THRESHOLDS OF ROTATION[1]

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The threshold of rotation is an ambiguous concept both with respect to the physical stimulus and to the indicator. The physical facts of rotation may be expressed in terms of angular displacement, angular velocity, and acceleration. In our ignorance of the extent of the general receptor-field for rotation and of the specific neuro-physical mechanisms of the vestibule, any one of these three physical characteristics of rotation, or any combination of them, may be the significant stimulus for the consciousness of rotation and the corresponding reflexes. There is evidence that, on occasion, each one of the three physical characteristics does in fact operate to condition a perception of rotation.

The concept of rotation threshold is further complicated by differences of professional opinion with respect to the relative reliability of the indicators. According as our bias is objective or introspective, the term 'threshold' may refer to compensatory eye-movement or to consciousness of rotation.

The lack of precision of the problem of the threshold of rotation is not an accident but the inevitable consequence of a stage of development. It seemed to us to call for exploration rather than for the massing of data. While by no means complete the exploration of techniques, stimuli, receptor-field, and indicators, has advanced to a point where some practical results are visible and where, if greater precision is desirable, coöperation is needed for detailed special investigations.

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An important and pressing practical bearing of the threshold of rotation relates to the orientation of the flier and to the relative importance, dependability, and possible correction of subjective data for the piloting of airplanes and gliders. There are well-authenticated accounts of aviators making a complete loop in the clouds without knowing it, of emerging from the clouds after making a half loop, flying upside down. Similarly, travelers lost in the desert or in snow fields are commonly reported to circle back to their own tracks. To keep a straight course on land, at sea, or in the air, without some objective point of reference is impossible for any considerable length of time. If this is true, it is of practical use to ask: What is the minimum rotation that the vestibular mechanism may be relied on to detect; under what circumstances does the vestibular mechanism function as an adequate control of locomotion; and how far may it be trained?

Scientific interests are also involved in a study of a rotation threshold. In any complete discussion of a sense mechanism the normal threshold should be included, but in the case of the vestibule there is an unusual scientific motive for the study of threshold. We are still none too sure of the precise mechanics of vestibular stimulation. It is very doubtful if actual movements of a fluid in minute tubes like the semi-circular canals can account for the relatively long continued after-effects of rotation and the long continued post-rotation reflexes. It seems highly improbable that an after-nystagmus which lasts twenty seconds after rotation stops can be conditioned by the momentum of a column of fluid in a canal less than half a millimeter in diameter and about a centimeter and a half long. Actual momentum movements, twenty seconds or more in duration, in such a canal are unthinkable. It is absolutely impossible to account for the newly discovered positive and negative after-images of slow acceleration[1] by any known physical characteristics of the vestibular fluids. As an important datum for a theory of the mechanics of the vestibule we must know the amount and kind of movement that conditions its characteristic

[1]Journal of Experimental Psychology, 1923, VI., pp. 10–11.

reactions. Further theoretical bearings of our problems include the extent of the receptor-field for rotation, the relative sensitivity of its several parts and the relative reliability of reflex and conscious indicators.

My personal systematic interests emphasize the latter aspect as one phase of the elementary conditions of human variability. Incidentally, the possibility of an unusually direct comparison between the reflex indicator of rotation (vestibular nystagmus) and introspective data seems to offer unusually accurate data in a methodological dilemma.

Extent of the Receptor-field for Rotation

It is commonly held that the receptor-field for rotation focuses in the mechanism of the vestibule. While this mechanism is relatively small, it is complex and highly differentiated. That it is equally sensitive for all three of the physical aspects of rotation, there is at present no evidence. The relative importance of data from the larger receptor-field is quite unsettled. Of that larger field, vision is presumably the most sensitive and reliable factor. In a previous paper[1] it was shown that very slowly accelerated rotation might proceed through from 100° to 200° without being reported by the rotating subject if his eyes were closed. With the eyes open it was possible to report similar rotation to a fraction of one degree. With sufficiently clearly contrasted points of reference the visual data for consciousness of rotation are extraordinarily fine.

It is quite possible that sense data of rotation are also given in audition, in kinesthetic perception, muscle strains, articular sensation, dermal sensations, as well as in consciousness of eye-movements and changing configuration of pressures. Data are occasionally reported relating to movements of the more or less loosely attached parts of the body, especially the contents of the abdomen. All of these data may on occasion be so faint as to be unrecognized and unplaced. Under such circumstances, since vestibular data have no known specific characteristics, it is easy to confuse them with data from the vestibule.

[1]Journal of Experimental Psychology, 1923, VI., pp. 7–15.

Notable illusions of rotation are readily produced by the artificial stimulation of the visual cues to rotation, as was conspicuously shown some years ago in the 'haunted swing' illusion. An analogous illusion is an every-day phenomenon whenever vision reports any slow movement of the environment without jar. One of the most familiar examples is the apparent movement of the observer when a parallel railway train begins to move out of the station. When visual and vestibular data actively conflict one has a more or less disturbing experience which we shall discuss from the photographic records of eye-movements in a subsequent paper. Even when the eyes are closed movements of shadows may possibly give a clue to rotation. But as far as we can discover this clue to rotation is neither delicate nor accurate. As far as our present records go it is negligible.

Auditory data may also function as an index to a rate of rotation which is well below the threshold of the vestibular mechanism. This fact was particularly annoying in our laboratory as we had no sound-proof room. Peculiarly disturbing were the noises of the heating apparatus, snapping of the radiators, and the less intense escape of air and steam. Accidental disturbances, such as the movement of classes, or individuals in the halls, or recitation rooms, were occasionally discovered to function in the complicated sense data of rotation.

Probably the most primitive of all rotation data are the dermal contact sensations. Pressure changes are often referred to by our subjects as clues to the fact of movement, or the sense data of rotation. This was especially true of slight changes in pressure sensation of a knee when it rested lightly and with relaxed thigh muscles against an upright of our rotating platform. Pressure cues were occasionally reported from everyone of the points of contact between the subject and the apparatus. Arm-rest, head-rest, and seat were especially prominent in the reports. Joint sensations were also occasionally reported. In a word, the sudden onset of rotation regularly produced inertia data from a considerable variety of organs, as well as from the vestibule.

Some of these data from the wide receptor-field have a much more favorable leverage than occurs in the vestibule. Slight knee pressure with relaxed thigh mucles is an illustration. In the case in point the thigh joint was practically over the center of rotation as were the semi-circular canals. The knee consequently was eccentric the entire length of the thigh and in a relatively favorable position for the operation of inertia. It proved to be on the whole a considerably more delicate receptor for rotation than the vestibular mechanism. We naturally tried to eliminate such possibilities in subsequent experiments. In our ordinary consciousness of rotation all of these non-vestibular data bulk large in comparison with the ill-defined data from the vestibule. The relative sensitivity of these various parts of the receptor-field deserves more systematic investigation than we were able to give.

The question whether any of these data affects the rotation reflexes deserves special attention. We have pointed out in a previous paper a general similarity between the nystagmus of rotation and the nystagmus of pursuit. They are often not differentiable in photographic records. Only their latencies and their course are different. Under these circumstances it seemed impracticable to answer the question whether visual data of rotation produced a reflex nystagmus. The auditory data, however, were studied by a preliminary exploration.

Auditory Receptor-field for Rotation

The apparatus for studying the question whether there was a reflex response to the effect of rotation on the auditory part of the receptor-field consisted of two parts, a revolving sound-cage to give the auditory stimuli and an eye recording apparatus. The latter did not differ in essentials from the eye recording apparatus already described in previous papers.[1] In this case, however, since the subject was to be stationary, the recording camera was firmly mounted on a heavy table instead of on the revolving platform. A head-rest, similar

[1] 'Latent Time of Compensatory Eye-movements,' Journal of Experimental Psychology, 1921, *IV.*, pp. 247 fol.

to that provided on the revolving platform, was placed in front of the camera at a suitable distance. The recording instrument was our mirror-recorder for photographing the movements of closed eyes.[1]

The stimulating part of the apparatus was a sound cage which was revolved by hand. The sound-cage carried a vibrating telephone receiver or a small electric buzzer of the watch-case type at an average distance of fifty centimeters from the subject. It proved difficult to produce an illusion of subjective rotation from the movements of this sound producing instrument as it revolved around the subject. This was probably due in part to the fact that the sound shadow of the recording camera passed the observer once each revolution when the sound producing instrument was directly in front. This sound shadow certainly disturbed the normal progress of the sound and led to an illusion that the sound instead of traveling in a circle went out to some distance and returned, changing its apparent path in a more or less complex way. The progression of the sound was clearest when it was behind the subject since in that position there was no sound shadow. There was, however, some difficulty in the subject's locating the sound behind him. It often seemed to oscillate back and forth in front. In addition to these factors which tended to prevent clear cut perception of an evenly rotating sound, an additional factor preventing the transfer of rotation from sound to subject was given in the latter's sophistication. The subject knew that he was seated at a heavy oak table which rested on the floor, that his head was supported by a head-rest on that table and that it was impossible for him to rotate. This produced a subjective set which was more or less inimical to the illusion of subjective rotation.

In spite of these technical faults of the apparatus, there was occasionally an illusion of subjective motion; that is to say, instead of the sound traveling around the subject the subject seemed momentarily to float independent of contact with the table, head-rest, and seat, and himself to rotate

[1]Journal of Experimental Psychology, 1921, *IV.*, pp. 165 fol.

while the sound stood still. Unfortunately, there was no regular premonition of these moments and they were at best fleeting. It was consequently an accident when they coincided with a moment of photographic registration of the eye-movements. Possibly the ideal arrangement would have been to take continuous records of eye-movements and to have noted the illusions of rotation on these records. Such a procedure, however, would have been expensive in time and photographic material, and it would have involved a continuous recording camera which we did not at that time possess. The records that we did take were intermittent records on sensitized paper, 5 in. x 7 in. in size. In spite of this inadequacy of the recording camera we have several cases in which subjective illusion and the eye record do in fact coincide. Two of the occasional coincidences of this sort are reproduced in Plate I., Records 1 and 2. These records show real nystagmoid eye-movements. There is no doubt about that. Whether they were exactly coincident with the illusion of subjective rotation or not we were unable to determine, but the coincidence was at least approximate.

In the effort to overcome the persistent mental set which was occasioned by knowledge of the impossibility of rotation, the instrument was redesigned and adapted to the rotating platform in the following manner. The sound-cage instead of being elevated above the rotating platform, where it would have interfered with the wire stays and electrical connections, was built up from the base of the rotating platform. To this end a board was cut to fit over the cylindrical stem of the supporting tripod below the rotating platform. An electrical buzzer was attached to the board and was counter-balanced by weights to keep the board in equilibrium. Under these circumstances it was possible to rotate at will either sound-cage or subject, or both subject and sound-cage. This new position of the sound-cage had a further advantage that the sound shadows from the recording camera were very much reduced. With this arrangement somewhat more numerous illusions of rotation were actually produced than with the previous one. But it seemed impossible to prevent some secondary clues, partly due to slight vibrations of the platform when the subject was started in rotation and partly due to the noises when the sound-cage was moved. In spite of all of these unfavorable circumstances the fact that occasionally nystagmoid movements were produced is the point to be emphasized.

Record 3 of Plate I. represents a short series of experiments with far-reaching implications of facilitation and rivalry if further experiments corroborate these results. The series grew out of the effort to prevent the sophistication of the subject as to the fact of his own rotation or stillness while the sound-cage was rotated around him. For this purpose relatively small oscillations of the subject were superadded during the continuous rotation of the sound-cage in one direction. The experiment aimed to create a crucial situation when one might find either one of the following significant alternatives. If the oscillation of the subject is the only factor influencing the ocular movements one would expect a vestibular nystagmus changing the direction of its deviation or compensatory phase with the changes in the direction of oscillation. If, however, the sound movements also influence the eye-movements one would expect to find a corresponding modification of the vestibular nystagmus. An extreme case of such influence would involve the suppression of the vestibular deviation which compensated for one direction of rotation and the substitution of a deviation corresponding to the rotation of the sound. Lesser degrees of such influence would involve the diminution of the vestibular deviation in one direction and its exaggeration in the direction corresponding with the rotation of sound. As a matter of fact both degrees of modification of vestibular nystagmus are found in Plate I., Record 3, which was taken from an untrained subject (subject *H*). The moments of extreme influence are lettered *A*. Moments of lesser influence are lettered *B*. Moments of deviation which were conditioned purely by sound are lettered *C*. The series, of which Record 3 is a part, was a purely exploratory one. Before these results can be regarded as definitive an extensive critical study of this phenomenon would be necessary. The preliminary results indicate that such a study is worth while. It seems possible that the ocular mechanisms offer particularly favorable conditions for a study of facilitation and rivalry in a complex nervous system.

The conditions of this nystagmus from moving sounds obviously could not have been vestibular in origin. It must have arisen from the illusory consciousness of rotation which is presumptively a cerebral function. Even under the best technical conditions it is very doubtful it it can be demonstrated whether such nystagmus is a true reflex or not. It may be of the nature of an ocular pursuit in response to the illusion of rotation. The difficulty of determining between ocular pursuit and reflex nystagmus has already been mentioned. As we previously stated, their photographs are often identical and they can be distinguished best by their latency. In our experiments, measurements of the incidence of the illusion could not be recorded with sufficient precision to differentiate a reflex from a reaction. It remains entirely possible that the occasion of the nystagmus was an imaginary movement of the environment due to the illusion of subjective rotation. It is also possible that the nystagmus was due to the visual imagery of the moving electric buzzer or some other part of the sound-cage. The whole experience is so fleeting and so difficult to obtain experimentally that a more exact description was not attempted. There is, however, no doubt that under favorable circumstances the illusion of rotation and a corresponding deviation of the eyes may be conditioned by auditory stimuli.

The artificial production of dermal and kinesthetic data of rotation proved impossible with any means at our disposal. Consequently, we have no new information as to whether or not they alone could produce either nystagmoid eye-movements or illusions of rotation.

Our ordinary data of rotation are doubtless complex. Vision, sound, contact, kinesthetic, and vestibular data, commonly coöperate. Artificial data from any single experimentally selected factor of this receptor-complex would be opposed regularly by antagonistic data from all the rest. Consequently, the stimulation of a single factor would only occasionally condition an illusion of rotation, when for some reason the negative factors from the rest of the field were inhibited or the selected factor was strongly reinforced. In spite of these experimental difficulties the relative importance of vestibular data and data from the other parts of the receptor-field seems fairly clear. Only occasionally did the sound displacement data occasion ocular deviation, or the illusion of rotation, when they were opposed by the data of standing still from the rest of the receptor-field. Electrical or thermal stimulation of the vestibule on the contrary regularly produces illusions of rotation and ocular reflexes even when it is opposed by negative data from all the rest of the receptor-field. Apparently, something analogous occurs in a common tendency of amateur navigators in the fog, which leads them to distrust the accuracy of the compass, when vestibular data indicate that they have been going straight. Similarly, air-pilots may fail to realize from the tension of straps and other kinesthetic data that they are flying upside down when their rotation has been too slow to be reported by the vestibule.

There seems to be no intrinsic reason, however, why any part of the receptor-field may not be reinforced or inhibited by proper training. The expert navigator trusts his compass implicitly in spite of negative indications from the vestibule. We have already seen that vestibular reflexes and consciousness of rotation may be inhibited by training.[1] It is highly probable that kinesthetic and pressure data could be made to control conduct in the air, if systematic training were designed for that result.

How far data from various parts of the receptor-field may reinforce each other we have only incidental experiences to indicate. Consciousness of rotation at or near the threshold was undoubtedly aided by environmental sounds and pressures of various sorts. A systematic quantitative study of these reinforcements and inhibitions would be illuminating but difficult.

[1]Journal of Experimental Psychology, 1923, VI., pp. 15 fol.

Thresholds of the Vestibular Mechanism

Three separate experimental stimulus-forms were utilized in our study of vestibular thresholds. The first was a succession of five and ten degree movements with sudden onset and *constant angular velocity*. The second was a series of ten degrees rotary movements approximating in angular acceleration and deceleration a *true sine wave*. The third was a succession of movements of considerably greater angular extent in which the *arithmetical acceleration was approximately constant* for twenty degrees of rotation. All three of these stimulus forms depended on the drive of a constant speed motor which operated on an offset arm from the rotating platform at a distance of one meter from the axis of rotation.

Constant Speed Motor

The effort to find a suitable constant speed motor delayed the experiments many weeks. It was highly important not only that the motor should be reliable within the limits of our experimental requirements but that it should be noiseless and especially that no noise should be produced by changing its load. Pursuant to statements of Dr. Seashore on the accuracy of high grade phonograph motors and because they operate quietly we were led to try out several types. There is a real need for a critical comparison of different makes of phonograph motors for psychological laboratory use. We were limited to relatively few but in that limited exploration of the relative value of different makes we found one that seemed eminently satisfactory at a reasonable cost. All the electric phonograph motors that we tried made too much noise. The hum of the magnet was usually audible even when there was no noticeable noise of moving parts. The best electric motor in our experience was the one built by the Pathé Company on the plan of an electric meter. It consists of a disk rotating in the magnetic field produced by an alternating current. The hum of this motor is very faint and there is no noticeable noise of moving parts. Unfortunately, the magnet noises which result from the addition of a load in moving the chair were reported by several observers. The heavy Pathé spring motor, on the contrary, operated at moderate speed entirely without noises which could be detected at a distance of a meter. The subject was not able to state when the motor started or when it stopped. There was no noticeable change when a load was added to it. The strength of the heavy spring was at all times more than was necessary to operate the controlling device, irrespective of the work that the motor was required to do in producing slow movements of the platform.

The driving pulleys were attached directly to the main shaft of the phonograph motor. They consisted of a cone of four pulleys, respectively, one fourth, one half, three fourths, and one inch in diameter at the foot of the V-shaped grooves. This gave the possibility of four variations in speed according as the belt was driven by one or another of these pulleys without alteration of the device which controlled the speed of the motor. We adjusted the speed of the motor so that the smallest pulley, applied directly to the offset arm of the rotating platform one meter from its axis of rotation, gave an angular velocity of one degree a second. The several pulleys gave corresponding angular velocities up to four degrees a second without readjusting the motor control.

Stimulus Forms

The three physical factors involved in rotation, namely, angular velocity, angular displacement, and angular acceleration are not entirely separable although each may be varied independently of the others. With any given angular velocity the total angular displacement is a function of time. But unfortunately, the duration of the stimulus is not the only stimulus phenomenon that is conditioned by protracted slow rotation. Increased angular displacement increases the probable interaction of various reinforcing factors such as change in the apparent position of sounds, direction of air currents, heat radiators from adjacent walls, and the like. It also produces definite adaptation phenomena. Every stimulus must reach its maximum velocity by some sort of acceleration. Small angular velocity may involve high acceleration for short periods. For example, an angular velocity of one degree per second may be attained in a tenth of a second. This would represent a stimulation onset of relatively high angular acceleration for a short period of time. Conversely, protracted slow angular acceleration might reach an angular velocity of indefinite magnitude if it were continued long enough. The effort to experimentally explore the relative effects of angular velocity and angular acceleration in vestibular stimulation gave rise to three stimulus forms.

Stimulus Form I (Sudden Onset and Constant Velocity)

In the first stimulus form (sudden onset and constant velocity) a continuous belt between the pulleys on the axis of the constant speed motor and a friction pulley in the hand of the experimenter was connected with the offset arm. According as the connection between the belt and the arm was made with the outgoing or returning side of the continuous belt the platform moved clockwise or counter-clockwise. We realized that the connection of the belt with the offset arm must be noiseless, positive, and immediate in its operation. We, consequently, experimented with a number of clamp devices and finally came to use a small peg on the offset arm, covered with surgeon's plaster, sticky side out. The thread belt moving toward or away from the motor could be brought into contact with this surface effectively and noiselessly with a minimum of effort. When the connection was made there was no slip and no noise. No serious additional friction was imposed by this device on the motor, except the friction of the platform bearings.

Photographic records of the onset showed that, though the velocity did in fact remain satisfactorily uniform, there was considerable variation from time to time in the onset acceleration. Practice in manipulation diminished this variation but it was inherent in the method.

Stimulus-form II (Sine Wave Acceleration)

In order to standardize the acceleration a secondary driving-wheel was interposed between the motor and the offset arm of the rotating platform. This secondary driving-wheel was connected with the offset arm by a rigid driving-rod. The driving-rod operated through cone bearings, one on the offset arm and one on the periphery of the wheel. The diameter of the wheel at the base of the V-shaped groove was the length of a double sine of five degrees of rotation of the rotating platform measured on the arc described by the cone-bearing on the offset arm. That is to say, one-half revolution of the driving-wheel would move the rotating platform through an arc of ten degrees. Continuous rotation of the driving-wheel under these circumstances oscillated the platform back and forth through an arc of ten degrees with a maximum velocity of one, two, three and four degrees per second according as the belt was on one or another of the cone of pulleys at the motor. In routine experiments the oscillations were interrupted at the extremes of each swing at a time when the angular velocity of the rotating platform was zero. The consequent form of the rotary movement may be described as follows: starting at zero the rotation reached a maximum velocity corresponding to the speed of the pulleys on the motor and declined again to zero as the cone bearing on the wheel reached its diametrically extreme position. In order to prevent the subject from rationalizing the sequence of clockwise and counter-clockwise rotations and prejudging what direction the next movement would take, the driving rod was fitted with two cone bearings which were separated by the diameter of the driving-wheel. By this device, after a clockwise movement of ten degrees, a shift of the driving-rod to the second bearing would permit a second clockwise movement of ten degrees, if contact between the driving bar and the pulley were interrupted entirely until the driving wheel reached its original position. With this arrangement the sequence of movements could not be predicted by the subject. The order of directions was determined by chance.

Stimulus-form III (Arithmetical Acceleration)

Our first effort to produce arithmetical acceleration was to interpose between the motor and the offset arm of the rotating platform a screw-shaped pulley which was turned on the surface of a cone. If this conical screw accelerator was driven at a regular rate by the motor, a thread from the offset arm of the rotating platform winding up on the screw would produce a regular acceleration corresponding to the continually changing diameters of the cone. This arrangement gave a perfectly even acceleration of the platform after it once started. Unfortunately, the beginning of motion regularly produced a slight but often perceptible jar. This resulted from the construction of the screw accelerator. The winding process did not start at absolute zero but at a velocity corresponding to the diameter of the little shaft on which the screw was turned. We had hoped that this initial inequality would be so slight as to be insignificant. When this proved not to be the case, the jar was completely eliminated by combining the screw accelerator and the driving-wheel of stimulus-form II. This cost the acceleration something of its previous mathematical exactitude, but the onset was always imperceptible.

No combination of driving-wheel and conical pulley that we worked out would give an absolutely even acceleration. Theoretical plotting of the curves and empirical corrections from photographic records showed that it was desirable to flatten the pulley so that the radius of curvature should gradually increase for the first few degrees of rotation of the chair. The accompanying photograph shows the best configuration that we were able to obtain. It looks to be perfectly even. An analysis of the rotation indicator of two photographic records shows the series of accelerations by two second intervals as given in Table I.

Table I shows the acceleration of rotation by combined conical screw accelerator and flattened driving-wheel, by two second intervals, reduced to hundredths of a degree. This was the unit of measurement.

TABLE I

11	11
9	10
8	10
10	12
11	10
12	13
13	10
14	12
10	10
11	13
11	10
9	9
10	10
Av. 10.7	10.7
M.V. 1.3	M.V. 1.1

Photographic records of these several forms of stimulus are shown in Plate II, Records 1 and 2.

Method of Report in Rotation Threshold Experiments

The manner of reporting awareness of rotation in rotation experiments is a matter of some importance. The simplest method of report might seem to be vocal, such as 'right,' or 'left,' 'clockwise,' or 'counter-clockwise.' Such vocal reports, however, demand a certain division of attention. They are of the nature of distractions from the main experiment. That is to say, the subject must not only perceive the direction of rotation but he must be careful to select the correct designation. Surprising as it may seem, the designations, right and left, required in many subjects considerable conscious effort. Nevertheless, once practiced, in series of discontinuous rotations, verbal reports are probably satisfactory.

The use of periodic verbal reports during protracted rotation on the contrary have certain theoretical and practical objections. Our attention was called to these difficulties by the statement of one of our observers that speech disturbed his observation of a protracted slow rotation. This was for a while inexplicable except on the theory of distraction of attention. In view of other experiences we are inclined to believe that a real interference from peripheral sources may accompany speech. Observation showed that all respiration moved the head more or less and produced undulatory illusions in protracted rotation. The best observations demanded relatively low respiration. Under these circumstances it is probable that articulation through its effect on respiration and consequent movements of the head introduces real vestibular disturbances that would tend to confuse threshold phenomena.

Wherever it was necessary to obtain actual records of the reports as part of the photographic record of the experiment we used manual report, *i.e.*, the pressing of keys. Like verbal report, manual report is capable of producing movement of trunk and head and should be restricted to finger movements of such a character that there was no consequent displacement of the body. The finger movement which proved most satisfactory was that of pressing a key between the thumb and fingers. Slight vertical movements of the fingers with the arms supported by proper rests also proved satisfactory.

Three forms of manual report were used for different purposes in those threshold experiments in which photographic records were taken. The first form was a predetermined arbitrary signal produced by pressing a telegraphic key between the thumb and fingers, either once for right movement (clockwise) or twice for left movement (counterclockwise). This telegraphic key was in series with the recording lamp and the breaks in the circuit appeared on the record as an interruption of the line which indicated rotation. This arbitrary signal did not prove to be satisfactory. It was unnatural, required practice, too much attention, and led to occasional false reactions. The second and third methods involved movements of the right and left hand respectively for right and left rotation. This method of reporting proved entirely natural, required no practice, and occasioned no unintended reactions. The second manual method involved pressing keys which lay under the right or left hand respectively, and which were connected by threads with the mountings of minute, concave mirrors. These mirrors reflected a recording beam on the right and left hand side of the record sheet. Judgments of rotation either to the right or left were indicated by displacement of the appropriate record line. Such records are reproduced in Plate III., Records 1 and 2. Judgments of no movement were indicated by both record lines remaining in their primary positions. The third manual method provided a telegraphic key for each hand. Pressing the right hand key interrupted permanently the electric circuit to the recording lamp and stopped the record of rotation. Pressing the left hand broke and immediately remade the lamp circuit, giving a short interruption of the record of rotation. These differentiated interruptions were entirely automatic and gave entirely satisfactory records. One added advantage of the manual report was the possibility of recording reaction latency as well as the judgment of movement and its direction. Not much weight is given to these measurements of latency, but they furnish some subsidiary evidence with respect to the threshold of rotation.

Vestibular nystagmus is doubtless the most natural indicator of rotation. It requires no attention nor voluntary effort. As a reflex it would seem to be the best possible indicator. Our experience in the study of the effects of repeated rotation led us to doubt the reliability of vestibular nystagmus in serial experiments. Nevertheless, a considerable number of ocular reactions were taken in conjunction with manual reactions. A comparison of the two methods of report has certain theoretical value in connection with the discussion between the thoroughgoing objectivists and introspectionists. Wherever taken the ocular reflexes were registered by the mirror-recorder. Two records are reproduced in Plate III., Records 1 and 2.

These records are the first and seventh, respectively, in a series of ten. Whereas in the first record the nystagmus of rotation and of stopping is clearly marked, in the seventh, taken at the same angular velocity, the nystagmus has almost disappeared. Similar changes occurred in all serial records.

It is somewhat surprising and, in view of certain pretensions of the extreme objective school, it is quite illuminating that, while the reflex tended to disappear, introspective indications of rotation were as accurate in the later records as they were in the first when the reflex was present.

Thresholds of Even Rotation with Sudden Onset

Rotation with sudden onset was produced by the mechanism of the first stimulus form, already described. That is, a continuous belt from the pulley of the motor was momentarily brought into contact with the offset arm and rotated the platform and the subject clockwise, or counter-clockwise, five or ten degrees according to a prearranged series of successive stimuli. The subject was instructed to report every change in his apparent condition of rest or motion. The velocities used were one, two, three, and four degrees of rotation a second. Reports were held to be correct when the report of rest or motion in either direction fell within any part of the period covered by the objective facts. That is to say, if during any period of rest or motion it was correctly and unambiguously reported the report was held to be correct however late it may have come in the period on which report was made. In all subjects 1° per second yielded an average of less than fifty per cent. of correct reports. For three subjects out of four, 2° averaged over fifty per cent. of correct reports. The details of these reports are shown in Table II. These records indicate that the threshold of rotation with sudden onset lies somewhere between one and two degrees per second. If one assumes that with three possible answers, clockwise, counter-clockwise, and still, the point of pure chance would lie at thirty-three per cent. correct answers, then the theoretical threshold would lie close to one degree per second. It should be noted, however, that for practical purposes the incidence of correct interpretation of vestibular data of fifty per cent. would be useless. It would mean that a subject was wrong just as often as he was right and the vestibular data would be absolutely unreliable. For practical purposes, consequently, the threshold of serviceable stimulation would lie close to 2° per second. Even at double this rate, however, it should be remembered that the vestibular data are not entirely reliable.

TABLE II

PERCENTAGE OF CORRECT VERBAL REPORTS OF CHANGES IN ROTATION, SUDDEN ONSET AND STOP

1° per second

B	JSF	N	RD	W
42	No records	33	22	No records
33		31	55	
31		28	55	
25		28	22	
55		39	—	
Average 37		32	39	

2° per second

B	JSF	N	RD	W
No records		56	58	
		72	67	
	69	81	70	25
	58	64	45	42
	31	72	64	47
Average..................	53	69	61	38

The procedure in these experiments was as follows: with the subject in position, eyes closed, head against the head-rest, arms on the arm-rests, after a ready signal, the platform was rotated by the belt from the motor at a speed of one, two, three and four degrees per second, either five or ten degrees clockwise or counter-clockwise according to a prearranged program. A five second period of no rotation intervened before each period of rotation. The prearranged schedule of rotations and pauses was plotted on cross section paper so that the experimenter had before him not only the program and plan of rotation but a record-sheet on which the responses of the subject could be noted as they were made, at approximately the correct moment of the process which was reported.

A number of interesting phenomena were disclosed by a study of these records. One of the most notable and one of the most frequent errors was the failure to note the actual rotation but to report as true motion the illusion of reversal after rotation had ceased. That is to say, slow clockwise rotation of ten degrees might pass unnoticed, but when it stopped the subject would be apt to report counter-clockwise rotation from the illusion of stopping. Similar errors might be disastrous in flying. A related phenomenon was more persistent, lasting on occasion through three of four changes of rotation. If, for example, the subject reported 'still' when he was moving clockwise, and 'counter-clockwise' when he stopped, he would not infrequently report 'still' when the movement was again clockwise. Occasionally a false orientation of this sort would reach further and false reports would be continued for several successive changes in the rotation. The rotation changes would be clearly distinguishable to the subject as changes. Interpretation of the sensory data proved less easy, or rather, less reliable. With more rapid rotations the subject frequently noticed a difference between onset and continued rotation. One subject reported 'it starts vigorously and disappears or fades away as though in the air.' Similar reports were not infrequent. This emphasized the necessity of experimenting with the second stimulus form.

Another series of threshold experiments with sudden onset and even rotation included the photographic records of eye-movements, manual reports of the second type, and rotation indicators. Each complete record lasted approximately fifty seconds. While the number of rotation changes within this period was necessarily few, the graphic method of report provided for much closer estimates of the perception of rotation and rest.

Consequently, in these experiments we did not merely count the number of right and false reports; but estimated the degree of correctness of the reports by counting the number of times that the two second time-lines occurred during correct reports of rest or motion as indicated by the manual method. Parts of two records are reproduced in Plate III. The percentages of correct judgments by two second intervals are given in Table III.

The fatigue experiments show the effect of beginning the series of judgments one minute after the series of rotations commenced.

Table III

Per cent Correct Judgments by 2 in. Intervals, Rapid Onset, Unknown Series of Speeds and Directions.

N				RD			
1° per second	2°	3°	4°	1°	2°	3°	4°
35	81	65	81	31	41		
27	50	54	96	10	20		
50				26	50		
46				37	50		
46	90	76	86	18	32		
62		71		54	32		
43				27	59		
				41	50		
54	72	67	92	59	18		
33	58	50	92	50			
16				63	77	83	62
12				65	73	70	50
				40			
				23			
				30	73	86	93
				75	63	27	90
Average, 39	70	64	89	41	49	66	74
Fatigue Experiments							
28							
22	75	44	93				
41	56	67	65				
Average, 30	65	55	79				

Thresholds of Rotation with Sine Wave Accelerations

The third experiment resembled the second except that the onset and stop were gradual instead of sudden. Rotation was produced by the driving-wheel. It was always ten degrees in extent and had the approximate form of a sine wave acceleration (see Plate II., Record 1). The results of this experiment are given in Table IV.

Perception of Oscillation

Following the precedent of our previous study of the effect of protracted rotation it seemed worth the effort to discover how the perception of oscillation differed from the threshold of rotation. The mechanical conditions for such an experiment were already furnished by the driving-wheel with the driving-rod connection between wheel and offset arm. If the driving-wheel was permitted to rotate continuously the platform and subject were oscillated back and forth through an angular distance that was determined by the diameter of the driving-wheel and the length of the offset arm, with a frequency that was determined by the speed of

TABLE IV

PERCENTAGE OF CORRECT VERBAL REPORTS OF CHANGES IN ROTATION. GRADUAL ONSET AND STOP

Maximum Speed	N	RD	JSF	W
1° per second	37	49	—	—
2° per second	65	44	—	—
	72	65	54	54
	80	48	49	24
	58	59	—	—
	72	54	—	—
	73	44	—	—
Average	70	52	51	39
3° per second	88	51	—	62.5
4° per second	71	95	—	69.8

the driving-wheel. Physically, such rotations took the form of harmonic oscillations in approximate sine waves of acceleration and deceleration. This wave form was only approximate since a true sine wave form would have required a driving-rod of infinite length between the driving-wheel and offset arm. Moving the axis of attachment on the driving-wheel toward its center by distances of one-half and three-quarters of its radius, respectively, reduced the amplitude and maximum velocity of oscillation in direct ratio without varying the frequency. In this manner three oscillation forms were obtained for each of the four normal speeds of the drive pulley as they were produced by the four pulleys on the axis of the constant speed motor.

Oscillation as contrasted with simple rotation exaggerated the importance of the acceleration in distinction from the angular velocity component of the stimulus. In our ignorance of the exact physics of vestibular stimulation the physical theory cannot be followed to its logical conclusion. But the results of the experiment leave no doubt of the importance of the acceleration feature. The effects of oscillating the walls of the vestibule against the momentum of the vestibular fluids would increase the total relative pressures by an amount which would depend on the frictional acceleration of the fluids. In other words, in a frictionless system in which the walls of the container move around a stationary fluid, maximum relative motion would coincide with maximum motion of the walls. Given a frictional acceleration of the fluids, however, which was almost equal to the angular displacement of the walls, then the greatest relative motion would occur when the walls suddenly reversed their direction. Under the latter circumstances one would also obtain markedly increased pressures against the appropriate walls of the vestibule.

The results of these oscillation experiments, as exhibited in Table V., seem to show a bewildering lack of regularity. Some facts, however, are conspicuously clear. In the first

Table V

Table V shows the percentage of correct judgments of direction of movement during oscillations of various amplitudes and frequencies. It also shows average reaction latencies in seconds, measured from the beginning of each oscillation.

Maximum Velocity	1° per Second			2° per Second			3° per Second			4° per Second		
Measured rate of oscillation	32″			16″			11.4″			8.4″		
One quarter oscillation	8″			4″			2.8″			2.1″		
Amplitude in degrees	2.5	5	10	2.5	5	10	2.5	5	10	2.5	5	10
Maximum[1] velocity, deg. per 1 sec.	.25	.5	1	.5	1	2	.75	1.5	3	1	2	4
Subject N:												
Per cent. right	40	50	86	8	33	96	44	96	100	72	82	54
Latent time in seconds	10	4.3	1.9	(.5)	2.8	1.2	3.1	1.6	1.9	1.5	1.7	1.6
Subject RD:												
Per cent. right	40	50	43	3	7	31	14	0	71	0	70	66
Latent time in seconds	3	7	10	5.7	5	2.4	.5	—	2	—	1.6	2

[1] Speed of driving-wheel in terms of angular velocity of the platform.

place, the individual differences between N, the graduate student, and RD, the older subject (myself), are more conspicuous in these oscillations than in any other phase of the threshold experiments. In both cases, however, the threshold for oscillation stimulus seems to be much lower than for direct rotation. In the case of subject N it lies conspicuously below a maximum velocity of one degree per second. In the case of RD the data are conflicting for reasons which will be discussed presently. But the fact that fifty per cent. of correct answers were given at a maximum velocity of one-half degree per second cannot be overlooked. A third obvious fact is the extremely long reaction latencies, especially in the case of RD. Analysis of the relation between these reaction latencies and the frequency of right judgments shows that the reaction latency may have a profound effect on the percentage of correct judgments.

The most conspicuous fault in the record of RD is found in cases of small amplitudes of the more rapid oscillations. In these cases there was zero ability to distinguish either oscillatory rhythm or the direction of movement. This seemed inexplicable until we took into account the long reaction latencies of RD. The average reaction time to oscillation in his case was 3.9 seconds. The most rapid double oscillation lasted 8.4″. At this rate each phase of acceleration would last 2.1″, which was considerably shorter than the reaction latency of RD. Under such circumstances it is a defensible supposition that increased demands on discrimination with a presumptive lengthening of reaction time would bring each successive reaction within the influence of a phase of oscillation which was different from that by which it was initiated. Confusion would seem to be inevitable. It is in fact shown by the notable breakdown of correct judgments with oscillations of small amplitudes in both the higher two speeds.

The more rapid reactions of subject N free his record from extreme disturbances of this sort. Under only one of the experimental circumstances did his average reaction time substantially exceed the duration of a single phase of oscillation. But even in his case it is conspicuous that the highest percentage of correct judgments is not found in the case of most rapid oscillation but rather in the 10° movements at lower speeds.

Perception of Arithmetical Acceleration

There remains to be considered the perceptibility of arithmetically accelerated rotation. As it was produced by our combination of driving-wheel and conical screw accelerator this arrangement developed maximum angular velocity only after approximately 20° of rotation at a uniform rate of acceleration. The percentages of correct reports of rotation series, in which five clockwise, five counter-clockwise rotations, and five similar periods of no rotation followed each other in chance order, are shown in Table VI.

Table VI

Percentages of Right Responses During Slow Accelerations

Maximum Velocity per Second	Subject N			Subject RD			Subject F			
	2°	3°	4°	2°	3°	4°	1°	2°	3°	4°
	53	67	93	33	20	87	60	93	93	80
	47	73	93	13	40	40	80	73	73	93
	66	67	87	40	53	73	70	83	83	86
	60	80	87	47	53	53	93	80		
							60			
Average	56	72	90	33	41	63	73	82	83	86

Table VI. shows large individual differences of sensitivity to the conditions which were presented in this experiment. Precautions to prevent extraneous data for the perception of rotation were taken as follows. Cotton was put into the ears of all subjects to shut out slight noises of the movements of the operator, etc. A motor fan, which stood on the rotating platform, was run during the experiment to cover any mechanical indications of motion that might have come from slight vibrations of the platform. Head and arm-rests were used as in previous experiments. Only one warning signal for each series was given. That signal preceded a series.

The most conspicuous phenomenon of this group of experiments was the peculiar and, in our experience, unique sensitivity of subject F. Our effort to discover the basis of this amazing sensitivity included a variety of modifications of the conditions of the experiment. These may be enumerated as follows: The subject's head was completely covered to shut out supposititious temperature radiations. Cushions were used on the seat, head and arm-rests to decrease contact changes. Head and knee contacts were eliminated. A telephonic head-set was worn giving a loud buzzing of the alternating current. Special blinders excluded all possible clews from shadows or other visual data. The last item in the 2° per second column and the last two items in the 1° per second column show the percentage of right answers after all these special precautions were taken. The conditions of the unusual sensitivity of subject F to gradually accelerated rotation were not discovered. He was an unusually conscientious and intelligent undergraduate and expressed himself concerning the phenomenon as follows: "I do not seem to feel any motion but I realize that I have changed my position in space." He conjectured that his experience in fancy diving had perhaps given him some unusual training in space orientation which he was unable to explain. The subject stated that he was able to keep his direction on the water in fog with a facility which surprised both himself and his companions. Tests of a colleague on the swimming team, also a skillful diver, showed no parallel sensitivity. Exceptional cases such as that of subject F ought to prove of peculiar value wherever the ability to keep orientation is of significance. Both the subject's introspection and his previous records as given in Table IV. would seem to indicate that we were not dealing in his case with mere vestibular functions.

General Conclusions

A summary of the percentages of correct judgment of rotation under the varying circumstances of our experiments is given in Table VII.

TABLE VII

SUMMARY OF PERCENTAGES OF CORRECT JUDGMENTS OF ROTATION UNDER VARIOUS CIRCUMSTANCES OF OUR EXPERIMENTS

Subject N				Subject RD			
Rapid Onset							
1°	2°	3°	4°	1°	2°	3°	4°
32 39	69 70	64	89	39 41	61 49	66	74
Sine Wave Onset							
37	70	88	71	49	52	51	95
Oscillation 10°							
86	96	100	54	43	31	71	66
Arithmetical Acceleration							
—	56	72	90	—	33	41	63

Under our experimental conditions, the threshold for rotation of rapid onset seems to be somewhere between one and two degrees per second, but a velocity of four degrees per second was too slow to produce uniformly correct judgments of rotation. Real assurance of the correctness of judgment of rotation obviously depends on angular velocity exceeding four degrees per second.

The difference between rotations of sudden onset and rotations of similar maximum velocity whose acceleration had the form of sine waves appears to be negligible within the limits of our experiments. Arithmetical acceleration, on the contrary, presented unfavorable conditions for the perception of rotation in the case of subject RD and favorable conditions for subject F.

The most irregular results occured in connection with the oscillatory rotations.

Our exploration of the thresholds of rotation represents only rough, though probably useful, approximations. The investigation of an absolute vestibular threshold for which it has prepared the way would require the elimination of the numerous sources of error which became clear in our experiments. Definitive measurements demand a sound and light proof room with felt walls to prevent temperature radiations. The driving mechanism should be outside the sound-proof room. The rotation should have definite configuration of onset and stop, probably of the sine wave form. The axis of rotation must be strictly vertical and the rotation must be free from jar and vibration. We know of no practicable means for eliminating those data of rotation that come from the dermal and kinesthetic extensions of the receptor-field. Report indicators should be natural and without disturbing influence on vestibular function. Our experience favors manual indicators. For theoretical purposes warning signals should doubtless precede each rotation.

If a simple test of the individual differences should become desirable it would probably be sufficient to limit it to a single stimulation form and a single maximum angular velocity. Rapid onsets could not be kept uniform. Gradual acceleration which showed the greatest individual difference was a tedious performance. The sine wave form of acceleration and deceleration is a rapid technique and affords the best guarantee against uneven starting and stopping. It is probably the best test form. If a single speed only is used, the best speed of rotation for such tests would probably be a maximum of 2° per second. That lies near the critical value. The percentages of correct responses to a continuous series of clockwise, counter-clockwise movements, and stops would furnish an unambiguous indication of the relative position of different subjects with respect to their ability to perceive and interpret rotation data. Any simple device which would give the subject's reaction time would doubtless increase the value of the test.

The implications of our threshold data with respect to direct orientation in the air may be expressed as follows:

1. Vestibular data from rotations of less than 2° per second are quite unreliable. With double that velocity judgments are often false.

2. Taking our previous study of the results of protracted rotation into consideration the vestibulai problems in flying would seem to be:

(*a*) Under what conditions in the air are vestibular data sufficiently accurate to be useful?

(*b*) How may vestibular illusions of rotation be corrected or compensated?

(*c*) How may we develop, coördinate, and systematize data from the various parts of the receptor-field into the most effective control of flying under varying circumstances? These circumstances should include the temporary loss of visual data at night or in fog, as well as the illusions of vestibular and of centrifugal origin.

Plate I

The records of Plate I. represent the effort to determine whether the receptor-field for ocular nystagmus includes audition. Record 1 shows a fine nystagmus with a compensatory deviation corresponding to the rotating sound. During this record there was a subjective illusion of drifting in the opposite direction to the rotation of the sound-cage.

Record 2 shows an exaggerated coarse nystagmus that occurred in a record during which the subject reported good illusions of rotation.

Record 3 represents a series of experiments in which sound-cage rotation and moderate oscillation of the subject were coincident. It shows a certain amount of rivalry and facilitation according as the direction of actual rotation opposed or was congruent with the movements of the sound-cage. Suppression of the vestibular deviation and substitution of deviation congruent with the movements of the sound-cage are indicated by *A.* Lesser degrees of interference are indicated by *B.* Deviations apparently caused exclusively by the sound are indicated by *C.*

Plate II

Record 1 of Plate II. is the photographic record of harmonic oscillations in the form of sine curves as they were produced by the interpolation of a driving wheel and driving rod between the motor and the offset arm of the rotating platform.

Record 2 is the photographic record of arithmetical acceleration as it was produced by the interpolation of the screw-shaped driving cone and the driving wheel between the motor and the offset arm of the rotating platform. The figures at the extreme right of record 2 show the measured accelerations in degrees by two second intervals. The unit of measurement was one hundredth of a degree.

Plate III

Plate III. shows photographic records of the course of even rotation with rapid acceleration and deceleration. In both of these records the rotation indicators have been retouched to render them more legible but the general character of the rotation

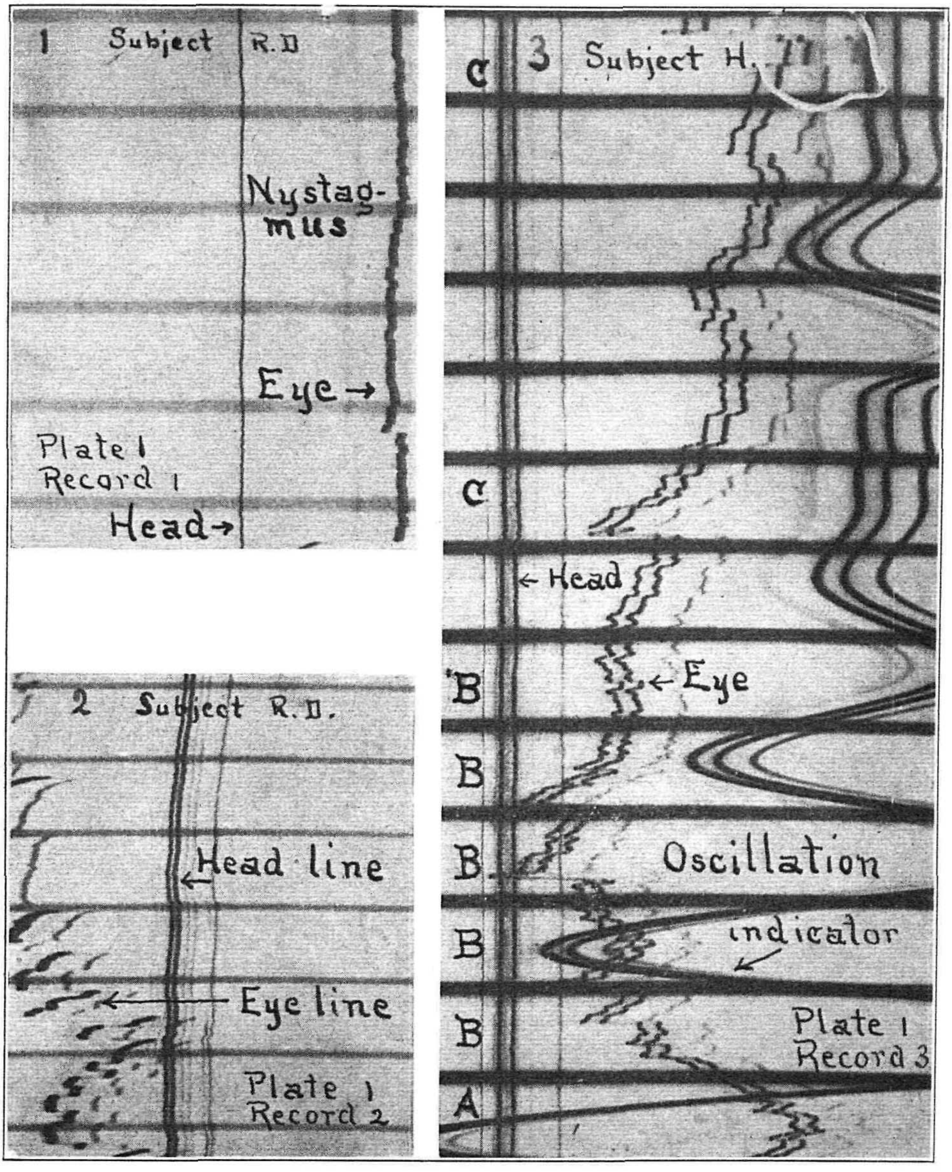
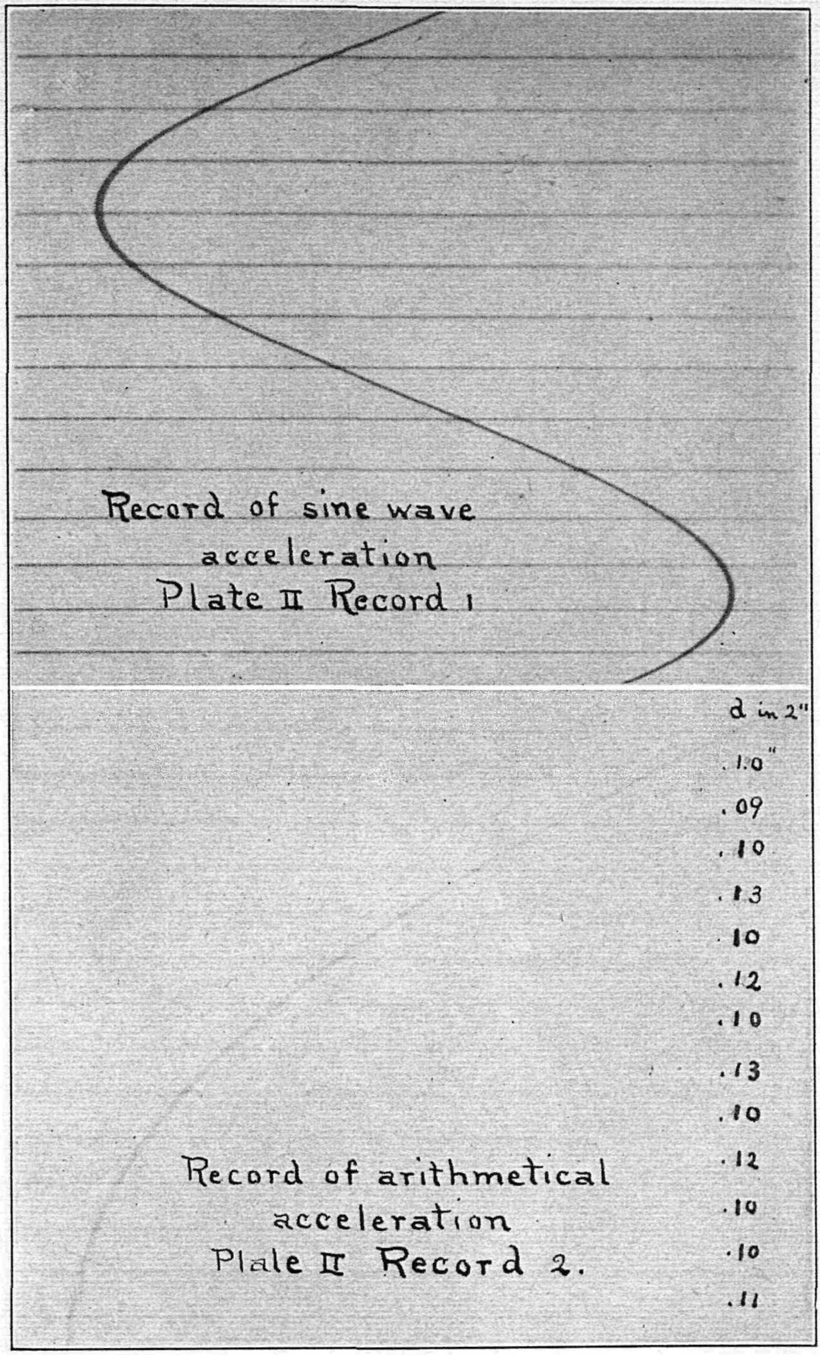
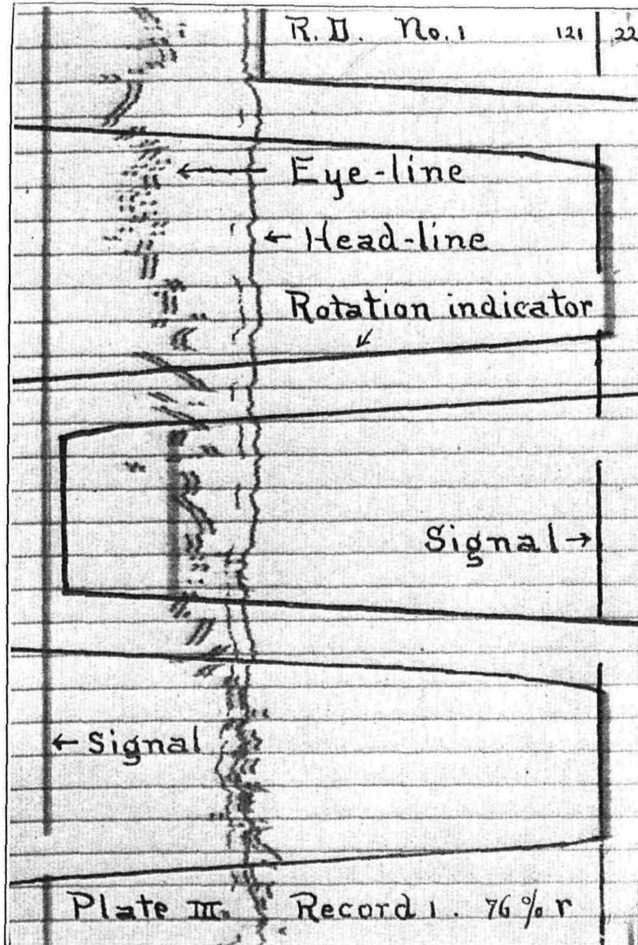


Plate I. Nystagmus produced or modified by rotating sounds.

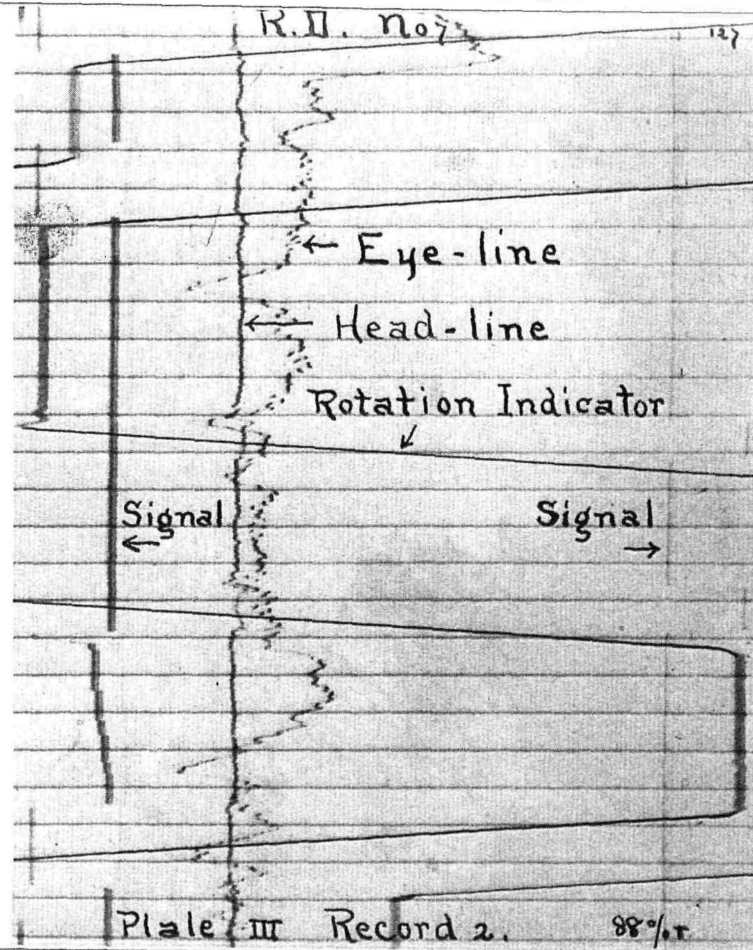


Records 1 and 2.

Plate II. Records of rotation with sine wave acceleration and with arithmetical acceleration.



Record 1.



Record 2.

Plate III. Records of responses to show rotation with rapid onset showing the disappearance of vestibular nystagmus after slight habituation.

and its irregularities at the moment of starting and stopping have not been altered. Second, it shows the disappearance of the compensatory nystagmus during a series of records of nearly threshold velocity.

Record 1 of Plate III. shows a series of rotations at four degrees per second. The compensatory deviations and nystagmus are clearly marked.

Record 2 is the seventh record of the series taken under similar conditions of rotation in which the compensatory deviations have either disappeared entirely or have been greatly reduced with a consequent complete change in the appearance of the eye record. It is significant that in record 2 the subjective knowledge of rotation was slightly more accurate than in record 1.