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ASSESSMENT OF SEMICIRCULAR CANAL FUNCTION: II. INDIVIDUAL DIFFERENCES IN SUBJECTIVE ANGULAR DISPLACEMENT PRODUCED BY TRIANGULAR WAVEFORMS OF ANGULAR DISPLACEMENT

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ASSESSMENT OF SEMICIRCULAR CANAL FUNCTION: II. INDIVIDUAL DIFFERENCES IN SUBJECTIVE ANGULAR DISPLACEMENT PRODUCED BY TRIANGULAR WAVEFORMS OF ANGULAR VELOCITY*

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SUMMARY PAGE

THE PROBLEM

Development of methods and procedures to provide psychophysical measures of semicircular canal function which have high test-retest reliability and which are practical from the point of view of short arcs of passive whole-body rotation about an Earth-vertical axis were accurate when subjects used a psychophysical procedure which involved counterdisplacement of a pointer on a dial. The required retrospective displacement judgments yielded more accurate mean estimates of angular displacement than were obtained in an earlier experiment which probably involved concurrent velocity matching. The differences in response curves in the various conditions of the two experiments clearly illustrate the importance of attention to psychophysical procedures prior to attempting to develop models of the vestibular endorgans to explain differences within a sample of aviation candidates, and the results obtained thus far indicate a high test-retest reliability (r_{12} = .94).

ACKNOWLEDGMENTS

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INTRODUCTION

Measures of nystagmus and sensations produced by sequences of graded semicircular canal stimuli have been used as signs of the integrity of the vestibular system, and the stimulus-response relationships derived therefrom have been called sensation or nystagmus cupulograms (1-8, 17). It has been indicated that the slopes of cupulograms are related to flight training (1) and are predictive of motion sickness (1,5) and that directional asymmetry, especially in sensation cupulograms, may be associated with susceptibility to spatial disorientation (3).

Unfortunately there is a difficulty in the use of sensation cupulograms for testing large numbers of subjects. Unless detailed and time-consuming instruction is provided, many subjects yield highly variable subjective responses to the sequence of graded stimuli. This variability is sufficient to raise serious questions about the reliability and, hence, validity of such measures, especially when there are constraints on the time available for instructing individual subjects.

The purpose of the present research is to find stimulus-response patterns which will reveal directional asymmetries in vestibular sensations when they exist. Our approach is based upon the assumption that subjective judgments which are made routinely in natural circumstances will require little instruction time and will also have a good probability of acceptable test-retest reliability.

In a previous experiment (16), it was found that short arcs of passive whole-body rotation about an Earth-vertical axis were fairly accurately estimated by a psychophysical procedure in which subjects used a pointer on a circular dial to indicate the perceived angular displacement of the body. As the subject rotated, he attempted to counterrotate the pointer so that it would maintain a constant heading.

In the present experiment, this same psychophysical procedure was followed, with one change; viz, subjects were specifically instructed to make their judgments with the dial pointer just after each angular displacement was completed. Thus, retrospective displacement judgments were required. This change was introduced because the impression had been gained in the earlier study that the concurrent act of adjusting the pointer during the stimulus might interfere with incoming sensory data, thereby leading to progressive underestimation of the larger displacements. Moreover, without specific instructions, a subject might choose to operate in either of two modes, concurrent velocity matching or retrospective displacement matching.

PROCEDURE

SUBJECTS

Twenty-six men volunteered for this experiment. The subject group comprised Naval Academy midshipmen, officer flight candidates, and medical students on temporary duty. The age range of the subjects was 19 to 25 years.

APPARATUS

The rotation device was a Stille-Werner chair, RS-3, to which a 6-ft diameter cylindrical frame was attached. Lightproof blackout material covered the frame encapsulating the subject. Internal illumination was provided by a 1.2-watt bulb located 1 ft above the subject's head. The axis of rotation was vertical.

The subject's head was at the center of rotation and ventroflexed about 30 deg by occipital headrests. In this position, the subject viewed a circular dial (10-in. diameter) marked off in 10-deg units. The dial face was in the Earth-horizontal plane and was mounted in a small box positioned just above the subject's lap so that it was viewed with a downward-directed gaze at a 14-in. reading distance. A pointer on the dial could be turned by the subject to indicate his estimates of angular displacement which were automatically recorded in the experimenter's control room. To mask external auditory cues, subjects wore audiometric headsets and heard "pink noise" during the vestibular stimuli.

METHOD

Subjects enclosed in the rotating device were turned through various arcs. Direction of turn was clockwise on some trials and counterclockwise on others. The subject was instructed to attend to "how far he was turning" and to indicate, just after the turn, his estimate of angular displacement by displacing the pointer on the dial in a compensatory direction. Verbatim instructions are presented in the Appendix.

The stimulus for each trial was a triangular waveform of angular velocity with the increase and decrease in speed accomplished by angular accelerations of the same magnitude and duration but of opposite sign. Figure 1 represents the counterclockwise angular velocity waveforms used in the experiment. (The clockwise stimuli are not shown but would be represented by inverted triangles projecting below the baseline.) Angular accelerations of two magnitudes, 10 and 15 deg/sec^2, were used to produce the velocity changes, and, as a result, a given duration of the stimulus gave two different angular displacements as indicated in Figure 1.

Two twenty-trial series, each series comprising ten clockwise and ten counterclockwise trials, were presented to each subject. The order of presentation of stimuli was scrambled, as shown in Table I, but it was the same for each subject and also in each series.

Subjects made their estimates quickly and only 15 to 20 sec intervened between each stimulus; thus a series of twenty stimuli were presented in about 7 min. Each subject was given a rest between the first and second series, but during this time a second subject was started. As a result, two subjects could complete the experiment in about 30 min.

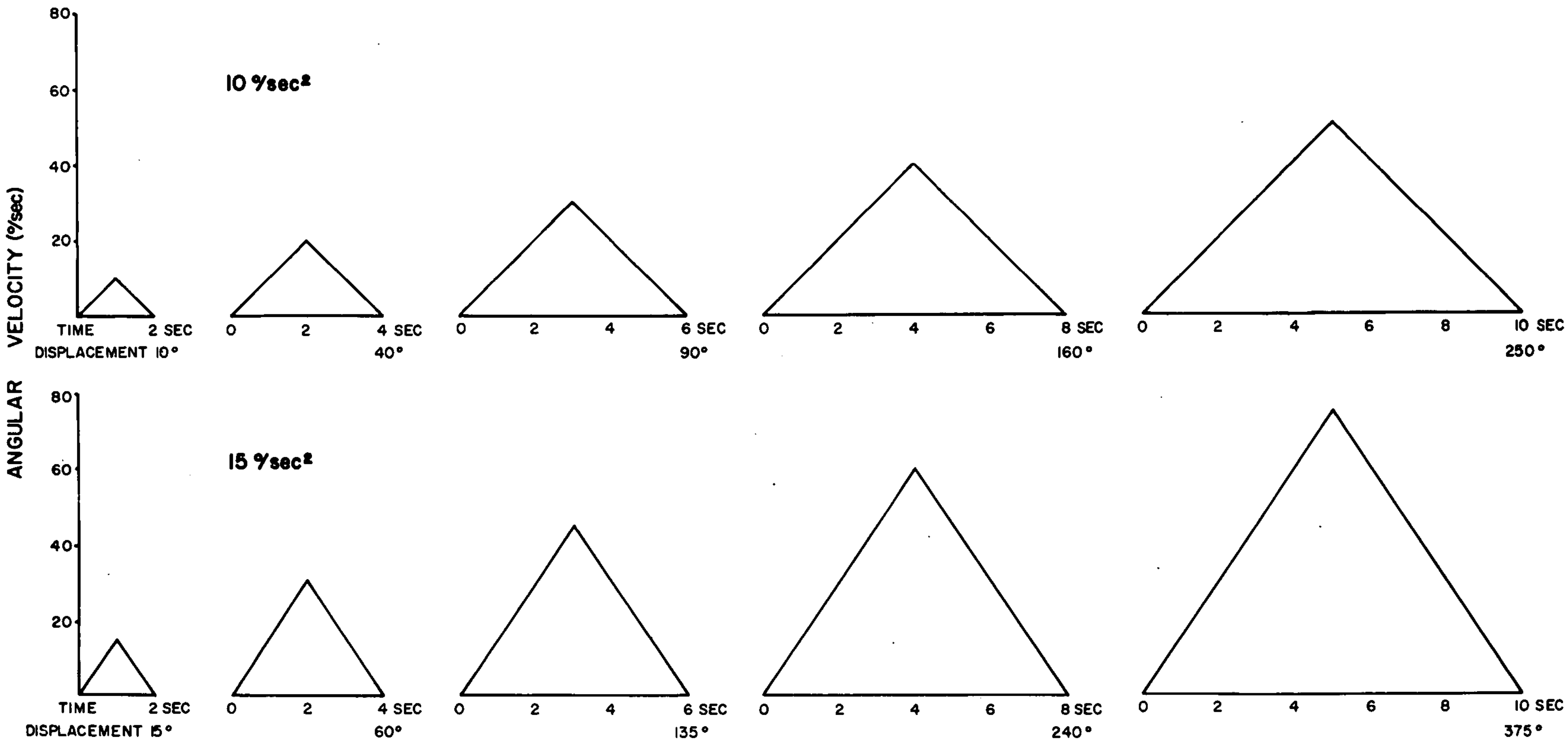

Figure 1

Illustration of Counterclockwise Stimulus Waveforms Produced by ± 10 deg/sec^2 Angular Accelerations and by ± 15 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)	15	10	15	10	15	10	15	10	15	10	15	10	15	10	15	10	15	10	15	10
Wavelength* (sec)	4	8	6	6	8	4	2	10	4	4	10	2	6	2	10	6	8	10	2	8
Displacement (deg)	60	160	135	90	240	40	15	250	60	40	375	10	135	10	375	90	240	250	15	160
Velocity# (deg/sec)	+30	-40	+45	-30	+60	+20	-15	+50	-30	-20	+75	+10	-45	-10	-75	+30	-60	-50	+15	+40

*Duration of triangular velocity waveform
#Peak velocity magnitude. Plus and minus signs designate counterclockwise and clockwise rotation, respectively.

RESULTS

The results are shown in Table II and Figures 2, 3, and 4. Figure 2 illustrates that the mean estimates of angular displacement were fairly accurate throughout the range of stimuli and that there were no pronounced discontinuities due to the different angular accelerations used within the series. Minor discontinuities are expected on the basis of cupula mechanics (15). Results from each of the 26 subjects are shown in Figures 3 and 4 where it is apparent that each individual showed a consistent trend but that there were conspicuous individual differences in the slopes of the lines of best fit through individual data plots. Each subject showed a fairly linear relationship between actual and perceived displacement, but the slopes of the lines representing this relationship differed among subjects. Each point in Figures 3 and 4 is a mean of four judgments by the respective subject, one judgment for one clockwise and one counterclockwise trial in each of the two series.

Table II

Mean and Standard Deviation of the Subjective Angular Displacement for Each of Ten Different Stimuli (N = 26)

	Degrees									
Actual Displacement	10	15	40	60	90	135	160	240	250	375
Estimated Displacement	16	20	48	68	92	144	166	238	244	351
SD	7.3	8.0	25.5	29.7	37.4	73.4	76.8	114.6	120.2	155.8

In order to estimate the degree to which subjects performed consistently between the two series of judgments, slopes of the lines of best fit through the raw data points of each subject were determined. The correlation between slopes from series one and series two was .93 for clockwise trials and .87 for counterclockwise trials. When the estimates from clockwise and counterclockwise trials were combined, the correlation between slopes obtained from the 26 subjects for the two series was .94. This is relevant to test-retest reliability, and it is clear that within one experimental session, subjects who yield a given slope in one series will yield a similar slope in a second series. Individual consistency within series is indicated by the correlations between actual and perceived displacement shown in Table AI which is presented in the Appendix. These high correlations (mean correlation is .95) are not especially relevant to test-retest reliability, but they demonstrate an orderly increase in displacement estimates as actual displacement was increased for most individuals tested. The fairly large standard deviations in Table II reflect the individual differences in slope which are also apparent in the individual plots shown in Figures 3 and 4.

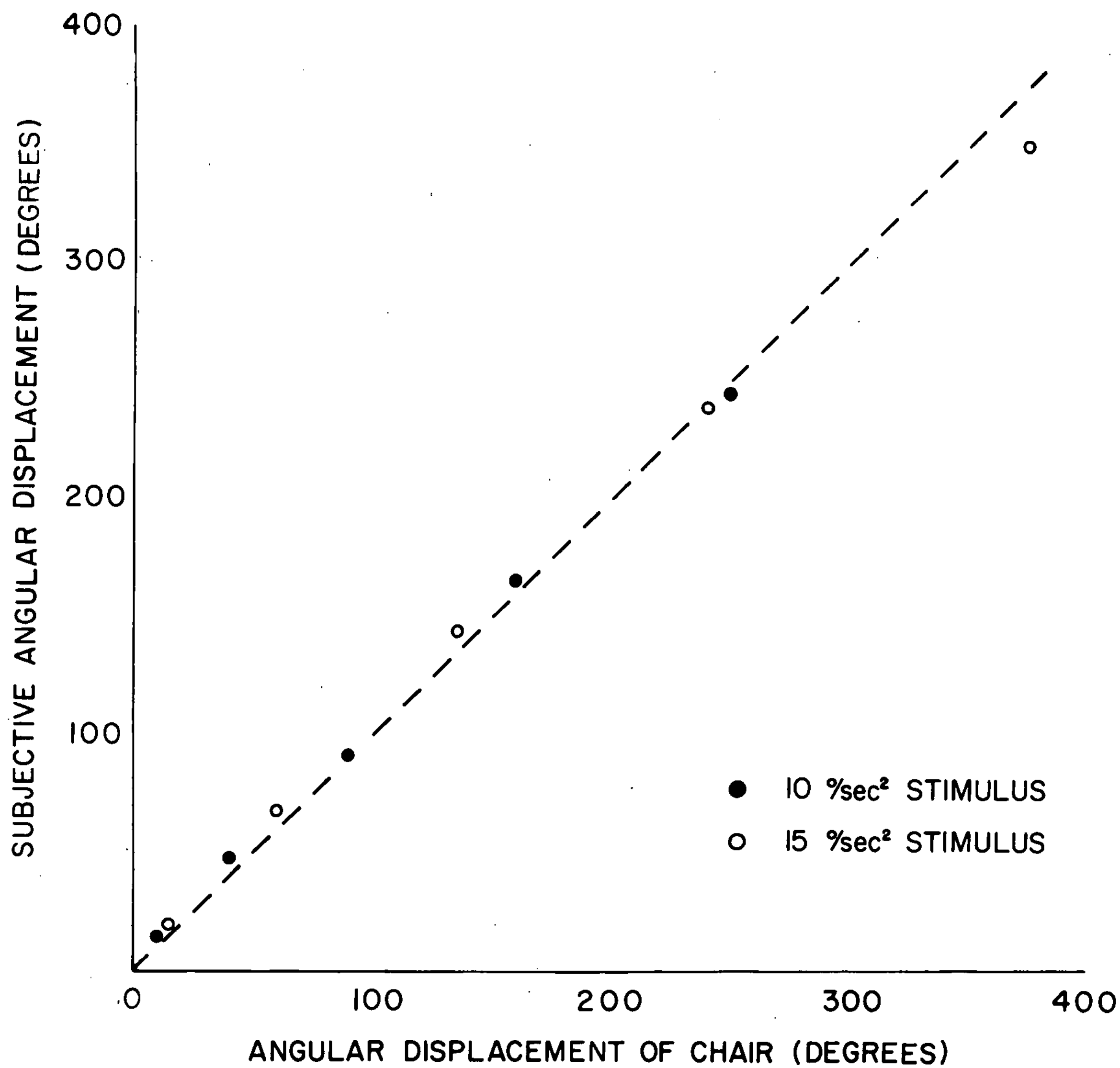

Figure 2

Relationship between Mean Estimates of Angular Displacement and True Angular Displacement Produced by Triangular Velocity Waveforms

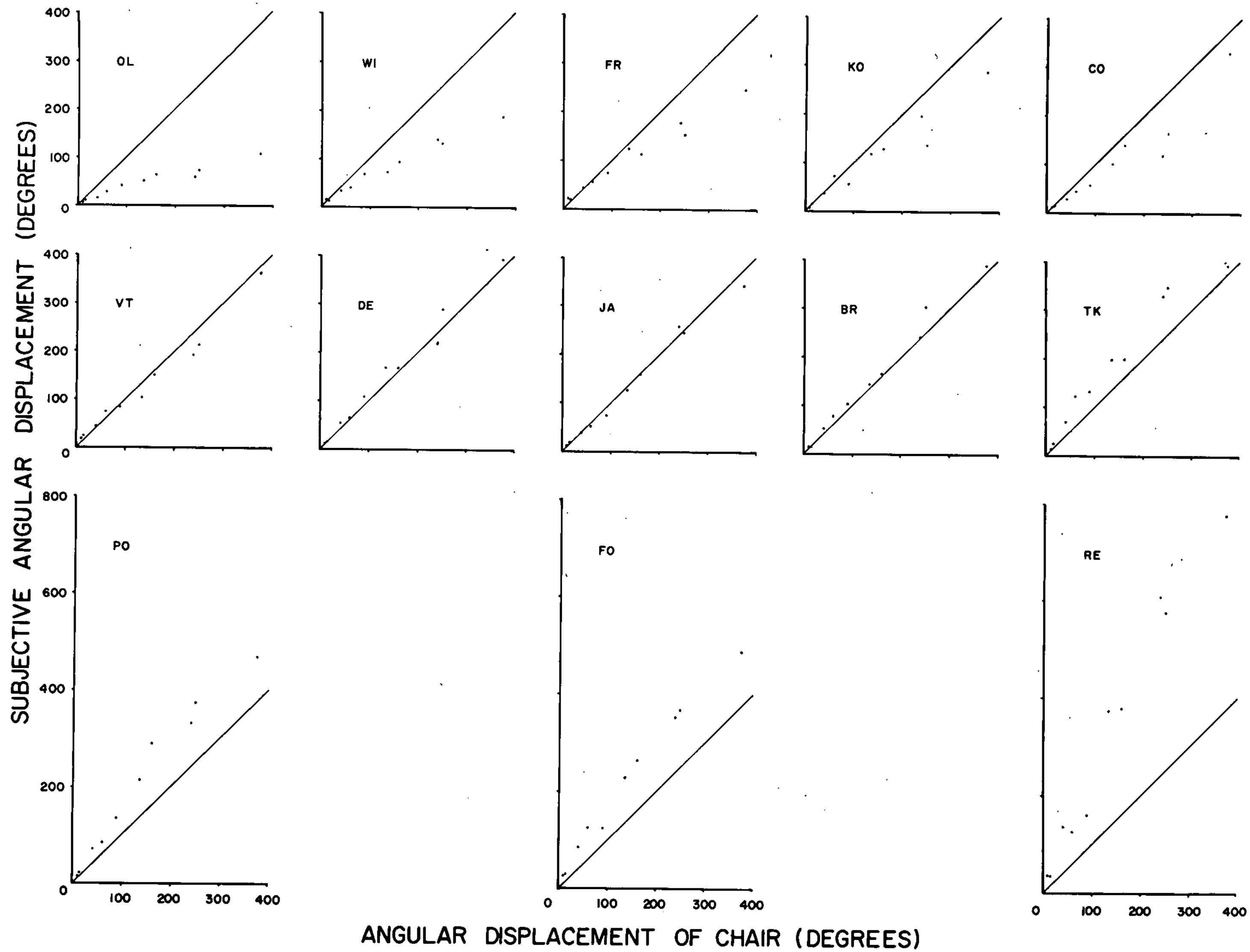

Figure 3

Individual Differences in the Relationship between Subjective Angular Displacement and True Angular Displacement Produced by Triangular Velocity Waveforms

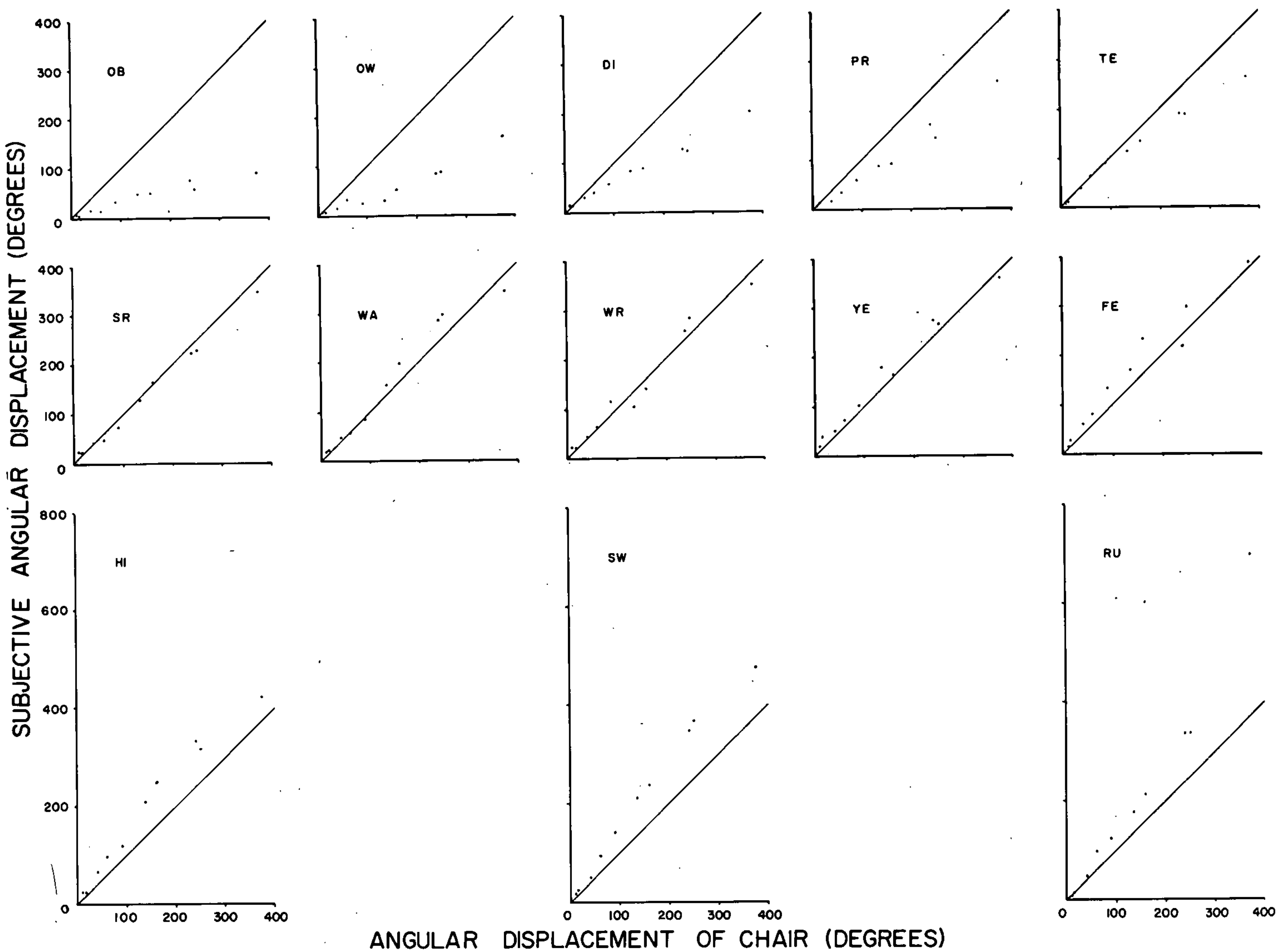

Figure 4

Individual Differences in the Relationship between Subjective Angular Displacement and True Angular Displacement Produced by Triangular Velocity Waveforms

DISCUSSION

The close correspondence between actual and mean estimated displacement found in the present experiment is to be compared with the results from the sequence in the previous experiment (16) when the dial with pointer was also used with 15 deg/sec^2 stimuli. As illustrated in Figure 5, the two sets of data diverge as the angular displacement increases. The mean estimates of the 375-deg displacement were 206 deg and 351 deg in the first and second experiments, respectively, and this difference is statistically significant ($t = 3.46$; $df = 35$; $p < .01$). There were several differences in procedure, but it appears likely that the improved accuracy in the present experiment was attributable to the requirement placed upon subjects to make retrospective displacement judgments, i.e., to delay judgment until the apparent initial displacement was complete. In the earlier experiment the subject's task was not sufficiently specified so that subjects might choose to make either retrospective displacement estimates or concurrent velocity judgments, but they usually adjusted the pointer during the stimulus. This means that subjects were probably making concurrent velocity-matching judgments at least part of the time, which is a task different from the estimation of total displacement after the stimulus is complete. Moreover, the act of adjusting the pointer and making judgments during the stimulus may have interfered with the processing of incoming sensory data. At any rate, the present procedure yielded fairly accurate mean estimates of even the greater displacements, and the data of individual subjects were internally consistent.

The procedure in the present experiment does not provide estimates of the final effect (the reversed motion from cupula overshoot) because subjects were specifically instructed to ignore this effect and to estimate only the initial subjective displacement. These final effects as measured in the earlier experiment were highly variable within subjects, and this seemed to be a poor basis for evaluating reliable individual differences. It is possible, of course, that retrospective displacement estimates of only the final effects might have yielded consistent within-subject reporting, but this was not evaluated.

With the triangular waveforms used, it is reasonable to expect (15) that the neural activity from the semicircular canals follows the form of the velocity curves shown in Figure 1 fairly closely. It has been indicated that the cupula displacement during natural head movements is approximately proportional to the instantaneous angular velocity; i.e., the semicircular canals are velocity transducers and the neural transducer feeds this same type of information to the central nervous system (9, 18, 20). That man can integrate this neural velocity information into accurate displacement estimates with stimuli like those used in the present experiment seems to follow from the results shown in Figure 2. Since the axis of rotation was aligned with gravity, the otoliths were not stimulated by a change in orientation relative to gravity in the present experiment. Therefore, it is reasonable to conclude that the velocity signals from the canals were integrated over time to give accurate average estimates of angular displacement.

When the axis of rotation is in a fixed tilted orientation, i.e., not aligned with gravity, the otolith system changes orientation relative to gravity at the same time that the canals are stimulated by angular acceleration patterns. It is usually assumed that,

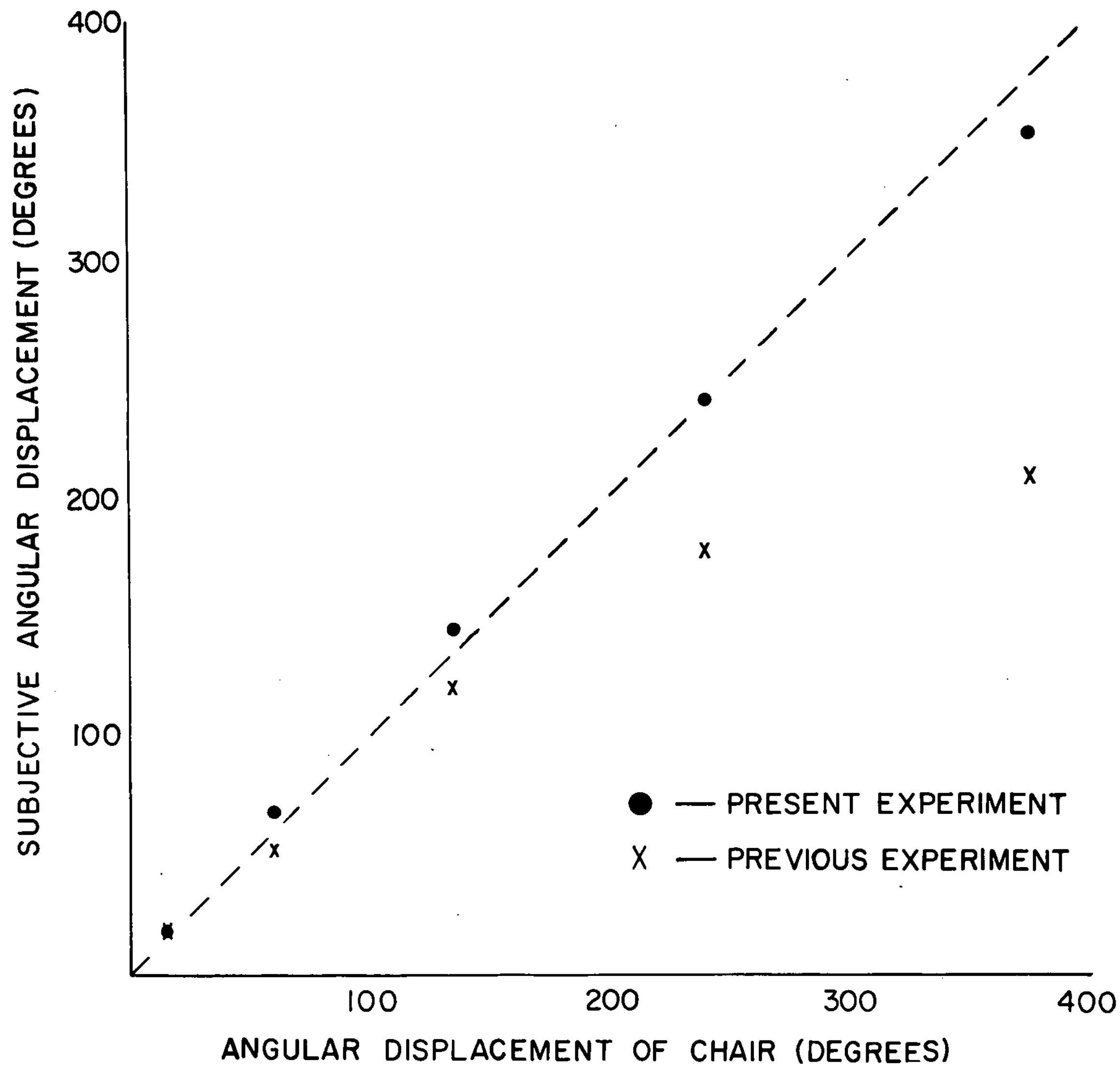

Figure 5

Comparison of Results Produced by Identical Stimuli, Triangular Velocity Waveforms Formed by ± 15 deg/sec^2 Accelerations, in Two Experiments. Concurrent Velocity Matching Was Required in the Present Experiment.

within the vestibule, the otoliths are the primary source of information about angular displacement relative to gravity, but the results of the present experiment indicate that the canals can contribute to fairly accurate estimates of angular displacement, even when the axis of rotation is not tilted. Although it is unlikely that the canals can provide direct position information about the direction of gravity, the results suggest a close synergistic relationship between the canals and otoliths in determining perception of tilt and angular displacement during the kind of dynamic stimulation of the canals and otoliths that occurs in natural movement when the axis of rotation is tilted. The angular velocity information available from the canals during a movement may be supported by change-in-position signals (19,20) from the otoliths, and conversely, the position signals from the otoliths during and after the movement may be supported by angular displacement information available from the integration of the velocity signals from the canals. The redundancy proposed herein for these systems may be useful in the development of finely coordinated movement (20), and it may be necessary to perceptual discrimination of different forms of motion such as static tilt and horizontal linear acceleration (10-14).

One of the purposes of the present research was to find stimulus-response patterns which will reveal directional asymmetries in vestibular sensations when they exist. That the stimulus waveforms used should be capable of detecting directional differences in response with different directions of cupula deflection is illustrated in Figure 6 where it is apparent that the initial effect from a "clockwise" waveform depends upon cupular deflections in one direction, whereas initial effects from a "counterclockwise" waveform depend upon cupular deflections in an opposite direction. Theoretically, then, directional asymmetries in sensation should be revealed by this stimulus relationship.

Practically, it remains to be shown that this procedure is a valid indicator of directional asymmetry. The stimulus waveforms were purposely selected because they are comparable to stimuli which are frequently experienced in natural movement. This was done because it was believed that commonly experienced stimuli might be more reliably reported than unnatural stimuli. Based upon the present findings, this hypothesis concerning reliability of the data is tenable. However, it is possible to have high reliability without high validity. For example, if some central nervous system disorder creates directional asymmetry, it is possible that an individual may adjust to naturally occurring stimuli so that the perceived directional asymmetry would be corrected. If so, this disorder might not be revealed in a person with an old lesion by stimuli which approximate natural stimuli. For this reason, it is desirable to confirm the theoretical case for validity by empirical checks of validity with known clinical material and with aviators who have established disorientation problems.

In addition to the possibility that this procedure may have validity as a pathognomic indicator, it has other practical aspects. The procedure requires little time for test administration and for data processing, and it can be automated easily. Moreover, there was a high test-retest correlation (.94) for the slope of the stimulus response relationship; i.e., individuals tended to have the same slope in two different tests, and from this it would appear that there are excellent prospects for high test-retest reliability.

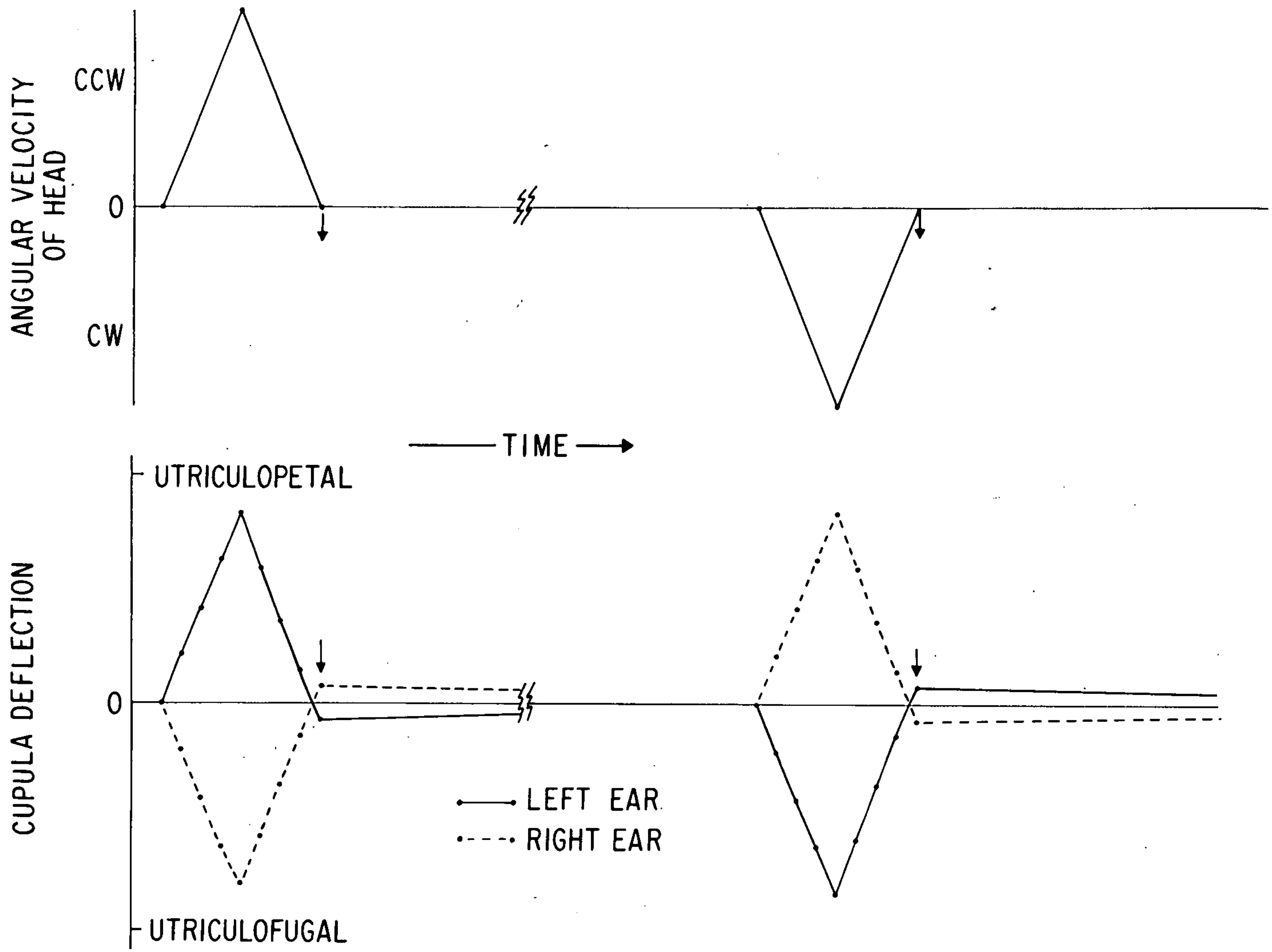

Figure 6

Illustration of Theoretical Cupula Deflection during and after Clockwise and Counterclockwise Triangular Velocity Waveforms

However, again these optimistic prospects should be confirmed by further experimentation in which more time intervenes between the first and the second tests.

There were substantial differences in the slopes of the stimulus-response relationships yielded by the different subjects even though the average slope approximated unity; thus the procedure appears to discriminate reliably between individuals. Such differences may reveal differences in the parameters of the response systems of different subjects and therefore are potentially important. A more detailed discussion of the theoretical implications of responses obtained with triangular velocity waveforms is presented in a separate paper (15).

SUMMARY AND CONCLUSIONS

1. A procedure was developed to test for directional asymmetry in vestibular turning sensations which meets practical requirements in regard to administration time and data processing.

2. Within a series of stimuli, individual subjects yielded consistent subjective judgments which indicated a near-linear relationship between actual and perceived angular displacement. The slopes of individual curves were correlated for two series of judgments and the test-retest reliability appears to be excellent; however, further experiments should be carried out in which a substantial time intervenes between the first and second test series.

3. The mean estimates of angular displacement with the stimulus patterns and psychophysical procedure used in the present experiment were approximately correct; in other words, the average slope was about unity.

4. There were substantial differences in the slopes of the stimulus-response relationship. Theoretically, this test procedure should reveal directional asymmetry in turning sensations when it exists, but experiments to investigate the validity of this procedure with clinical case material are required.

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APPENDIX

Instructions to Subjects

"You will be rotated either to the right or to the left through some part of a circle. It may be just a few degrees, or more than 360°. Your task will be to judge how far you think you have turned by using this dial.

"This is the way it will work: At the beginning of each trial, the pointer will be on zero. While you are rotating, just sit there, keep your head still and pay attention to how far you have turned. When you feel that you have stopped, indicate to us how far you have turned by turning the pointer on this dial the same distance. Most people find it easier to do this by using a compensating movement of the pointer. What this means is that if you feel yourself turn 90° to the right, move the pointer back 90° to the left, or back to the point where you think you started. Do you have any questions?

"You will be rotated and stopped. Just sit there and pay attention to how far you turn. After you feel that you have stopped, indicate how far you have turned by moving the pointer back to the point where you started. Hold it there until I tell you to return to zero. Try not to listen to outside noises, but if outside noises bother you or influence your estimates, let us know. Do you have any questions?"

At this point a practice trial was given using the 15 deg/sec^2, 6-sec period waveform. The final effect (reversed motion) brought on by stopping was discussed and the subject was told to ignore this effect and to concentrate on the displacement which had occurred up to the apparent stop.

Table A1

Correlation and Slope of the Relationship between Subjective Angular Displacement (Single Raw Scores) and True Angular Displacement for Each Subject

	Series 1				Series 2			
	CW		CCW		CW		CCW	
Subject	r	Slope	r	Slope	r	Slope	r	Slope
OB	.61	0.12	.98	0.29	.95	0.23	.96	0.30
OL	.92	0.21	.98	0.40	.93	0.25	.86	0.25
DI	.97	0.52	.90	0.39	.99	0.55	.97	0.55
FR	.98	0.57	.97	0.75	.97	0.58	.98	0.54
WI	.98	0.42	.94	0.34	.95	0.65	.96	0.51
KO	.98	0.74	.95	0.79	.91	0.63	.95	0.69
CO	.94	0.62	.83	0.46	.94	0.68	.93	1.04
PR	.98	0.68	.94	0.60	.98	0.81	.95	0.62
WA	.98	1.07	.93	1.01	.97	0.96	.88	0.98
SR	.98	0.88	.97	0.95	.97	0.88	.99	0.95
DE	.98	1.07	.98	1.06	.98	0.95	.99	1.03
VT	.85	0.77	.92	0.77	.93	0.80	.91	1.06
FE	.93	0.98	.96	0.96	.95	1.03	.97	1.03
TK	.94	1.04	.98	1.20	.95	1.15	.97	1.03
HI	.96	1.21	.94	1.16	.98	1.10	.97	1.18
SW	.96	1.34	.96	0.97	.94	1.49	.97	1.44
RU	.95	1.70	.96	1.53	.97	1.82	.98	1.81
RE					.98	2.45	.98	1.90
PO	.98	1.21	.95	1.14	.97	1.49	.96	1.38
JA	.99	0.95	.98	0.97	.99	0.96	.95	0.96
BR	.96	1.20	.97	0.95	.99	1.01	.97	1.00
OW	.82	0.43	.97	0.46	.96	0.35	.88	0.34
TE	.99	0.94	.99	0.59	.95	0.71	.97	0.58
YE	.96	0.88	.98	1.02	.95	0.95	.99	0.98
WR	.97	0.69	.96	1.10	.99	0.93	.97	1.13
FO	.99	1.30	.99	1.33	.96	1.26	.98	1.29

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13. ABSTRACT

Mean estimates (N = 26) of short arcs of passive whole-body rotation about an Earth-vertical axis were accurate when subjects used a psychophysical procedure that involved counterdisplacement of a pointer on a dial. The required retrospective displacement judgments yielded more accurate mean estimates of angular displacement than were obtained in an earlier experiment which probably involved concurrent velocity matching. The differences in response curves in the various conditions of the two experiments clearly illustrate the importance of attention to psychophysical procedures prior to attempting to develop models of the vestibular endorgans to explain results. The method used in this experiment is sufficient to detect prominent individual differences within a sample of aviation training candidates, and the results obtained thus far indicate high test-retest reliability (r_{12} = .94).

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