class (D) concerning *physiological processes.* This was sub-divided into nine groups. The first one

(*a*) Contained the hypothesis attributing the after-effect to the *passage of after-images* across the retina. In which way this passage of after-images is to be conceived is not always clear. Johannes Müller

[1] Porterfield: *Treatise on the eye, the manner and phenomena of vision,* Edin. 1759, Vol. II. p. 416. "An object moving with any degree of velocity will appear at rest, if the space it runs over in a second of time be to the distance from the eye as 1 to 1400."

$$(\tan \tfrac{1}{1400} = \tan \cdot 000714 = \tan 2' \, 28''.)$$

[2] G. G. Schmidt: *Hand- und Lehrbuch der Naturlehren.* Giessen, 1825, S. 472. Angular velocity has to be 2′ 15″ to be sensed at once as moving.

[3] G. G. Valentin: *Lehrbuch der Physiologie des Menschen,* 1844. He found that distance traversed by the second hand of a watch per second to distance from eye to be 1:2292 in order to be immediately aware of movement (*i.e.* angular velocity 1′ 30″).

(1840) was the first to advance this theory; a few years later (1845) it was endorsed by Ruete. The after-images of the body moving across the retina disappear in rotation as they are caused, *i.e.* they move, as it were, in the same direction as the object, and relative to this retinal movement stationary objects appear to move in an opposite direction. Not until 40 years later do we find this theory of after-images again advocated, but then apparently in a somewhat modified form by Tschermak (p. 11). He speaks of an "induction wave" caused to move backwards on the retina by an irregularity in the excitation of the anterior and posterior borders of the image; the irregularity causes a difference in the phases of the after-image. Whatever this may mean, it is evident that the retinal process, producing the after-effect, is no longer conceived in the same direction as that of the objective movement, as was done by Johannes Müller, but in an opposite direction. Julius Hoppe is still more obscure, as has been seen on p. 18. But Wundt gives the view with admirable clearness: "Indem ein schwaches Nachbild der gesehenen Bewegung[1] im Auge zurückbleibt, scheint ein fixirtes Object in Folge der Relativität der Bewegungsvorstellung in entgegengesetztem Sinne bewegt zu sein. Das Nachbild in der Regel zu schwach, um selbst gesehen zu werden, genügt doch, um auf das Object die zu seiner eigenen entgegengesetzten Richtung zu übertragen[2]." Stern (p. 18) endorses this view and believes to have observed this after-image moving in the same direction. Also Tschermak and Hoppe support this theory of after-images.

But I have been unable to confirm Stern's observation, which prompted me to perform Experiment 31 (p. 85). There are also certain difficulties in the way of the theory. For we know that a serial movement from a drum or similar apparatus produces the best effect. If we select a series of alternating black and white stripes we have the most effective and, at the same time, the most simple condition of experiment. The stripes are then the stimuli that travel across the retina. If we now imagine that the image of one single stripe has just passed across a given field of the retina, the part of the retinal field where the light stimulus entered upon it has already somewhat recovered, *i.e.* the after-image-streak is weakest at this part and strongest at the part where the light stimulus left the field, and the fading away of the after-image-streak in the direction of the movement is, as conceived by the above authors, the cause of the after-effect. The greater, then, the

[1] From the context it is quite clear that he means not "an after-image of the seen *movement*" but an after-image of the *object* seen moving.

[2] *loc. cit.* Bd. 2, S. 585.

difference in fatigue at the beginning and at the end of the given retinal field, the more powerful and lasting the after-effect. If, however, instead of a single stripe, we have the whole series passing across the retina, the difference of fatigue between that of the beginning and the end of the field becomes quite obliterated, as is evident from the following considerations:

Let *AZ* (Fig. 13) represent the length of the retinal area stimulated and, to simplify matters, let it be of such a length and the rate of movement such that, by the time the stimulating stripe has reached the end *Z* of the area (the movement being from *A* to *Z*), the recovery at the beginning *A* is complete. The curve of the after-image-streak is then represented by curve *a*. The fatigue left behind by the stripe just vanished by curve *b*, that of the previous one by curve *c*, and so forth to *e*. The after-image due to the stripes that have not yet reached the end *Z* and have already entered on the retinal area are represented by curves *f* to *k*. The retinal fatigue of any one point of the area is then represented by the sum of the heights of the curves at that point, and this, as is evident from the diagram, is everywhere equal. It may be objected that the after-image curve is not represented by a straight line, but a little consideration will show that this does not affect my argument. In a serial movement, as represented by alternating black and white stripes, provided such rate be chosen that the after-effect of one stimulus has just died away when the new stimulus puts in an appearance, the sum of the two overlapping after-images is the same at any point of the field, whatever the form of the curve.

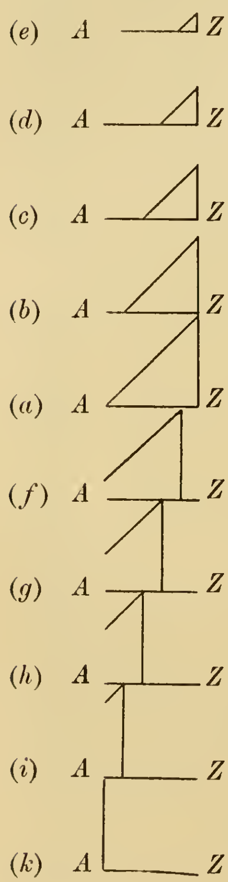

Fig. 13.

A further difficulty is presented by Experiment 26 (p. 75). If the after-image-streak were concerned in the production of the phenomenon, a movement opposed to this would counteract and modify it, but could hardly produce a perfect case of "interference" as we obtained in the said experiment.

In sub-class (*b*) are those theories which attribute the phenomenon to local retinal effects, analogous to negative after-images of colour and light. What these local retinal effects are we are not told by the exponents of this view, Dvořák and Mach We may consider this class together with sub-classes (*d*) and (*e*), which treat of definite local retinal effects, the former of the "displacement of retinal elements" (Budde, p. 11, and Beevor, p. 17), and the latter of "modified blood-flow in the retina" (Zehfuss, p. 9). Neither the theory of the blood-flow following a movement nor that of the retinal elements being drawn along by a movement, furnish the least explanation of the quiescent period intervening between the second objective movement and the after-effect.

We may next consider class (*c*), which we passed over. It deals with Plateau's "principle of oscillation (in the function) of a sense-organ," which was also advocated for a while by Oppel. This "principle of oscillation" was advanced by Plateau as a general explanation of such phenomena as complementary colours, contrast, irradiation, etc., and is stated by him as follows: "Lorsque la rétine est soumise à l'action des rayons d'une couleur quelconque, elle resiste à cette action et tend à regagner l'état normal, avec une force de plus en plus intense. Alors, si elle est subitement soustraite à la cause excitante, elle revient à l'état normal par un mouvement oscillatoire d'autant plus intense que l'action est prolongée davantage, mouvement en vertu duquel l'impression passe d'abord de l'état positif à l'état négatif, puis continue généralement à osciller d'une manière plus ou moins regulière, en s'affaiblissant; tantôt se bornant à disparaître et à reparaître alternativement, tantôt passant successivement du négatif au positif et vice versa[1]."

This theory does not seem sufficiently definite to have explanatory value. Moreover, there is no evidence of any return back from the negative state to the original positive state, as required by a theory of oscillations.

Prof. Silvanus P. Thompson's later theory of "retinal fatigue plus association of contrast" forms the next class (*f*). The "retinal fatigue" is too vague for discussion. But the "association of contrast" appears to indicate a psychological explanation; this has been shown to be untenable on p. 91.

Class (*g*), "secondary nervous impulse." Thompson's earlier theory seems to have been of this nature, but it was very vaguely expressed and was subsequently abandoned in favour of that of "retinal fatigue" just discussed. Heuse is also an advocate of retinal wave currents, but he is very obscure as to their properties.

[1] "Essai d'une théorie générale comprenant l'ensemble des apparences visuelles," etc. *Nouveaux mémoires de l'Académie Royale de Bruxelles*, Tome VIII. p. 64, 1834.

Class (h), the theory that the feeling of innervation to the antagonistic eye-muscles is the cause of the phenomenon, has only one champion, viz. Classen. We need not enter here into the much debated question of the "feeling of innervation." Heuse has vigorously attacked Classen's hypothesis. He objects that if the eyes are turned for some time towards one side, or if they are moved towards one side and then back to their normal position several times, no apparent movement is afterwards produced.

Experimentally, this theory is disproved by the fact that after-effects are produced, as *e.g.* in Experiment 24 (p. 74), by movements in opposite direction and close together, and by a chromotrope slide B as in Experiment 4 (p. 35). In this latter experiment we have concentric areas of alternating centrifugal and centripetal movements, and we cannot possibly conceive any arrangement or combination of eye-muscle contractions to account for these.

We now come to the last class (i) of hypotheses, which assert that the origin of the after-effect of motion is to be sought in the central nervous system. Oppel (1859) is the first to do this, but he refrains from committing himself to any detailed theory. Aitken (1878) also simply asks whether the experiments do not suggest that "the seat of the illusion is deeper than the retina?" Bowditch and Hall (1881) say: "The inference that the seat of the illusion may be central rather than peripheral seems at present most natural." They also state: "The readiest assumption seems to be that the impression of motion either affects a different cerebral centre than that of rest, or that one is more centralized or perceptive and the other more peripheral or more purely sensory....We cannot resist raising the question whether we may not be here very near the *quale* of real, pure sensation, not perhaps one, as we might infer from Vierordt, itself motion, but only the more primitive element from which motor effects are inferred." Then come Exner (1894) with his bold and elaborate theory and, lastly, Szily, who seconds it.

We have seen that Exner assumed a movement-centre which is constituted as described above (p. 15). If the image of a moving object passes across the retina in a given direction the central stations of the retinal elements are stimulated in corresponding rotation, say in the order a, b, c, etc. Then, it was argued, the nervous excitations arrived at shorter intervals, *i.e.* with greater frequency, at the summation-cell E than at the summation-cell It; hence the A_3-cell became more stimulated than the A_1-cell; and this greater excitation of the A_3-cell than the A_1-cell constituted the subcortical condition for a "sensation of movement" in a given direction. The stimulus having passed off, summation-cell E was left in a more fatigued state than summation-cell It, so that now A_1 became more stimulated than A_3, and this greater stimulation of A_1 as compared with A_3 constituted the subcortical condition for the experience of the after-effect of movement in the opposite direction.

It appears to me that Exner is falling here into a serious error. It is indeed quite comprehensible that the nerve-impulses caused by a single stimulus passing across the retina should arrive at one summation-cell with greater frequency than at the opposite one. He appears, however, tacitly to infer that the same holds good for a continuous succession of stimuli. But this will not be the case; for each of the centres a, b, c, etc. sends off the *same number* of innervations in both directions, so that they cannot, except at the very beginning of the experiment, arrive at a faster rate at E than at It. Some sort of grouping of the innervations doubtless happens, but we have no reason to assume that this invariably happens in favour of E.

Exner might possibly attempt to overcome this difficulty in a way similar to that in which he sought to overcome the difficulty of two simultaneous movements in opposite directions giving rise to their respective after-effects (*vide* p. 17). He might assume sets of summation-cells for very small retinal areas. A stimulus will pass right across such

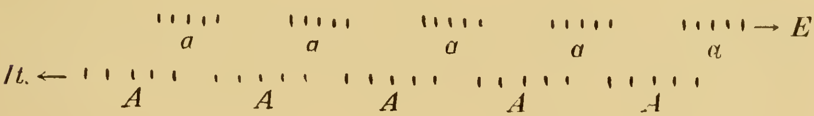

Fig. 14.

a small area, exciting successively each element in it, before the following stimulus reaches that area. The excitations from each stimulus would then arrive in quicker succession at the summation-cell in the direction of the movement, viz. E, than at the summation-cell in the opposite direction, viz. It. Fig. 14 represents the innervations arriving from one of these areas. Each a represents all the innervations caused by one stimulus in the direction towards E; each A represents all those caused by one stimulus in the opposite direction, viz. towards It. Each dot represents an innervation, and the distance between them the interval in their succession. Suppose the grouping of the a's to be that corresponding to the optimum rate of objective movement. If, now, the rate of objective movement be increased, the intervals between the innervations will be decreased and the rate at which E is stimulated will move away from the optimum rate. Likewise the intervals between the innervations of A will be decreased, but the rate at which they arrive at It will approach the optimum, and eventually the intervals for A will be more favourable than for a. We should then get the paradox of the movement, as seen, being in the opposite direction to that of the physical stimulus. Hence such a device as this, to bridge over the objections advanced against Exner's hypothesis, falls to the ground.

Another, but less important, objection against Exner's movement-centre is this: Experiment tends to show that the connexion with the eye-muscles is not as direct as indicated in his diagram (Fig. 1), for, if this were the case, the tendency of the eyes to be drawn in the direction of the after-effect ought to correspond to its intensity, whilst introspection reveals no such tendency at all. If the objective movement is proceeding whilst the eyes fixate a point in front, the strain to keep the eyes fixating is very great indeed, and the relief, when the movement ceases, is unmistakable and immediate; the pleasurable feeling-tone of the relief is quite marked, though it lasts but for a moment. The after-effect may be very intense and last for 10—20 seconds, yet the strain to keep the point in front fixated is experienced no more.

We have now finished the criticism of all the hypotheses advanced in explanation of the phenomenon, and find that, either for *a priori* reasons or on account of incompatibility with experimental evidence, all of them have to be rejected. A new explanation in harmony with the ascertained facts is still to be found.

The negative after-effect of seen movement has been compared by many observers to negative visual after-images of light and colour. Lists have been drawn up by Exner and others stating the agreements and differences of these two phenomena. But there has been little notice taken of the many other instances in physiology of this tendency to alternation between opposite processes. We find, *e.g.*, that a flexion-reflex predisposes to and may actually induce an extension-reflex and *vice versâ.* Speaking of spinal successive induction, Sherrington writes: "The exaltation after-effect may ensue with such intensity that simple discontinuance of the stimulus maintaining one reflex is immediately followed by 'spontaneous' appearance of the antagonistic reflex. Thus the 'flexion-reflex,' if intense and prolonged, may, directly its own exciting stimulus is discontinued, be succeeded by a 'spontaneous' reflex of extension, and this even when the animal is lying on its side and the limb horizontal—a pose that does not favour the tonus of the extensor-muscles[1]."

The spinal phenomenon does more than merely present an analogous alternation of opposite processes; it also suggests a definite manner by which such alternation may occur on looking at movement; excitation is accompanied by inhibition. In the following I have accepted McDougall's theory of drainage[2], and the modification I have ventured to introduce into his schema will, I hope, make it somewhat simpler.

Fig. 15 is the schema of the movement-centre as conceived by me. For simplicity's sake we will consider first the movement of a point across the retina. Let a_1, a_2 and b_1, b_2 be connected retinal elements in a straight line and adjacent or nearly so. These elements are connected

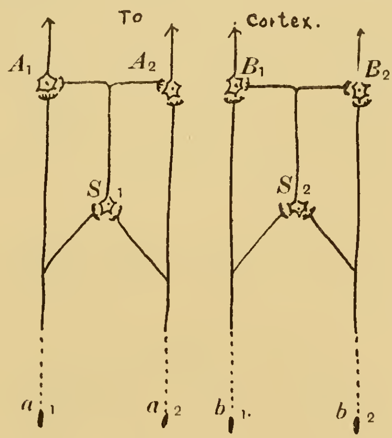

Fig. 15.

with series of neurones, as indicated by the dotted lines, giving off collaterals to the various centres of brightness, of colour, perhaps of "local sign," etc. Also a branch, as indicated by the drawn outline, towards a "subcortical centre of movement," consisting of summation-cells A_1 and A_2, B_1 and B_2, etc., that pass their excitations on to the cortex, the organ of consciousness. A_1 and A_2, B_1 and B_2 form each a pair. Now, if a physical stimulus passes across the retina in such a direction that the stimulation takes place in the direction a_1, a_2, etc., a_1 becomes first stimulated. The excitation passes on to A_1 and also to the "Schaltzelle," S_1. From S_1 two paths are open to the innervation,

[1] Sherrington: *The Integrative Action of the Nervous System*, p. 208.

[2] Wm. McDougall: "The Nature of Inhibitory Processes within the Nervous System." *Brain*, 1903, Vol. xxvi, p. 153.

viz. towards A_1 and A_2. But the resistance at the synapse S_1—A_1 has been lowered owing to the direct excitation of A_1 from a_1, so by far the greater part of the excitation from S_1 will pass on to A_1 and comparatively little to A_2. Then a_2 is stimulated and the excitation passes on towards A_2 and S_1. Here, however, the resistance at the synapse S_1 is lower than at the synapse A_2, hence most of the excitation from a_2 passes on to S_1 and thence, for the same reason, to A_1. In other words, by the successive stimulation of a_1 and a_2, A_1 becomes more strongly excited than A_2. The same thing happens with other pairs of central cells, *e.g.* B_1 becomes more strongly excited than B_2. The fact of A_1 and B_1 being more strongly excited than A_2 and B_2 I hold then to be the subcortical condition of the experience of movement in the given direction a_1, a_2, etc. If now the movement stops suddenly, then there is no difference in the excitations reaching A_1—A_2, B_1—B_2, but A_1 and B_1, being more fatigued than A_2 and B_2, owing to the previous excessive stimulation, send off less innervations to the cortex than these, and my theory is then that this fact of A_2 and B_2 having now more tonus than A_1 and B_1 constitutes the subcortical condition of an apparent movement in the opposite direction.

The inhibition theory here followed makes the assumption, that if a neurone is stimulated, the resistance of the immediately adjacent afferent synapses at that neurone is lowered. In considering movement in any direction it becomes necessary to make a further assumption, which is, however, in harmony with other physiological observations[1]; this is, that the lowering of the resistance at the synapses on the excitation of a neurone does not reach its maximum instantaneously, but gradually. After having attained its lowest point, the resistance rises again in a similar manner. This occurs even when the stimulus continues, owing to so-called "fatigue[2]." "There is abundant evidence," says Sherrington, "that different synapses differ from one another." We may, therefore, assume another characteristic quality of the synapses of this centre, viz.

[1] Such a behaviour of the resistance at the synapses would be analogous to the "Action-time" of light. *Vide* McDougall: "The variation of the intensity of visual sensation with the duration of the stimulus." *Brit. Journal of Psych.*, 1904, Vol. I, p. 151. Also Flügel and McDougall: "Further observations," etc. *Brit. Journal of Psych.*, 1909, Vol. III, p. 178.

[2] Cp. Sherrington: *The Integrative Action of the Nervous System*, p. 222: "The waning of a reflex under long-maintained excitation is one of the many phenomena that pass in physiology under the name of 'fatigue.' It may be that in this case the so-called fatigue is really nothing but a negative induction. Its place of incidence may lie at the synapse. It seems a process elaborated and preserved in the selective evolution of the neural machinery."

their exceedingly quick recovery from "fatigue," which would be explicable by natural selection. Immediately on the cessation of a stimulus, or even on the reduction of its intensity, *e.g.* when a grey stripe follows a white one, as in Experiment 6, the synapse regains at once its former state.

We have commenced by treating of movement of a point only. Let us next consider movement of a line, as would actually happen under the usual experimental conditions. It must be borne in mind that, as far as the retina is concerned, movement of a straight line must be taken as equivalent to movement at right angles to its length, as pointed out already on page 28. For this purpose we shall require at least four retinal elements working together in combination. Fig. 16 represents the schema of such a group. $a_1, _2, _3, _4$ are again retinal

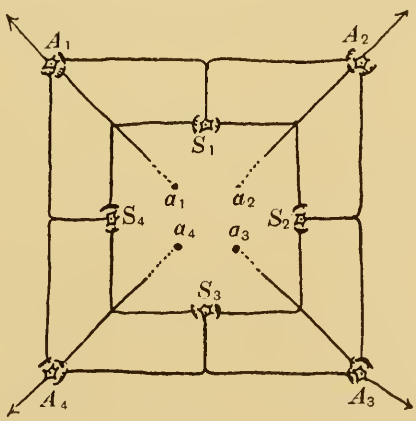

Fig. 16.

elements whose relative adjacent position on the retina is indicated in the diagram. $A_1, _2, _3, _4$ are again the more central summation-cells in connexion with them, and $S_1, _2, _3, _4$, "Schaltzellen," connecting adjacent neurones as before. Suppose then a stimulus to travel across the retina in a horizontal direction from left to right, so that a_1 and a_4 are excited simultaneously before a_2 and a_3 are similarly excited; then, for reasons set forth above, A_1 and A_4 will receive nearly the whole of the innervations, and A_2 and A_3 very little. The same thing applies, *mutatis mutandis*, to movements from right to left or in a vertical direction. Let us take next, movement at an angle of 45° to the horizontal from lower left to upper right; a_4 becomes first excited, then a_1 and a_3 simultaneously, and then a_2 last. The result of this will be that A_4 is most excited, receiving almost the whole of the innervations from a_4, a_1, and a_3. A_1 and A_3 are feebly but equally excited, the former from a_1 and a_2, the latter from a_3 and a_2. A_2 is excited least of all. Next let us take movements at any other angle, say, *e.g.* from lower left to upper right again, but of more than 45° to the horizon. Now a_4 is excited again first of all, but then a_3 is excited before a_1, while a_2 is again excited last. As the retinal elements are very close together, it seems reasonable to assume that the stimulus passes from a_4 to a_3, and thence to a_1 before the lowering of the resistances at S_3 and S_4 have reached their maximum. Consequently, as a_3 is reached by the stimulus before a_1, the resistance at S_3 will not have had time to become as much lowered as the resistance at S_4; hence less energy will be drained away from A_3 than from A_1. The relative degree of excitation of these cells corresponds then to the varying directions of movement, and their relative fatigue after the excitation to the directions of the after-effect.

This theory is in harmony, first, with the results of previous observers, and, secondly, with those of my own experiments. Let us begin by examining the former.

On pp. 27—28 I have stated the results of previous observers which I have been able to confirm. No. 1, namely, the general fact that the uniform passage of light stimuli over the retina gives rise to the after-effect, evidently agrees with the theory; so does No. 2, that the after-effect is more marked if a fixation-point is used; so also do No. 3, that the after-effect is limited to the retinal area affected by the objective movement, and No. 4, that the after-effect follows immediately on the stimulus movement. No. 5: the observation of the after-effect improves with practice rather than blunts with use, is also quite in harmony with this theory and confirms its subcortical basis. No. 6 states that if corresponding areas of the two retinae are stimulated by movements in opposite directions, then, if both eyes are closed or both remain open, there is no after-effect; but if only one eye is open this manifests its own after-effect, although more feebly than if that eye had been stimulated alone or both eyes together by the same movement. This observation is another case, like Experiment 1 on p. 30, of the after-effect being reinforced by peripheral stimuli, and will be explained in connexion with that experiment on p. 103. The same remarks apply to No. 7, which treats of haploscopic stimulating movements in different but not opposite directions, when the behaviour of the after-effect is analogous. No objection to the theory can be raised from the result No. 8: the after-effect is obtainable from any rate of movement, from the lowest, which can at once be sensed as movement, to the highest, which is short of flicker. No. 9: if one eye alone is stimulated by an objective movement, whilst the other remains closed, and if then the stimulated eye be closed and the other opened, the after-effect will appear in the corresponding part of the visual field of the not-stimulated eye. This result is probably merely a question of fusion of the two retinal fields, like results Nos. 6 and 7; possibly it may indicate some connexion between the centres of the two retinae, the stimulation of the one retina affecting also the centre of the other retina. This has, however, no direct bearing on my theory. I want to speak with more reserve about result No. 10, that pseudo-movements produce an after-effect, as I have made no experiments except those confirming the mere fact. It would appear, however, reconcilable with the theory, if the points a_1 and a_2 (similarly, b_1 and b_2) be not quite adjacent to one another but only approximately so. This point deserves some systematic investigation, which, I believe, will yield some interesting results that may throw further light on the phenomenon. No. 11, that the after-effect is also noticeable in the subjective field of vision, does not affect the theory.

Let us now turn to the further results obtained from my own new experiments. From Experiment 1, we concluded that the after-effect was much more noticeable in the objective than in the subjective field of vision, apparently because it here received a reinforcement by a peripheral visual stimulus (p. 31). This observation is quite in agreement with and explicable by my theory. First, it may be argued that the observation of entoptic phenomena, such as any apparent movement of the "Eigenlicht," requires some training and practice, and that this may account for the inability of some observers to notice the after-effect in the subjective field of vision. But apart from this, we have the following considerations: Let a movement stimulate the retinal elements a_1, a_2, etc. (Fig. 15, p. 99), in the given order. Then the summation-cell A_1 becomes more fatigued than A_2. If now the eyes are closed, no further stimuli reach these elements a_1, a_2, etc., nor consequently the more central summation-cells A_1, A_2, etc. Although these latter be then in different states of tonus, yet the centripetal currents even of the less fatigued, *i.e.* A_2, might be too weak to affect consciousness. If, however, the eyes be opened and stationary objects looked at, all the retinal elements a_1, a_2, etc., are equally stimulated.

They affect A_1, A_2, etc., to the same degree and the centripetal currents from these summation-cells become strong enough to affect consciousness and any difference of tonus in them can now manifest itself as the after-effect.

Experiments 2—4 were all directed to the same end and they proved that the after-effect of movement in the objective field is more marked on a highly illuminated projection-ground with distinct contours than on a darker one with less distinct contours. This result then confirms still further the considerations arising from Experiment 1.

In Experiment 5 we examined the dependence of the after-effect upon the distinctness of the exciting moving objects, and in Experiment 6 we followed up the result by investigating whether the difference of brightness was the essential factor in the production of the after-effect. We found that distinctness of contours was not essential, and that a more intense stimulus, alternating with a less intense one, produced a more marked after-effect than if it alternated with a more or less complete cessation of stimulus.

Part of our hypothesis, as explained on pp. 99 *seq.*, has been deduced from the result of these experiments. If the objective movement of alternating black and white stripes has been taking place in the direction from a_1 towards a_2 (Fig. 15) the resistance of the synapse at A_1 was more reduced than that of the synapse at A_2, hence A_1 received more energy (neurin, neurokyme) than A_2. When a black stripe succeeds a white one the synapses, which had been fatigued, immediately regain their former state, whilst no energy is poured across. If, however, a grey stripe succeeds a white one, there is still some little energy streaming across into the summation-cell A_1, whilst the synapse nevertheless recovers, owing to this diminution of the stimulus. The consequence is that A_1 receives more energy from alternating white and grey than from alternating white and black, and remains therefore more fatigued in the end, thus giving rise to a more powerful after-effect.

By Experiment 7 we showed that, within limits, the after-effect increases with the number of stimuli that pass a given retinal area in the unit of time. This fact is not only compatible with our hypothesis, but it may be deduced from it as a necessary consequence. The more frequently the retinal elements are stimulated, the greater will be the difference of excitation of the summation-cells and the greater the difference in the resulting fatigue, *i.e.* the more powerful the after-effect. This is another instance of the constantly observed fact that a succession of weaker stimuli produce a more powerful reflex-action than less numerous but stronger stimuli.

In Experiments 8 and 9 we found that the after-effect increases with the number of stimuli affecting the given area at the same time. This fact is also deducible from our hypothesis. Let a given number of moving alternating black and white bands stimulate a given area of the retina and let n be the number of groups of retinal elements in this area that are stimulated at any given moment by the moving bands, for, as we have seen above, the edge of the moving white band must be considered as the stimulus for the experience of movement. If now the width of the bands be decreased, *i.e.* their number for the given retinal area increased, say m times, the number of groups of retinal elements affected at the same time is also increased m times, hence it is evident that each group will be stimulated m times more frequently during a given period than before, and the after-effect is increased, provided that the frequency at which the excitations arrive at the summation-cells does not exceed the optimum.

Experiments 10—13, to ascertain the influence of the velocity of the stimulating movement, still indicate the same point; they are therefore all in accordance with our hypothesis.

The results of Experiment 14 were very indecisive and do not affect our theory one way or the other.

By Experiment 15 we found that the after-effect adds itself algebraically to an objective movement, which is also quite compatible with our theory. Suppose a movement has been going on in the direction from a_1 towards a_2 (Fig. 15), then summation-cell A_1 has been more strongly excited than summation-cell A_2. On the cessation of the movement, summation-cell A_1 is more fatigued than summation-cell A_2, thus giving rise to the after-effect. If now a movement takes place in the opposite direction, viz. from a_2 towards a_1, summation-cell A_2, which is, as we have seen, in a better state of tonus than summation-cell A_1, receives more nervous energy than A_1, *i.e.* the difference of tonus between the two summation-cells is still more increased than if the preceding movement in the direction from a_1 towards a_2 had not taken place. Therefore a movement appears faster if it has been preceded by a movement in the opposite direction, so that there is a certain degree of summation of the two effects.

Experiment 16, concerning the velocity of the after-effect, has no obvious bearing upon the theoretical aspect of the question.

Experiment 17, showing that all colours produce the after-effect, and Experiment 18, that the after-effect is the same if the different colours are of the same brightness, do not contradict our hypothesis. Neither is this the case with Experiment 19, where we have shown that alternating different colours of the same brightness produce an apparently undiminished after-effect. Each new colour is then a new stimulus. This is quite in accordance with the previous result in Experiment 6, where we have already seen that difference of brightness is not a dominant factor in the production of the after-effect. The bearing of this experiment on other interesting questions in vision cannot be discussed here.

No difficulty is offered as regards the hypothesis by the results obtained by Experiments 20—22. These show essentially that an after-effect is obtained by stimulation of the cones as well as of the rods, which might have been expected. However, the difference of the after-effect in these two cases, although not affecting our hypothesis, seem very interesting and will be discussed separately.

Exner found it consistent with his theory that movements covering small areas, especially when two such movements were of opposite directions and close together, should not give rise to an after-effect. However, Experiments 23—24 show that after-effects can be obtained in such cases, and this result is quite in accordance with our hypothesis.

In Experiment 25 we found that when the after-effect of a stimulation has passed away for consciousness, a disposition remains for some time that makes itself felt by shortening subsequent after-effects of opposite sign. This, translated into physiological language and in the light of our hypothesis, simply means that the equality of the tonus of the summation-cells is not fully restored although their difference has ceased to rise above the threshold of consciousness.

The generalized result of Experiment 26 we expressed in empirical language as follows : When several objective movements stimulate the same retinal area simultaneously or successively, an effect is produced which is the resultant of the after-effects of the various movements. To explain this in terms of our hypothesis, utilizing Fig. 15 (p. 99), let the first and longer movement have taken place in the direction from a_1 towards a_2, then the summation-cell A_1 receives more nervous energy than the summation-cell A_2. On the cessation of this movement A_1 is considerably more fatigued than A_2. If then another movement in the direction from a_2 towards a_1 stimulates the retina, the summation-cell A_2 receives more innervation than A_1. But this second movement is of very short duration and the small excess of innervation that reaches A_2 gives rise to a transitory fatigue from which this summation-cell recovers very quickly. The consequence is, that while

A_2 too is fatigued, the tonus of both A_1 and A_2 is about equal; hence the quiescent period. A_2, however, soon recovers from the transitory fatigue and returns to its proper tonus, whilst the more lasting fatigue of A_1 continues, consequently the remainder of the after-effect of the first movement, that was disturbed by the second movement, again becomes noticeable.

The result of Experiment 27, namely, that successive stimulation of alternating opposite sign rapidly produces a decrease in the duration, etc. of the after-effect, seems deducible from our hypothesis, as a fatigue of both summation-cells.

In Experiment 28 we found that when fatigue had been produced in the same manner as in Experiment 27 (*e.g.* by alternating movements of opposite sign in a horizontal direction), the after-effect to a movement in a vertical direction was only slightly affected thereby. At first sight this might appear inconsistent with our hypothesis, for on looking at Fig. 16 a movement from right to left, stimulating A_1 and A_4 exactly simultaneously, and a return-movement from left to right, stimulating A_2 and A_3 exactly simultaneously, would result in fatiguing all the summation-cells $A_{1, 2, 3, 4}$ equally. But such exactly simultaneous stimulation must be an exceptional case. As a rule, one cell, say A_4, will be stimulated first and most intensely, whilst the same will occur to A_2 on the return-movement, so that A_1 and A_3 are much less fatigued in the end.

In Experiment 29 we found that fatigue produced by alternating movements of opposite sign is independent of the colour of the light producing it. This is to say, that if fatigue is produced in the light of any colour, it is maintained in the light of any other colour. This, of course, could not have been deduced *a priori* from our theory; in fact, after Experiment 19, the opposite result would not have been surprising. The relation of these two experiments, 19 and 29, as well as their bearing on light on colour vision, will be considered later; all we have to do here, is to draw attention to the fact that the result of Experiment 29 is not antagonistic to our theory.

In Experiment 30 we found that the after-effect was not influenced by attention. This result does no more touch our theory than an opposite result would have done, whilst it indicates that the seat of the after-effect is lower than the cortex.

Experiment 31 was merely made to disprove L. William Stern's assertion of the existence of an after-image of an object in motion.

Experiment 32 gives an attempt to imitate the after-effect according to the description given of it by Tschermak. But the result was found to be totally unlike the real after-effect. Both in the after-effect and in the experimental imitation of it, the retina is stimulated by stationary objects, which stimulations are propagated to the visual centre. In the after-effect, the cortex also receives excitations from the "Centre of Movement" caused by different states of tonus of the summation-cells; whilst in the pseudo-after-effect, the cortex receives all the stimulations incident to an actual objective movement, *i.e.* not only excitations from the movement-centre reach it, but also others directly from the retinal elements stimulated by the objective movement.

Experiment 33, which consisted in a direct simultaneous comparison of an after-effect with an objective movement, was made with the object of bringing out the difference of these two experiences. I hold that in an objective movement we have two factors, viz. (*a*) the experience of movement proper, similar to the after-effect, and (*b*) the change of position in space. This is best expressed by Ebbinghaus: "Sie (*i.e.* Bewegungsanschauung) ist keineswegs identisch mit dem sie in der Regel begleitenden Bewusstsein, dass sich ein gleicher Empfindungsinhalt zu verschiedenen Zeiten an verschiedenen Orten befindet, sondern ausserdem enthält sie noch etwas Anderes und darüber Hinausgehendes, nämlich das nicht weiter zurückzuführende und abzuleitende Bewusstsein eines räumlichen Überganges, des kontinuierlichen Durchlaufens einer Raumstrecke. Dieses Bewusstsein aber ist in Fällen, wie den eben erwähnten, nicht ein blosser Gedanke, ein auf Ueberlegung beruhender Schluss, *sondern eine unmittelbare und eigenartige sinnliche Anschauung*[1], ebenso unvermittelt und sinnlich lebhaft wie die gleichzeitigen Empfindungen von Farbe und Berührung. Das ist der eigentliche und bleibende Sinn der berühmten Beweise des Eleaten Zeno gegen die Bewegung, dass wir in ihr eine ursprüngliche Anschauungsthatsache anzuerkennen haben und sie nicht durch eine Summierung von beliebig vielen Orten und Momenten in einer begreiflichen Weise gleichsam hervorbringen können. Man kann sich ganz gut denken, dass es Wesen gäbe, die, mit unserer Raum und Zeitanschauung ausgestattet, dass successive Aufspringen eines gleichartigen Eindrucks an verschiedenen Orten volkommen gut wahrzunehmen vermöchten, die aber von Bewegung als ein Hindurchgehen durch die zwischenliegenden Räume keine Ahnung hätten[2]."

To such beings the experience that we attribute to a centre of visual movement-sensations would be lacking, and they would not experience the after-effect of movement.

[1] The italics are mine.

[2] Ebbinghaus: *Grundzüge der Psychologie*, 1902, Bd. 1, p. 467.

Thus the after-effect is different from the experience of seeing an objective movement, in that the latter contains two components (*a*) and (*b*), as described above, whereas the after-effect contains (*a*) alone. The physiological basis of (*a*), as manifested in the after-effect, is, according to our theory, the difference in the strength of the innervations sent to the cortex from the summation-cells, owing to their difference of tonus; whereas the experience which we have of an objective movement is not only due to a similar difference in the strength of the innervations from the summation-cells to the cortex now owing to their unequal stimulation from the periphery, but in addition to the changing excitation of those central parts corresponding to the affected retinal elements and their local values, due to the change of position in space of the stimulus. That we cannot analyse this latter experience is due to the simple fact that we do not experience the component parts separately, or better, the physiological bases do not act singly.

Experiment 34, to examine whether an analogous after-effect existed in the sense of touch, has no direct bearing on our hypothesis. I mention here that the negative result of this experiment must not be considered as final; some observations made since then show me that the subject is worthy of further investigations.

In addition to the foregoing facts bearing on the general nature of the physiological substratum of the phenomenon, there were some other experimental results of a more special significance.

Experiment 19 seems particularly interesting (provided always that the technical difficulties can be considered as sufficiently overcome, see p. 64). We find in it ground for speculation as to the relation of colour and brightness-sensations, as well as to the position of these cortical centres relative to our "movement-centre." These speculations are rendered still more interesting by the results of Experiment 29 (p. 80), where we found that fatigue produced by any given colour is maintained for movements of any other colour. To pursue this subject further lies, however, outside the province of this paper.

The results of Experiments 20 and 21 may also prove to be of theoretical interest. We have found there that the after-effect in dim light and that in the peripheral fields greatly resemble one another, and differ much from the after-effect produced by stimulation in bright light and in the central parts of the visual field. We may therefore infer that, in the one case, the after-effect is due to the stimulation of the rods, and in the other to the stimulation of the cones. In the former the after-effect is greater, more bulky or massive, but of shorter duration; there is, as it were, the same "quantity" of after-effect running off in a shorter time, or, in other words, there is more of the after-effect whilst it lasts. Here, too, we may find some light thrown on the much discussed question respecting the "velocity" and the "intensity" of the after-effect. In the peripheral field we are more frequently tempted to say that the after-effect is more or less "intense," whilst in the central field we feel generally more inclined to speak of the "velocity" of the after-effect.

This fact perhaps throws light on the observation of Exner[1] that the peripheral parts of the retina are more sensitive to the perception of movement than the more central parts. For this is just what one would expect from the above fact that the after-effect in the periphery is more intense but of shorter duration. Of the same nature, also, appears to be the well known fact that the flicker of a rotating disc persists at greater velocity in the periphery than in the centre.

V. SUMMARY AND CONCLUSIONS.

In this investigation the following results of previous observers have been confirmed:

1. The uniform passage of light-stimuli over the retina in any given direction for a certain time produces the after-effect of an apparent movement in the opposite direction.

2. This after-effect is more marked if the eyes do not follow the movement, but remain fixed on a stationary point.

3. The after-effect is limited to the retinal area affected by the objective movement.

4. The after-effect follows immediately after the stimulating objective movement.

5. The observation of the after-effect improves with practice.

6. If corresponding areas of the two retinae are stimulated by movements in opposite directions, these movements do not neutralize one another but engender "rivalry." Then, if both eyes are closed or both remain open, there is no after-effect. But if only one eye is open, this eye manifests its own after-effect, although more feebly than if the other eye had not been stimulated.

[1] S. Exner: "Über das Sehen von Bewegungen und die Theorie des Zusammengesetzten Auges." *Sitzungsber. d. Wien. Acad. d. Wissensch.* 1876, Bd. 72, Abth. 3, S. 156—190. S. Exner: "Über optische Bewegungsempfindungen." *Biolog. Centralblatt*, 1888, Bd. 8, S. 14.

7. If corresponding areas of the two retinae are stimulated by movements in different, but not opposite, directions, rivalry and fusion of these stimulating objective movements occur. One eye alone open has predominantly its own after-effect, but both eyes open produce complete fusion.

8. The after-effect is producible by any rate of the stimulating objective movement, from the slowest which can at once be sensed as movement to the highest which is short of flicker.

9. If one eye alone is stimulated by an objective movement, whilst the other remains closed, the after-effect will appear in the corresponding part of the visual field of the not-stimulated eye, but it will be somewhat feebler.

10. Pseudo-movements, *e.g.* stroboscopic movements, produce an after-effect exactly as an actual movement does.

11. The after-effect may also be noticed in the subjective field of vision, *i.e.* with closed eyes.

An objection has been raised as to the legality of the inference drawn by Exner, Szily and others from the observations recorded under (9). It has been pointed out that it was not a logical conclusion from this experiment to attribute the after-effect to a central origin.

The results of the experiments devised for this investigation are as follows:

Experiment 1. It is far more difficult to discover the after-effect in the subjective field of vision than in the objective; in other words, the after-effect is more easily discovered if the field of vision is filled. It is argued that this fact is probably due to the reinforcement of the after-effect by the peripheral visual stimulus.

Experiments 2—4. The after-effect of movement is more marked in a brightly illuminated objective field with distinct contours than in a darker field with less distinct contours. Statements by previous observers are generally to the contrary, but there appear to have been no systematic experiments made upon this subject.

Experiments 5 and 6. (1) Distinctness of contours is not the essential factor in the production of the after-effect of movement.

(2) If, during the passage of images over the retina, a stimulus of a given intensity alternates with one of less intensity, the after-effect of movement produced is more vivid than if such stimulus alternates with a (more or less complete) cessation of stimulus.

Experiments 7—9. The after-effect increases in one or several ways, within limits, with the number of stimuli simultaneously affecting a given area of the retina, and/or with the frequency with which the stimuli pass given retinal elements.

EXPERIMENTS 10—13. The after-effect at first increases very rapidly with the objective velocity, but soon reaches a maximum and then gradually diminishes with further increase in speed. From the data of the last of this group of experiments some idea is obtainable as to the form of the curve of the after-effect as dependent on the velocity of the objective movement.

EXPERIMENT 14. If a moving series of alternating dark and light stripes excite the retina, a slightly better after-effect seems to be obtained if the stripes be of equal width ; but if the alternate dark and light stripes be not of equal width it seems not to matter which stripes are increased and which decreased in width.

EXPERIMENT 15. The after-effect adds itself to an objective movement.

EXPERIMENT 16. Here it is shown that the "velocity" of the after-effect is comparable to the velocity of an objective movement.

EXPERIMENTS 17 and 18. The after-effect of movement is independent of the quality of the light.

EXPERIMENT 19. In the case of different colours difference of brightness is not essential for the production of the after-effect, but different colours of the same brightness will produce it also. With respect to this result I refer again to the technical difficulties of the experiment.

EXPERIMENT 20. The after-effect is produced both with light and dark adapted eyes ; or in other words, rods as well as cones are receptive to the after-effect.

EXPERIMENT 21. (1) The duration of the after-effect diminishes as we move from the centre towards the periphery.

(2) In the central field, the after-effect is very marked and distinct, and gradually and evenly diminishes. In the peripheral field, it sets in with more vigour, appears to be rushing more powerfully during the first moment, but very rapidly diminishes and vanishes below the threshold.

(3) The after-effect in the peripheral field greatly resembles the after-effect with dark adapted eyes.

(4) The after-effect due to the stimulation of the rods is different in character from that obtained by the stimulation of the cones. The former sets in more powerfully, but diminishes more rapidly than the

latter, which, however, is more distinct and diminishes more gradually, and therefore lasts longer.

(5) Any after-effect in a not-stimulated area is of opposite direction to that of the stimulated area.

(6) The influence of the stimulation of a more central area on a more peripheral not-stimulated one decreases towards the periphery.

(7) If a retinal area other than peripheral is stimulated by movement, the more central adjacent area is more affected than the more peripheral adjacent one.

(8) The more peripheral a stimulated area is, the more powerfully it affects the centrally adjacent area; the latter area is more affected than the still more central one.

EXPERIMENT 22. No after-effect is produced by an objective movement occupying the whole visual field.

EXPERIMENT 23. Movement in small areas (subtended by an angle of 1′) produces an after-effect.

EXPERIMENT 24. If the movements in small areas such as are subtended by an angle of at least 1′, are in opposite direction and the areas close together, the after-effects do not neutralize one another; both exist together, but they are weaker and of shorter duration than when the movements are of the same direction or affect more widely separated retinal areas.

EXPERIMENT 25. When the after-effect of a stimulation has passed away for consciousness a disposition remains for some time that makes itself felt by shortening and weakening subsequent after-effects of opposite sign.

EXPERIMENT 26. When several objective movements of different directions stimulate the same retinal area simultaneously or successively, an after-effect is produced which is the resultant of the after-effects of the various movements.

EXPERIMENT 27. The duration, etc., of the after-effect rapidly decreases on successive stimulations of alternating opposite sign, *i.e.* fatigue is set up.

EXPERIMENT 28. After fatigue has been produced by a long series of movements alternating in sign (so that the after-effect is greatly reduced), the after-effect of movements at right angles to the directions of the previous ones is only very slightly affected, if at all.

EXPERIMENT 29. Fatigue produced by alternating movements of opposite sign is independent of the colour of the light producing it, *i.e.* the fatigue is maintained in light of different colour.

Experiment 30. The after-effect of movement is produced, although the mind does not attend to the objective movement, but is closely occupied with some other activity.

Experiment 31. This disproves L. William Stern's statement, that an after-image-streak of a moving object is noticeable after short stimulations.

Experiment 32. Here is shown the incorrectness of the description of the after-effect as "a shadow passing across the stationary surface," made by Tschermak.

Experiment 33. A direct and simultaneous comparison of after-effect and an objective movement in the same direction is here given.

Experiment 34. Under the experimental conditions described there is no analogous after-effect of movement in the case of touch.

In the theoretical part of this paper the various classes of hypotheses that have been advanced in explanation of the after-effect have been considered. Each hypothesis has been individually examined and has either been shown to be untenable on *a priori* grounds or been disproved by means of experiments. The last hypothesis examined is that of Exner. Although it is the one most in harmony with the experimental evidence, it cannot, as has been shown, be upheld for *a priori* reasons. We indicated at the same time that a "movement-centre" cannot have that direct connexion with the eye-muscles which Exner advocates.

Attention has been directed to certain similarities between the after-effect of seen movement and the rebound-effect observed in spinal reaction. As this latter is attributed to inhibition and fatigue, these factors have been used in the elaboration of a new hypothesis, following Exner in so far as to assume a "centre of movement."

This hypothesis has been tested by the results of previous observers as well as by those of the experiments described in this paper. All these numerous observations appear to be in agreement, or, at any rate, not in contradiction with my hypothesis.

In passing, scope is indicated for interesting speculations, *e.g.* respecting the relation of colour and brightness-sensations. Some light appears also to be thrown on the difference of the function of the parts of the "Centre" corresponding to the rods and to the cones respectively.

Although, then, we have here what Whewell calls a "consilience of induction," our hypothesis is still a great distance from becoming satisfactory proof. It is yet necessary to apply the "method of difference." To find the exception that proves the rule we have, as far as I can see, to look to pathology for assistance; nature has to perform the "experimentum crucis" herself. It may be argued, I think, that if there is a lesion in this theoretical "centre of movement," the after-effect ought to be impaired under some conditions, possibly intensified under others. For this purpose it would be necessary to examine a great number of cases, especially those where there is some lesion affecting the optic tract[1]. I began examinations on these lines some time ago, but, owing to circumstances, could not pursue them far enough. In this connexion I have to thank Sir Victor Horsley and Dr S. A. K. Wilson for the facilities kindly afforded me at that time. If it is possible to prove this theory conclusively, it is evident that an abnormal increase or decrease in the intensity of the after-effect may afford some valuable aid in diagnosis.

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[1] It is not altogether impossible that the examination of deaf-mutes may throw some interesting light on a connexion of our "movement-centre" with a centre for the impressions derived from the labyrinth and the semi-circular canals.

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