

ASSESSMENT OF SEMICIRCULAR CANAL FUNCTION: I. MEASUREMENTS OF
SUBJECTIVE EFFECTS PRODUCED BY TRIANGULAR WAVEFORMS OF
ANGULAR VELOCITY

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SUMMARY PAGE

THE PROBLEM

Development of methods and procedures to provide a reliable measurement of sensations produced by semicircular canal stimulation.

FINDINGS

Two methods were compared for measuring subjective angular displacement produced by triangular waveforms of angular velocity while subjects (N = 11) were enclosed in a vertical-axis rotation device that excluded visual and auditory cues of angular motion. Accuracy of subjective estimates was influenced by the methods and by the magnitudes of the accelerations comprising the stimulus waveforms. Results suggest that one of the methods, with slight modification, will provide reliable indication of the subjective effects of controlled semicircular canal stimulation. A follow-up experiment, reported separately as Part II, deals with this modification.

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INTRODUCTION

Two well-known aspects of the general reaction to semicircular canal stimulation which tend to co-vary in magnitude and direction are nystagmus and the sensation of rotation. However, it has also been clearly demonstrated that there are systematic departures from strict correspondence between the sensation of rotation and nystagmus. Sensation may decline while nystagmus does not (12, 14); sensation may stop while nystagmus continues (14); the slopes of sensation and nystagmus cupulograms are not the same (8, 9, 16).

The fact that sensation differs systematically from nystagmus in certain circumstances indicates that sensation reflects neural function which differs in some respects from that which mediates nystagmus. "Of these two measures, the nystagmus response is the more stable (Benson, 1967), but the subjective response has greater relevance to the illusory sensations which disorientate aircrew and to that common symptom of labyrinthine disorders, vertigo" (2). It is, therefore, important to assess sensation as well as nystagmus in the evaluation of vestibular function for it is possible that the sensation may provide an indication of function which is not assessed by evaluation of the nystagmus response alone.

Several methods have been used to measure the sensation of rotation produced by semicircular canal stimulation and these methods may be categorized roughly into: 1) methods in which the subject reports the onset or the cessation of the sensation, i.e., time measures; 2) methods in which the subjective velocity is estimated directly; 3) methods in which angular displacement is estimated by requiring the subject to signal each time he has rotated through a given angular displacement.

Each of these methods has been used with some success. The time measures have served a useful purpose in the past (8-10, 16) and they may remain important in the future with oscillatory stimuli (17) and with triangular waveforms (15), although the usefulness of cupulometry as a predictor of airsickness has been challenged (7). Cupulometry involves measurement of the duration of the gradually decaying after-sensation from an angular impulse, and the subject must estimate the end of a gradually decaying sensation. Threshold judgments of this type are usually variable (cf. 12, p. 71), and there is the added disadvantage that only one data point is obtained with each stimulus. This leads to a lengthy procedure for obtaining stimulus-response relationships.

The immediate sensation produced by simple stimulation of the canals seems to be subjective angular velocity, and the method of magnitude estimation (20) would appear to be applicable to measurement of the magnitude of subjective angular velocity throughout the course of the response (3, 5). This method (and related methods) is advantageous in that it yields data which permit comparison of relative magnitudes during the time course of a single response and during iterative stimulation, but the method does not permit comparison between subjects of response magnitude. The data

are analogous to readings obtained from an uncalibrated tachometer or speedometer; the speed can be observed to be increasing or decreasing or constant, but its magnitude is unknown. Thus, between-subject comparisons can be made on rate of change of "subjective magnitude" or in regard to relative peak magnitudes with different stimuli, but there is no basis on which to decide whether or not one subject has a response of greater magnitude than another at a comparable point during the course of a stimulus. This is true aside from any consideration of the difficulty of the subject's task; the method simply does not provide this information. Because assigning numbers in arbitrary units to the magnitude of the instantaneously sensed velocity is not a natural judgment, magnitude estimation requires instruction and practice (3,5).

The repeated judgment of angular displacement during the course of a stimulus and its after-effects is another method which has been used for studying subjective angular velocity. Typically, the subject has been asked to signal each time he has rotated through some prescribed angle, e.g., 90, 180, or 360 deg, and the stimuli have produced sensations of magnitudes and durations which required a number of successive estimates (1, 11, 12, 14). Time between successive signals has been used to calculate mean subjective velocity within intervals. It appears likely that some of the difficulty encountered with this method may arise from the stimulus characteristics which necessitate making series of successive estimates. The subject is either encapsulated or in the dark, and therefore he must imagine an external reference point from which to commence his displacement estimate. Assuming that the immediate vestibular sensation is angular velocity, the task requires the subject to integrate his angular velocity data over time, to maintain a fixed concept of whatever angle is prescribed for estimation, to signal when this angle has been traversed, and then to imagine anew another fixed external reference point from which to recommence his angle estimation task. The prolonged maintenance of a fixed external reference and shifting to new points of reference seem to be sources of difficulty. The instruction to "signal every time you rotate through 90 deg," although it sounds simple, demands a fairly difficult set of judgments from the subject. In many subjects, lengthy instruction and practice are required before the subject gains confidence that he is performing the task and before the responses produced conform approximately to the theoretical expectations. Such procedures are acceptable for experimental purposes, but they are not practical if subjective data are to be useful in evaluating large numbers of people.

However, the judgment of angular displacement has the advantage that the natural experience of the individual provides a concept of magnitudes of angular displacement. Most subjects have well developed concepts of the navigational consequences of a quarter turn, a half turn, or a full turn. If two people signal that they have turned in 1 sec through different angles, e.g., a quarter turn vs. a full turn, then there is reason to believe that the magnitude of the average subjective angular velocity was greater in one person than in the other. This method of estimating subjective velocity may be suitable for the study of individual differences in response magnitudes as well as in regard to the changes in magnitude over time or with different stimuli or with iterative stimulation if the problem of training the subject can be overcome.

It would appear that most of the difficulties encountered in this method can be reduced by using stimuli which produce the sensation of turning through a short arc and by providing the subject with a device for indicating his perceived angular displacement. Man turns himself through small arcs with reasonable accuracy even in darkness, and this is a judgment which is made so frequently and easily in natural movement that it is not usually appreciated. In natural active movements, there is much more than semicircular canal sensory data available to regulate the desired angular displacement. However, when rotation about an Earth-vertical axis is passive and the subject is encapsulated to prevent visual (and other) cues about an external reference, the semicircular canals are probably the primary data source for judgments of angular displacement, and it was under these circumstances that subjects were tested in the present experiment.

PROCEDURE

SUBJECTS

This experiment is a study comparing two methods of subjective reporting and is preliminary to a second experiment (18) which examines one of the methods with a larger sample of subjects. Eleven young naval officers with normal vestibular function served as volunteer subjects in this first experiment.

APPARATUS

A rotation device with its axis of rotation vertical, i.e., aligned with gravity, was used. It was a Stille-Werner RS-3 rotator modified by attaching a concentric cylindrical enclosure (6 ft in diameter) to the rotary structure. The subject's head was positioned by occipital rests at the center of rotation and was ventroflexed to place the plane of the lateral canals approximately in the plane of rotation. The enclosure was lightproof, and to mask auditory localization cues, audiometric headsets supplied with "pink noise" were employed.

METHODS

Perception of angular displacement was indicated by two methods: A. Light displacement method: A spot of light was projected onto a white strip chart which conformed to the inner wall of the cylindrical enclosure. The subject was instructed to turn the light source in a compensatory direction in an effort to keep the light spot directed toward a fixed position in space; i.e., he was to maintain the light in a constant compass heading. The light source could be turned through 120 deg. Subjects were instructed to quickly reposition the light and recommence tracking in the event that the perceived turn exceeded the excursion limits of the light. In practice this never occurred. B. Dial indicator method: The subject viewed a circular dial (10-in. diameter) marked off in 10-deg intervals. The enclosure was dimly illuminated by a small light over the subject's head. The face of the dial was in the Earth-horizontal plane and was supported just above the subject's lap so that it was viewed with

a downward-directed gaze and at a reading distance of about 14 in. The subject was instructed to move a pointer on the dial in a compensatory direction so that the pointer would maintain a fixed (compass) heading.

The stimulus for each trial within a series was a triangular waveform of angular velocity in which the accelerations comprising the waveform were of the same magnitude and duration but of opposite sign. Durations and magnitudes of accelerations varied between trials. Figure 1 represents counterclockwise angular velocity waveforms used in the experiment; clockwise stimuli, not shown in Figure 1, would be represented by comparable triangles of the same form but inverted and projecting below the baseline. Angular accelerations used were of two magnitudes, 5 deg/sec² and 15 deg/sec². As a result, a given duration of a stimulus could not be associated with a particular displacement.

Two twenty-trial series, each series comprising ten clockwise and ten counterclockwise trials, were presented to each subject. Six subjects used Method A in the first series and Method B in the second series. Five subjects used Method B in the first series and Method A in the second series. The order of presentation of vestibular stimuli was scrambled, as shown in Table I, but it was the same for each subject in each series.

Although the perrotational responses were of primary interest, after-effect responses were also recorded. These had the form of a brief turning sensation of opposite direction to the primary response. As the after-effects were typically of brief duration, it was possible to use rest intervals of only 20 sec between stimuli.

RESULTS

The perceived angular displacements as indicated by recordings of the subjects' adjustments of the dial indicator and of the light spot were related to the actual angular displacements of the body as shown in Figure 2 for the 5 deg/sec² stimuli and in Figure 3 for the 15 deg/sec² stimuli.

COMPARISON OF METHOD A AND METHOD B

It is apparent in Figures 2 and 3 that the mean estimates made by displacement of the light spot were consistently less than the mean estimates made by displacement of the dial indicator. The slopes of the best-fitting straight lines were determined for each subject for each of the two series ("light series" and "dial series") to permit statistical tests of the differences in the stimulus-response relationships yielded by the two methods.* Table II presents 't' tests which indicate that the differences in the mean slopes yielded by the two methods are probably not attributable to chance.

*Straight line fits were used for simple statistical tests of the differences between methods. It is clear that data points for Method B with the 15 deg/sec² stimuli depart systematically from a straight line.

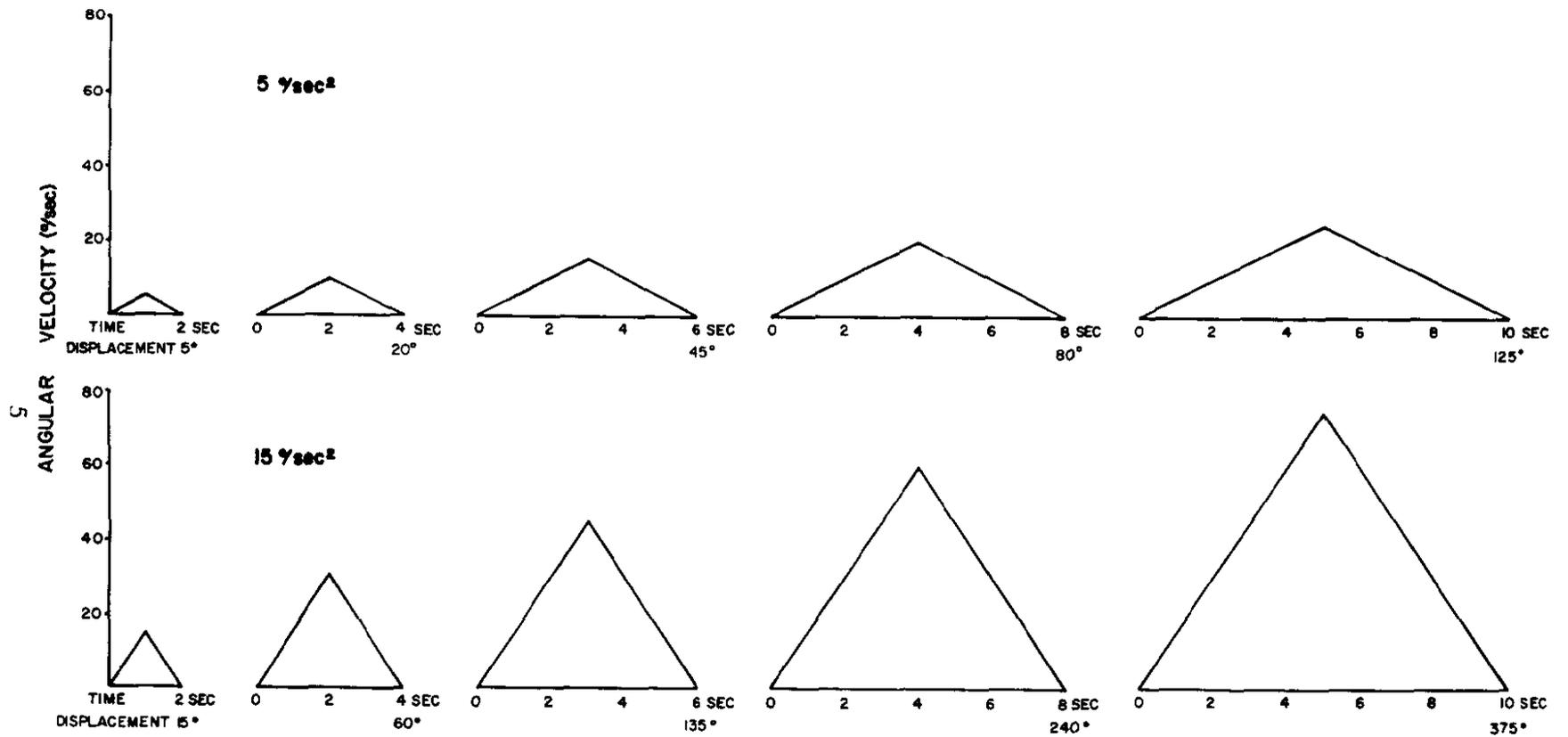


Figure 1

Illustration of Counterclockwise Stimulus Waveforms Produced by $\pm 5 \text{ deg/sec}^2$ and by $\pm 15 \text{ deg/sec}^2$ Angular Accelerations

Table I

Order of Presentation of Stimuli within Series

Trial Number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Accel. (deg/sec ²)	5	5	5	15	15	15	5	5	15	5	5	15	5	15	15	15	5	5	15	15
Wavelength* (sec)	4	8	10	6	4	10	4	8	10	10	2	8	6	2	6	2	6	2	8	4
Displacement (deg)	20	80	125	135	60	375	20	80	375	125	5	240	45	15	135	15	45	5	240	60
Velocity# (deg/sec)	-10	-20	-25	-45	+30	+75	-10	+20	-75	+25	-5	-60	+15	+15	+45	-15	-15	+5	+60	-30

*Duration of triangular velocity waveform

#Peak velocity magnitude. Plus and minus signs designate counterclockwise and clockwise rotation, respectively.

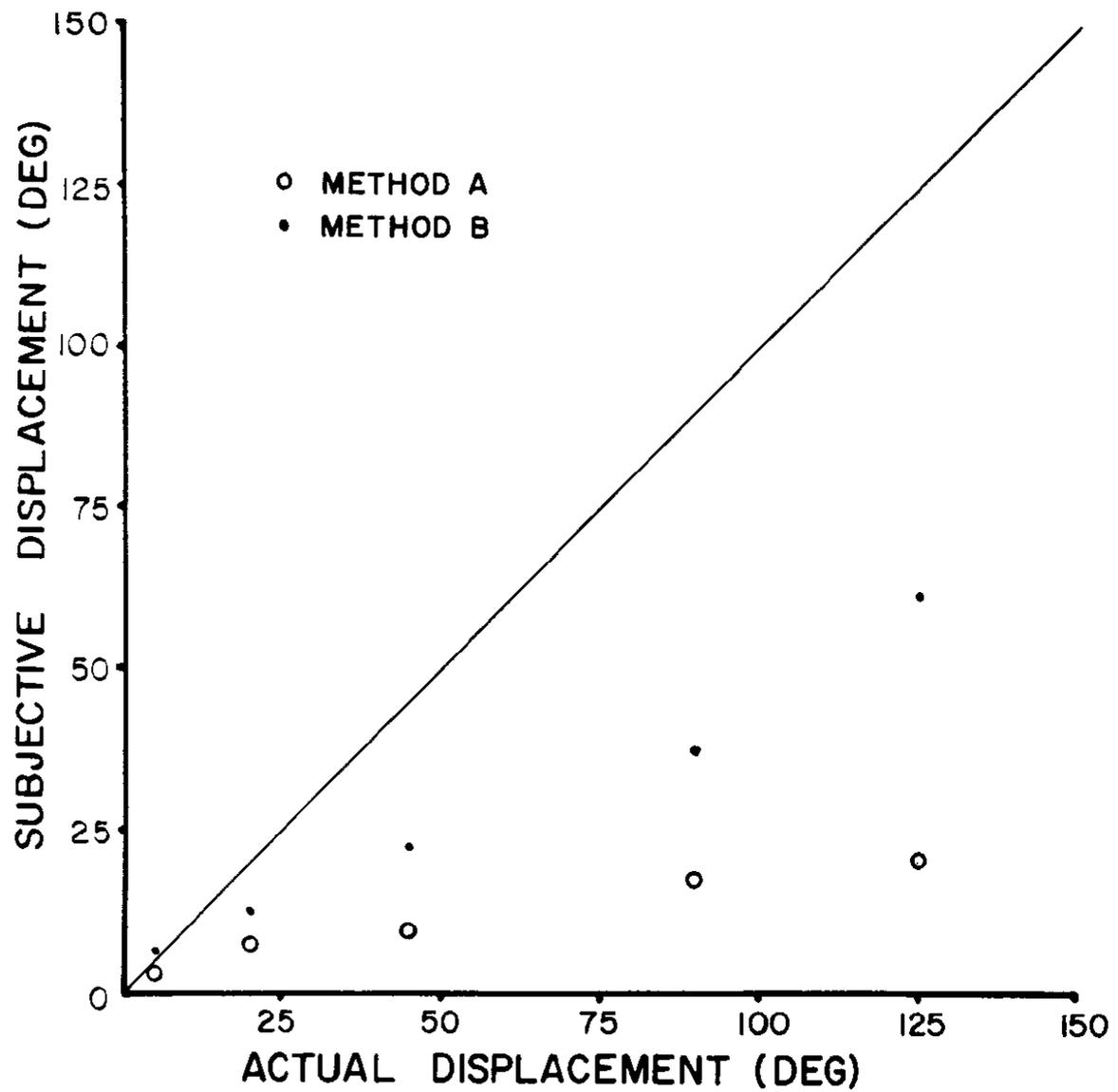


Figure 2

Mean Displacement Estimates Obtained with the Two Experimental Methods When the Triangular Waveforms Were Produced by 5 deg/sec² Angular Accelerations

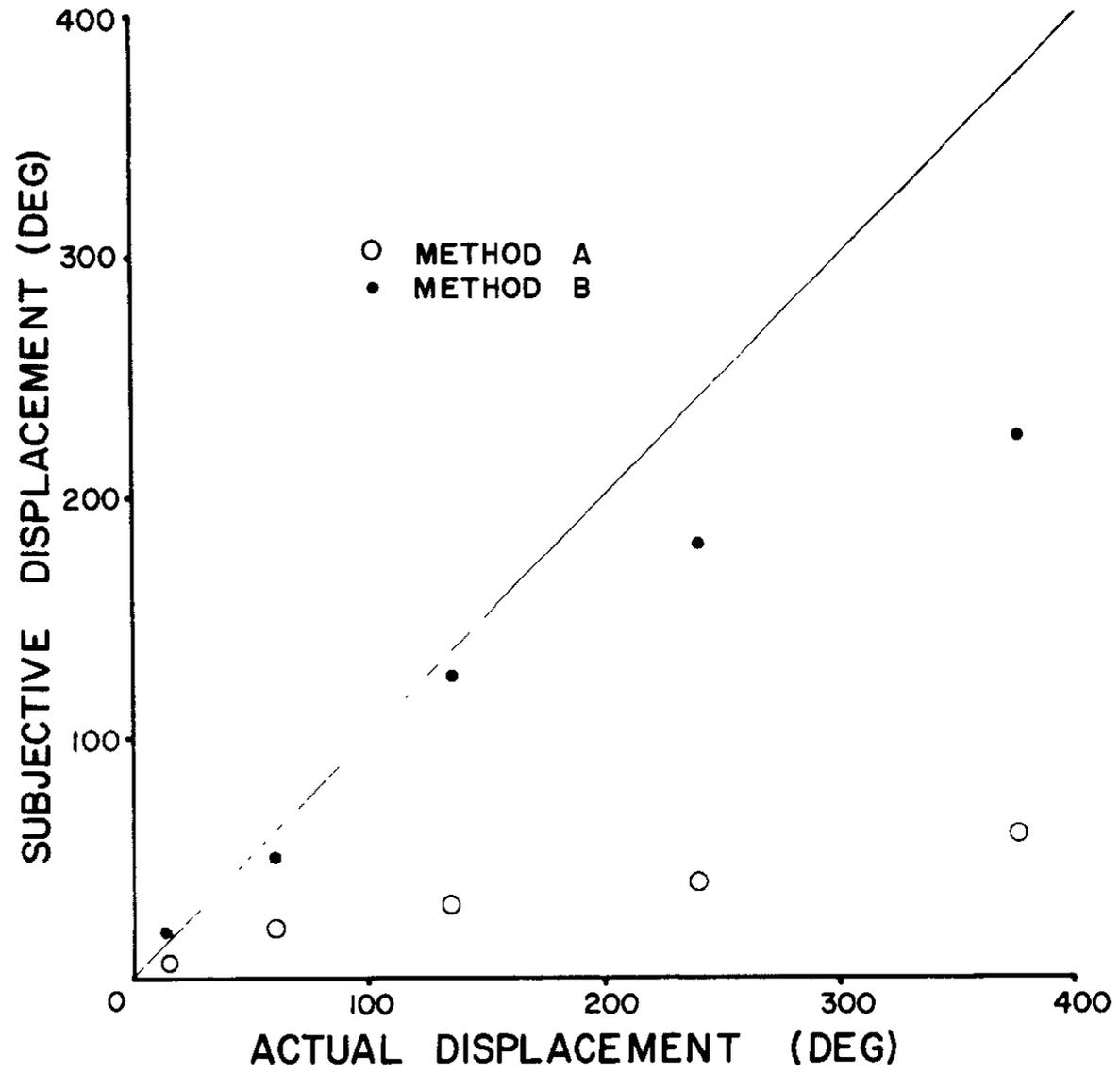


Figure 3

Mean Displacement Estimates Obtained with the Two Experimental Methods When the Triangular Waveforms Were Produced by 15 deg/sec² Angular Accelerations

Table II

Comparison of Mean Slopes of Stimulus Response Relationships Obtained by the Two Experimental Methods by Use of 't' Tests for Related Measures

	5 deg/sec ² stimulus	15 deg/sec ² stimulus
A. Light spot: mean slope	0.15	0.121
B. Dial indicator: mean slope	0.445	0.534
t	4.16	6.54
df	10	10
p	<.01	<.01

COMPARISON OF SUBJECTIVE DISPLACEMENTS PRODUCED BY 5 AND 15 deg/sec² STIMULI

The slope of the stimulus-response relationship obtained with Method A was far below unity with either set of stimuli, and there was not much difference between the two response curves. However, with Method B (the dial indicator), there was a systematic difference between displacement estimates made during angular velocity waveforms comprising the 15 deg/sec² angular accelerations (Figure 3) and estimates made during stimulus waveforms comprising the 5 deg/sec² angular accelerations (Figure 2). The 2, 4, 6, 8, and 10 sec wavelengths with 5 deg/sec² accelerations produced actual displacements of 5, 20, 45, 80, and 125 deg, respectively, but the respective displacement estimates were only 6, 13, 22, 37, and 61 deg; whereas, for the 2, 4, and 6 sec wavelengths with the 15 deg/sec² accelerations, the respective displacements were 15, 60, and 135 deg which were nearly matched by the respective estimated displacements of 18, 51, and 120 deg. Thus within comparable ranges of displacement, the mean slope of the stimulus-response relationship differed, depending upon whether the 5 or 15 deg/sec² acceleration was used. Slopes were determined for individual subjects within this range of displacements, and a mean slope of 0.45 with the 5 deg/sec² stimuli was significantly less than the mean slope of 0.86 with the 15 deg/sec² stimuli ($t = 3.37$; $df = 10$; $p < .01$).

REVERSED EFFECT FOLLOWING THE STIMULUS

The triangular waveform of angular velocity, which is the stimulus, and the initial subjective angular velocity, which is the response, have the same direction;

and with the stimuli used herein they terminated almost simultaneously. The results described above referred to displacements estimated during this initial subjective angular velocity. Actually the subjective angular velocity terminated slightly before the stimulus velocity did, and after this there was a brief period in which the subjective angular velocity was in the opposite direction, hereafter referred to as the final effect, because the cupula slightly overshoots its rest position just as the head motion ceases (15). As expected, the mean angular displacements during this final effect were far less than the initial displacement estimates, and they tended to increase as the initial effects increased. Probably because the stimuli for these final effects are weak and involve a gradually decaying sensory signal, the responses were more variable than those obtained from the initial effect.

Table III presents means and standard deviations for the initial and for the final effects. It is to be noted that in the initial effects, the means generally exceeded the standard deviations whereas in the final effects, the opposite was true. The fairly large standard deviations for initial as well as for final effects reflect fairly prominent individual differences, but this should not be taken as a sign of variability within the data yielded by individual subjects. As will be shown in a second experiment (18), there was good internal consistency within individual sequences of judgments of the initial effects.

DISCUSSION

Cupula displacement regulates the rate of discharge of the ampullary nerves, utriculopetal displacement augmenting and utriculofugal displacement diminishing the rate relative to a spontaneous resting level of activity in the ampullary nerves of the horizontal canals. It is widely believed that the magnitude of responses such as nystagmus and subjective angular velocity elicited by semicircular canal stimulation is regulated by the firing rate of the ampullary nerves, subject to further control by central neural mechanisms. It is therefore not unreasonable to assume that cupula displacement, plotted with respect to time, provides a curve which represents subjective angular velocity, especially when total response time is short. Further, if the subjective velocity can be integrated fairly accurately over time, then the area under the curve should be proportional to subjective angular displacement.

The stimulus waveform and corresponding cupula deflection curves, based upon equations elaborated by several authors (10, 12, 15, 17, 19) are shown in Figure 4. With the stimuli used, the positive portion of the cupula curves is quite similar in shape to the stimulus waveform; and assuming that the peak subjective velocity approximates the peak stimulus velocity, then the subjective displacement estimates should correspond to true displacement fairly closely.

With regard to the initial subjective effect, the average estimates made in this experiment with the dial were fairly accurate for a range of 15 deg/sec² stimuli producing displacements up to 125 deg. For greater displacements there was an error of underestimation which increased as the stimulus waveforms lengthened. This progressive

Table III

Mean and Standard Deviation of the Angular Displacement Estimates for the Initial and Final Effects

		Body Displacement:		5°		20°		45°		80°		125°		
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
5 deg/sec ² stimulus	Method A	Initial effect	2.2	1.4	6.4	4.1	9.4	4.9	14.8	6.3	20.9	10.2		
	Method B	Initial effect	6.3	4.7	13.9	7.0	22.4	11.1	37.3	15.5	61.1	30.8		
	Method A	Final effect	0.3	0.5	2.1	3.6	1.6	6.9	4.7	6.2	5.7	9.7		
	Method B	Final effect	3.1	3.4	5.2	5.2	8.4	9.9	14.2	7.9	20.5	15.9		

		Body Displacement:		15°		60°		135°		240°		375°		
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
15 deg/sec ² stimulus	Method A	Initial effect	8.0	5.8	18.0	10.6	27.7	14.5	35.0	23.2	54.5	33.9		
	Method B	Initial effect	18.0	8.4	51.8	26.2	120.4	63.0	176.6	93.2	206.8	94.4		
	Method A	Final effect	1.0	2.0	5.7	6.4	17.0	16.8	9.7	9.3	30.0	23.3		
	Method B	Final effect	6.4	5.0	18.0	17.0	24.7	23.1	29.8	19.5	48.4	30.7		

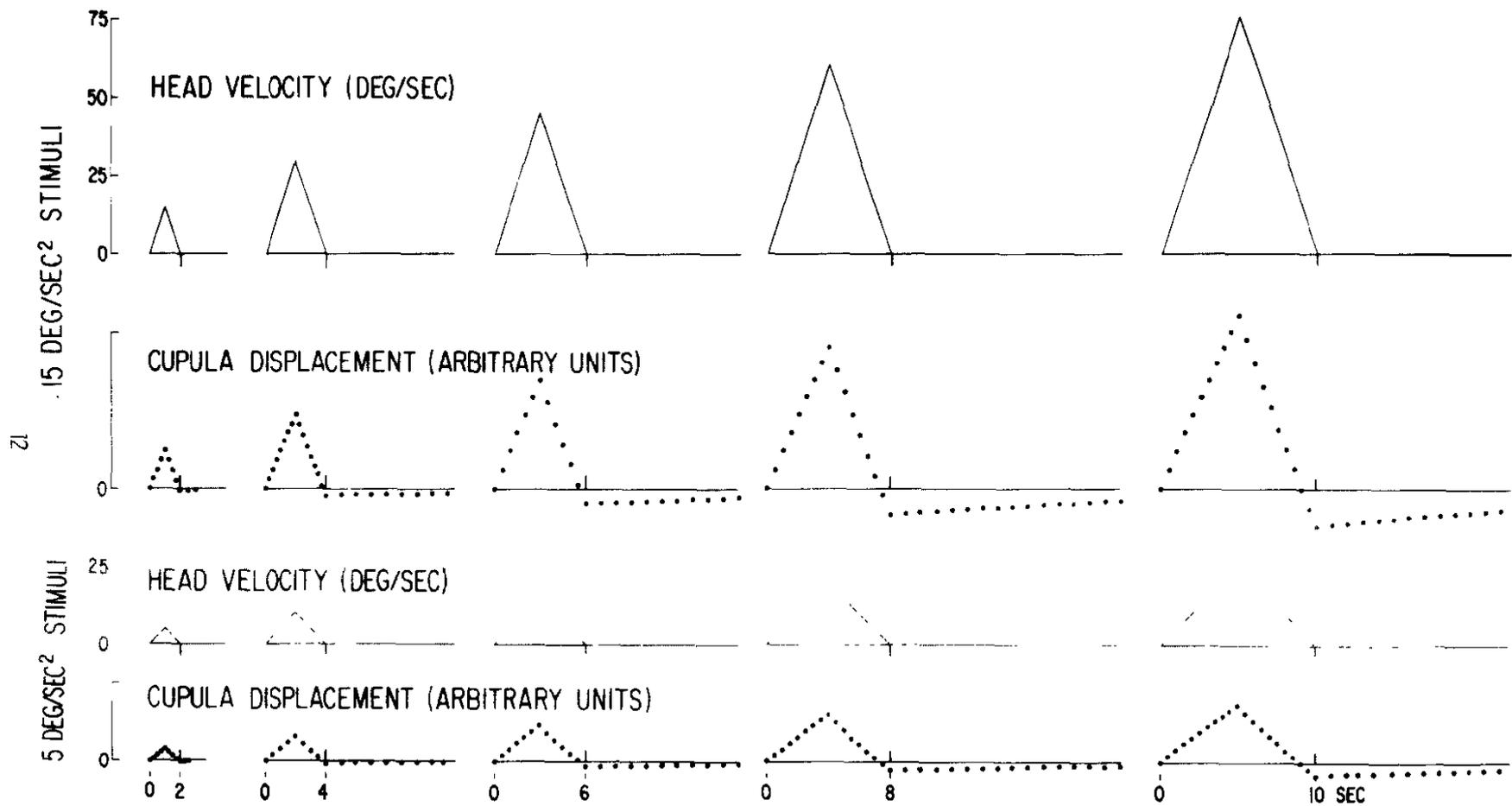


Figure 4

Illustrating Theoretical Cupula Deflections during and after Stimulus Waveforms. Time Constant ($\frac{\pi}{\Delta}$) Used in Calculations Was 20 Sec.

underestimation with the longer waveforms is to be expected on the basis of cupula mechanisms (15), but the amount of underestimation shown in Figure 3 is probably partially attributable to method artifact. This is inferred from the second experiment, involving a slight modification of Method B, which yielded more accurate average estimates with the longer stimulus wavelengths (18). From the subsequent experiment it may be inferred that subjective angular velocity (and the integration of this signal) is fairly accurate in the average subject for these stimulus patterns and that this is revealed when a particular procedure is followed in the reporting of the subjective event.

The portion of the cupula response curves below baseline in Figure 4 should be associated with the final effect. It is clear that the final effects did increase with longer stimuli as expected. However, the ratio of response magnitude to area under the theoretical curve is considerably less for the final effects than was the comparable ratio for the initial effects. This tendency toward underestimation of prolonged weaker signals is also apparent in the initial, as well as final, responses yielded by the 5 deg/sec^2 stimulus. In Figure 4 it is apparent that the final effect with the longer 15 deg/sec^2 stimuli and the initial effect with the longer 5 deg/sec^2 stimuli involve low input signals maintained for fairly long intervals. It is suggested that the error of underestimation of these signals lies in the processes involved in integrating the lower signal rates over the longer intervals. This is deduced from the fact that the peak nystagmus velocity with a 5 deg/sec^2 stimulus applied for 5 sec is at least $1/3$ of that obtained with a 15 deg/sec^2 stimulus applied for 5 sec (4). In other words, the ampullary sensory input with these lower stimuli (the initial and final effects from the 5 deg/sec^2 stimuli and the final effect from the 15 deg/sec^2 stimuli) is probably present in an appropriate magnitude, but integration of the lower signal rate over an interval of several seconds is inaccurate and yields underestimation of displacement. This "integration error" may be due to a threshold zone which would subtract more from the lower, longer signals. It is, of course, possible that the lowered estimates with the 5 deg/sec^2 stimuli may have resulted from the intermixing of the different magnitude angular accelerations within the same sequence of trials; i.e., stimulus waveforms comprising 5 deg/sec^2 accelerations may have been underestimated because of the presence of the 15 deg/sec^2 stimulus waveforms.

The difference in results obtained with the light spot and with the dial is curious. It was present in all subjects and there is little doubt that some systematic factor in the procedure produced it. Possibly the restricted angular excursion of the light contributed to this difference, but introspective comments suggest that counterrotation of the light spot (which appeared at eye level) tended to diminish the subjective impression of body rotation. It is to be noted that the directions of the light and eye velocities relative to the skull are the same, and if these velocities are matched in magnitude, then the image of the light spot will be fixed on the retina. Thus, the nystagmus slow phase would not be impeded by the visual stimulus, nor would there be slow movement of the image over the retina. The absence (or reduction) of either of these forms of visual-vestibular interaction may have significance for the reduced estimates of body displacement indicated with the light spot, but this is conjectural. The fact that individuals with paralyzed

eye muscles still see the oculogyral effect (6) would tend to detract from this explanation, but whether these people experience velocities comparable to the "normal experience" is not known. Our subjects still experienced the "oculogyral effect" with the light spot, but their estimates of angular displacement were low in relation to the true displacement and in relation to the estimates made with the pointer on the dial. What has been said of the light spot in regard to retinal fixation might also apply to the pointer. However, the subject was looking down onto the dial face which was clearly fixed in his lap, and the pointer moved relative to the dial. Thus, the subject saw the pointer move relative to a scale which was easily identified with his body. These may seem to be subtle differences but they made large and consistent differences in the subjective estimates.*

Thus far it has been implied that subjects in this experiment were making displacement estimates. However, because the light and the pointer were being moved during the stimulus, it could be said with some justification that the subject's task involved velocity matching; i.e., as a given angular velocity was experienced, the pointer was counterrotated with an equivalent angular speed in order to keep it at a constant compass heading. From observation of the subjects' performance, it appeared that some subjects moved the pointer simultaneously with the changing subjective velocity, whereas others delayed until the first effect was completed or was almost completed before making an estimate. In the latter case, subjects were making a displacement judgment after all "data were in," whereas in the former, subjects may have been attempting velocity-matching judgments at least part of the time. Concurrent velocity matching involves a different process than does retrospective displacement matching, and furthermore, the concurrent psychomotor performance required in velocity matching could interfere with the processing of incoming sensory data. This ambiguity in the subject's mode of operation in performing the task was avoided in a second experiment in which subjects were required to wait until the initial effect was completed before giving their displacement estimates. The data of the second experiment (18) illustrate that this procedural change yields results in which the greater angular displacements are much more accurately estimated than in the present experiment.

*Results in this present study are reminiscent of results in an earlier study concerned with estimates of linear displacement (13, p. 17).

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