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VESTIBULAR RESPONSES TO SINUSOIDAL ANGULAR ACCELERATION STIMULI WITH SUPERIMPOSED OFFSET VELOCITIES

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SUMMARY PAGE

THE PROBLEM

To determine the effectiveness of an offset baseline velocity in facilitating sinusoidal cupulometric measurements of the vestibular fitness of flight personnel.

FINDINGS

Thirty subjects were exposed to a sinusoidal rotation stimulus of 0.025 cps and a peak velocity of 63 deg/sec, which was superimposed on a constant rotational velocity of 153 deg/sec clockwise (CW), 153 deg/sec counterclockwise (CCW), or 0 deg/sec. The phase lag of nystagmus and sensation directional transitions was determined and used to derive a functional index, $2\zeta/\omega_n$, equivalent to the Π/Δ index obtained by conventional cupulometry. Nystagmus-based values were found to be independent of the base velocity and its direction. The phase lag of the CCW-to-CW transition in sensation of turning increased with a CCW offset velocity and decreased with a CW offset. The opposite effect was observed for a CW-to-CCW transition.

Further investigation is required before sinusoidal cupulometry based on turning sensation can be practiced under offset velocity conditions. In contradistinction, sinusoidal cupulometry based on nystagmus can be practiced under offset velocity conditions without difficulty.

INTRODUCTION

Various studies have reported that the numerical index of semicircular performance provided by cupulometry (1,2,5,8) is of value in the analysis of vestibular function. This index can be written either as Π/Δ where Π and Δ describe the theoretical viscous damping and rotational stiffness, respectively, of the cupula-endolymph system; or as $2\zeta/\omega_n$ where ζ and ω_n describe the damping ratio and undamped characteristic angular frequency, respectively, of the same system. With conventional techniques, which we label as "impulse cupulometry," a series of quick stops after constant velocity rotation to the right and left is used as the driving stimulus, with nystagmus and/or the subjective sensation of turning selected as the response. Since the procedure requires a considerable amount of time to derive a single Π/Δ index value for each direction of rotation, impulse cupulometry has received limited clinical application. However, by using a low-frequency sinusoidal angular acceleration stimulus, we have been able to considerably reduce the amount of time required to obtain the desired index value. This method, which we have called "sinusoidal cupulometry,"is based on measuring the phase difference between the directional transitions in the driving stimulus and the associated reversals in the direction of the nystagmus or turning-sensation response. In addition to reducing the amount of rotational time to which a subject must be exposed, the method has advantages in terms of the ease with which the nystagmus transitions can be scored and in terms of less dependence on the actual magnitude of the nystagmus response.

In the present study, one part of a continuing program to evaluate the limitations and capabilities of sinusoidal cupulometry, a constant velocity offset signal is superimposed on the cyclic driving stimulus that normally oscillates the subject about 0 rpm. By controlling the magnitude and direction of the offset velocity, rotation can be continuous in either direction. Since the angular acceleration stimulus remains the same with or without this offset velocity, it would be expected that the directional transitions in the nystagmus and turning sensation would be unaffected if these response measures, one objective and the other subjective, derive primarily from an acceleration stimulus, as dictated by the conventional semicircular canal theory.

APPARATUS

STIMULUS

The basic experimental stimulus used in this study was a continuous sinusoidal angular oscillation with a frequency of 0.025 cps, peak angular acceleration of 10 deg/sec^2, and a peak angular velocity of 63 deg/sec. This oscillation was superimposed upon a continuous rotation of 90 deg/sec counterclockwise (CCW), 0 deg/sec, or 90 deg/sec clockwise (CW) to provide the three stimulus configurations to which each subject was exposed (see Table I). The stimulus patterns were produced by rotation of the Human Disorientation Device (HDD), described in detail previously (6), about its vertical axis. This device operates as a power servomechanism with closed loop control based on velocity feedback. Command signals for production of the sinusoidal oscillation and the selected offset velocity were derived from a low frequency function generator and a manually adjusted dc power source, respectively.

Table I

Characteristics of Experimental Stimuli

		Constant Angular Velocity (deg/sec)		
		+90 (CCW)	0	-90 (CW)
Cyclic Frequency	Cycles/Second	0.025	0.025	0.025
Cyclic Period	Seconds	40.0	40.0	40.0
Peak Angular Displacement	Degrees	406	406	406
Peak Angular Velocity	Degrees/Second	+153 (CCW)	±63	-153 (CW)
Peak Angular Acceleration	Degrees/Second^2	10	10	10

The output signal of the function generator was recorded, and a timing marker representing its peak negative and positive values -- corresponding to peak HDD velocities or, conversely, the zero acceleration points -- was superimposed on it to provide a reference for calculating phase differences between the stimulus and response.

RESPONSE

Horizontal ocular nystagmus displacement recordings were obtained by the corneo-retinal potential technique. The displacement signal was derived from the difference in potential between silver electrodes placed at the outer canthi. The signal was amplified by a differential input amplifier preamplifier and transmitted by sliprings to one channel of a direct-writing recorder after filtering to minimize muscle-potential artifacts.

The experimental subject indicated bodily sensations of turning to the left or right by pressing the appropriate response switch on two pistol grips he held during the test; the switch would deflect the pen on a second channel of the recorder to the left or right as long as the sensation persisted.

PROCEDURE

EXPERIMENTAL

Thirty marine officers in the Navy flight training program served as volunteer subjects in the present study. They were drawn from a pool awaiting assignment to basic flight training and had no known defects of hearing and equilibrium. Each subject was instructed in the general purpose of the experiment, the procedures for recording nystagmus and reporting his bodily sensations of rotation, and the nature of the rotational stimuli to which he would be exposed.

For each test, a subject was seated in the HDD cab with his head erect and centered on the vertical axis of rotation. He was secured rigidly but not uncomfortably to the experimental chair by means of chest, waist, and ankle straps, as well as a head clamp. The cab was then closed and darkened completely and, still at rest, the nystagmus recording circuits were calibrated by having the subject fixate alternately two target lamps separated by 40 degrees of arc in the horizontal plane.

He was then exposed to one of the three series of stimulus patterns comprising a 3 x 3 Latin Square of the form

I	O	CCW	CW
II	CW	O	CCW
III	CCW	CW	O

Such a design has the advantage that, by replication of the same square, it is possible to evaluate the biasing of the responses by the order of presentation of the stimuli (4). In this study the square was replicated ten times. Subjects 1,4,7,....28 received stimulus order I; subjects 2,5,8,....29, order II; and subjects 3,6,9,....30, order III.

ANALYTICAL

Nystagmus phase shift was measured as the time interval between the onset of angular acceleration in one direction and the instant at which the subsequent transition of the slow component of nystagmus direction occurred. A left-to-right or "L-R" transition is that in which the direction of the slow component of nystagmus changes from toward the subject's left to toward his right in response to a change in the direction of acceleration from his right to his left. The converse holds for a right-to-left or "R-L" transition. This interval was compared to the cyclic period of the stimulus and expressed in conventional electrical degree nomenclature where one cycle equals 360 degrees. The procedure has been described in more detail in a previous study (7).

The phase lag of the change in direction of turning sensation relative to that of the acceleration stimulus was measured in similar fashion, using the midpoint of the period between successive responses as the reference point for change of response direction. A clockwise-to-counterclockwise or "CW-CCW" transition is that in which the direction of the subject's perceived sensation of turning changes from clockwise to counterclockwise in response to a change in the direction of acceleration from his right to his left. The converse holds for a counterclockwise-to-clockwise or "CCW-CW" transition.

RESULTS AND DISCUSSION

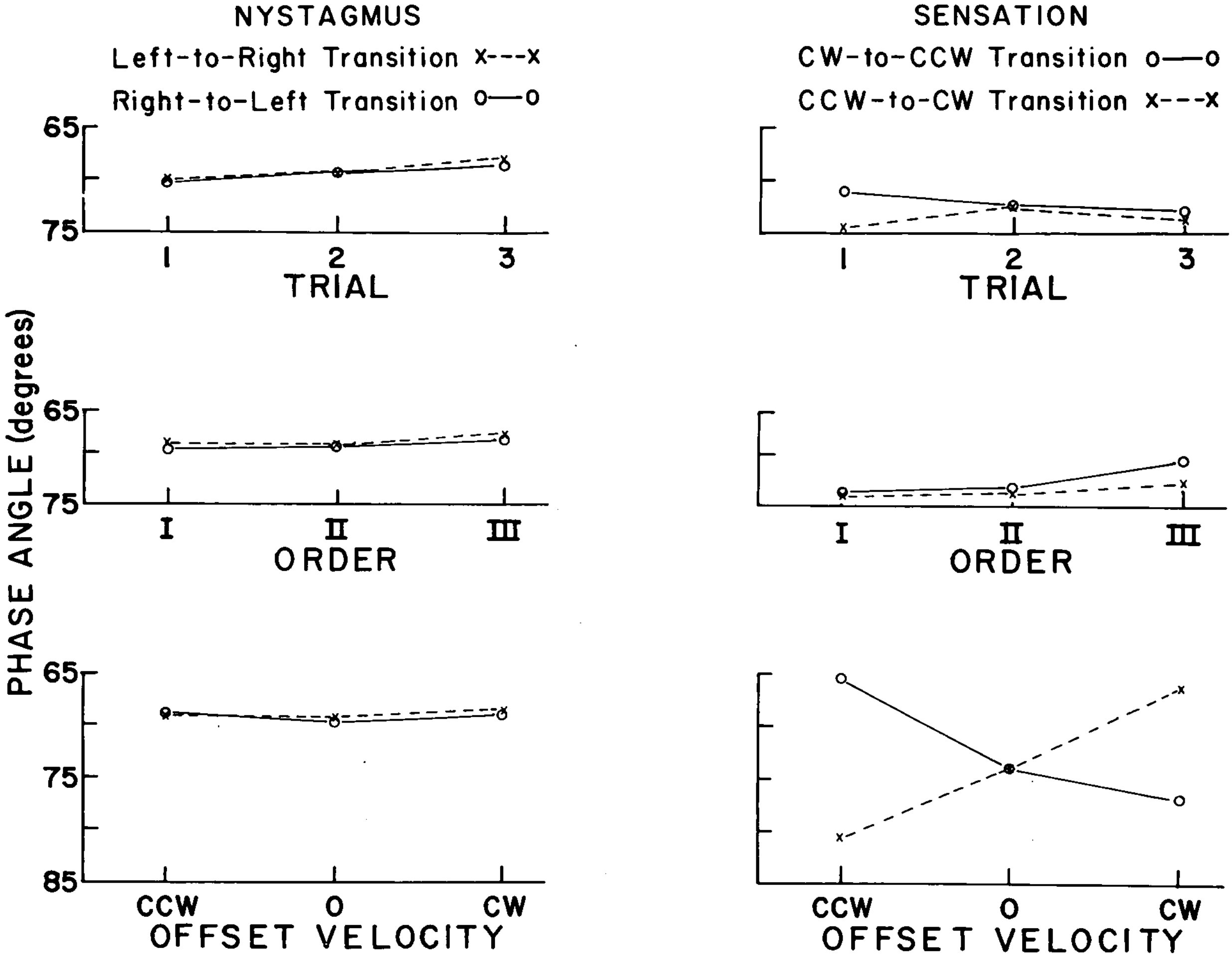
The mean phase lag of the directional transitions in the ocular nystagmus and turning-sensation responses of the 30 subjects exposed to the sinusoidal angular acceleration stimuli are presented graphically in Figure 1 as a function of trial number, order of presentation, and the offset velocity. For both forms of response, separate means are plotted for the left-to-right and right-to-left transitions occurring during each stimulus cycle. The nystagmus data derive from Table A I in the appendix which separately lists the response of each subject, with each entry representing the mean of five responses in the denoted direction. The turning-sensation data are similarly listed in Table A II.

Visual inspection of the nystagmus data in Figure 1 indicates that the primary experimental variable, offset velocity, as well as the variables of trial and order of presentation, had little effect on the ocular phase shift response. There was a consistent but small effect associated with trials, phase lag tending to decrease slightly from Trial 1 to Trial 3. The observed shift is in line with the authors' observation that long-term continuous exposure (30 min to 1 hr) of subjects to sinusoidal stimuli usually results in a gradual decrease in phase shift with time. In terms of the Π/Δ ratio for the semicircular canals, repeated exposure to these oscillations decreases the ratio, which could be considered equivalent either to decreasing the viscous damping, Π, or increasing the stiffness, Δ, of the cupula-endolymph system, or both.

That offset velocity had no effect on nystagmus phase lag is in accordance with expectations since it offers further confirmation that angular acceleration per se is the adequate semicircular canal stimulus. As implied by the data in Figure 1, the direction of the nystagmus response at a given time within a stimulus cycle remains unchanged, even though offset velocities are introduced which result in the subject's rotating continuously throughout the trial in only one direction or the other. These data also indicate that if a rotating device has technical limitations which prevent smooth transitions through zero velocity, sinusoidal cupulometry based on nystagmus transitions can still be practiced through the introduction of constant level offset velocity

Figure 1

Effect of trial, order of presentation, and direction of offset velocity on nystagmus and sensation phase shift.



which will allow the sinusoidal oscillations to occur in a velocity range more optimal to the drive system of the rotator.

Visual inspection of the turning sensation data in Figure 1, however, immediately indicates that a constant level offset velocity significantly affects the subjective judgments of the time at which a reversal of rotation occurs. Further, the phase lag of the CCW-to-CW transition in sensation of motion increases with a CCW (leftward rotation of the subject) offset velocity, and decreases with a CW offset. The opposite effect is observed for the CW-to-CCW transition. For the variables of trial and order of presentation there was little phase difference between the two directional transitions. However, all of these sensation data show a much greater variability than those obtained with the nystagmus data, even allowing for the fact that one is a subjective measure while the other is an objective measure. For example, with the zero offset condition, the mean and standard deviation of the nystagmus phase shift, including both directions of response, are 69.6° and $\pm 2.39^\circ$, respectively. The mean and standard deviation of the sensation data are 74.0° and $\pm 11.64^\circ$, respectively.

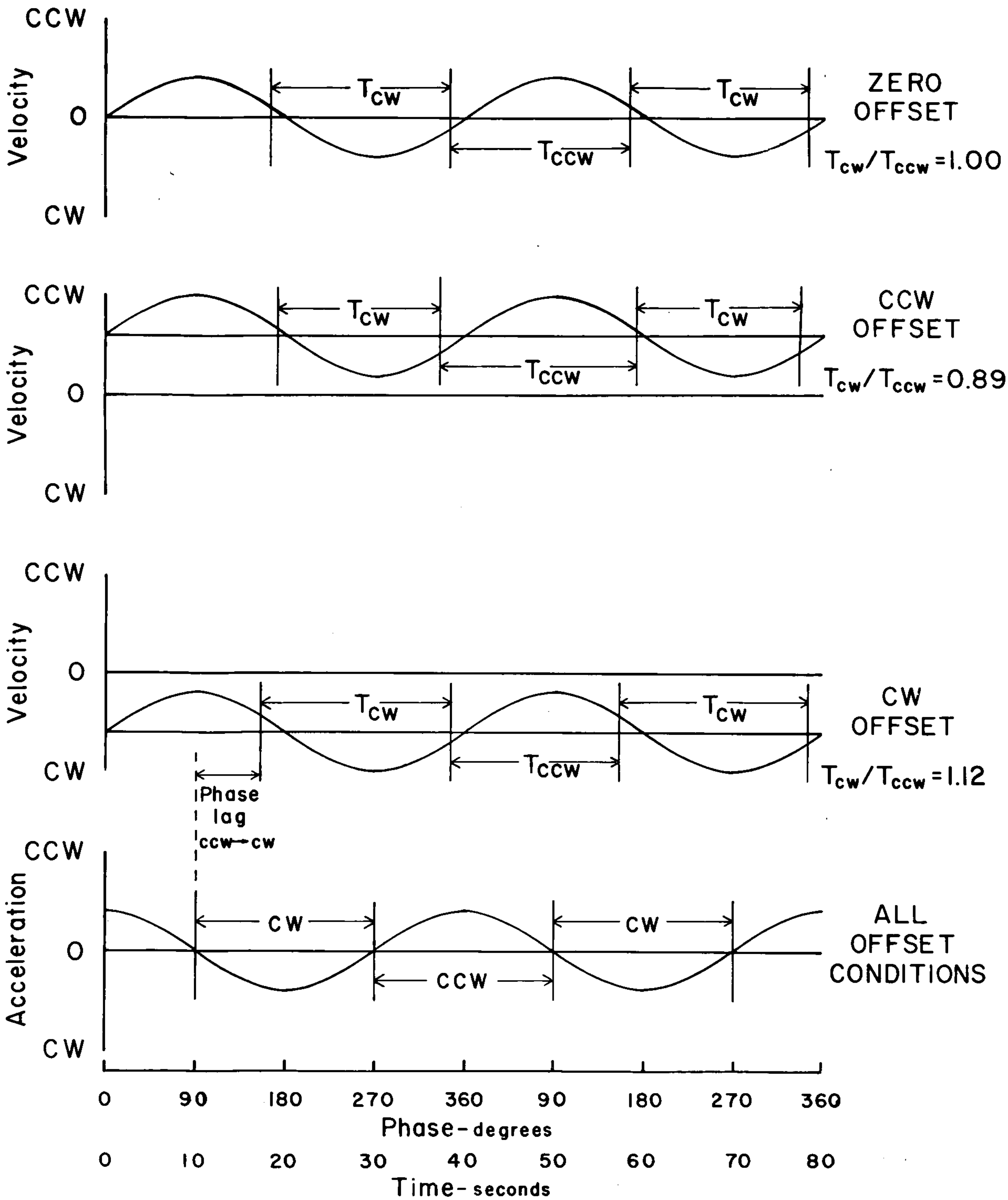
This same zero offset velocity also allows a comparison of the Π/Δ index ratio for the two response measures. As calculated from $\Pi/\Delta = 2\zeta/\omega_n \cong \tan\phi/2\Pi F$ where ϕ is the measured phase lag of the response and F is the stimulus frequency in cps, $\Pi/\Delta = 17.6$ for the nystagmus data while $\Pi/\Delta = 22.2$ for the sensation of turning data. Conventional cupulometry has typically given Π/Δ values of, say, 16 for nystagmus and 10 for sensation (5). Clearly the present data approximate the value for nystagmus but certainly not that for sensation.

To relate the sensation phase shift data collected with zero offset to those obtained with the CCW and CW offset conditions, sequential phase/time plots of these steady-state data are presented in Figure 2. The sinusoid at the top represents the instantaneous angular velocity of the subject under zero offset conditions where CCW and CW rotations occur sequentially in time. The second sinusoid describes the angular velocity profile for the CCW offset condition where rotation occurs at all times in only this direction, and the third corresponds to the CW offset velocity profile. The last sinusoid shows the profile for the angular acceleration stimulus which is identical for all three of the offset conditions. The time or phase point at which each transition in the direction of sensation of turning occurred is separately plotted on each of the three velocity curves. The phase lag of the response is depicted at the bottom of the figure where phase and time are referenced from an arbitrarily selected point during steady-state rotation.

At time $t = 0$, the subject is being angularly accelerated to his left (CCW) and senses the direction of rotation accordingly. At time $t = 10.0$ sec, the device begins to angularly accelerate the subject in the CW (yaw rightward) direction. Considering for the moment the CW offset stimulus condition, he does not sense this reversal until approximately 7.3 sec (66°) later. He then begins to sense CW rotation which continues for T_{CW} seconds and then reverses to a CCW sensation approximately 77° after the angular acceleration direction reverses from CW to CCW at $t = 30.0$ sec, phase $= 270^\circ$. The duration of the CCW sensation (yaw leftward) of turning which follows is denoted

Figure 2

Effect of superimposing counterclockwise and clockwise offset velocities on a sinusoidal angular acceleration stimulus upon the duration of subjective turning sensations (T). Turning sensation is lengthened whenever its direction coincides with that of the offset velocity.



as T_{CCW}. When the zero offset velocity profile is used as reference, it can be seen that the subjective sensation of turning leads the velocity transitions, the subject sensing a change in direction of rotation before the actual change occurs.

With these observations as background, it can be seen from Figure 2 that with zero offset, the duration of the sensation of turning CW is about the same as that for turning CCW, with the ratio of T_{CW}/T_{CCW} being near unity. However, when an offset is introduced which makes the subject rotate CCW continuously, the data indicate that he senses CCW rotation longer than he does CW rotation since $T_{CW}/T_{CCW} = 0.89$. The opposite effect is observed for CW offset with $T_{CW}/T_{CCW} = 1.12$. The significance of these differences in sensation cannot be defined with certainty. There is the possibility that, since the direction of the longer duration is associated with that portion of the cycle in which the absolute speed approaches its maximum value, the magnitude of linear (centripetal) acceleration effects may be influencing the judgments of duration of turning differentially. It is also possible that the subjects were using some machine characteristic such as vibration or acoustic noise to achieve their judgments. The amount of indoctrination in the task may also have been a factor. It is interesting to note that Cramer (3), studying subjective responses to oscillation about the yaw axis using twenty pilots trained in the observational task, obtained a mean phase shift of 60° at 0.02 cps; this value gives $\Pi/\Delta = 14$ as an approximation. Further investigation is required before sinusoidal cupulometry based on turning sensation can be practiced under offset velocity conditions. In contradistinction, sinusoidal cupulometry based on nystagmus can be practiced under offset velocity conditions without difficulty.

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APPENDIX A

INDIVIDUAL NYSTAGMUS AND TURNING-SENSATION DATA

APPENDIX

TABLE A I

Mean Nystagmus Phase Lag in Degrees for a Sinusoidal Acceleration Superimposed on a Constant Velocity Rotation Based on Left-to-Right and Right-to-Left Transitions of Slow Component. All Entries Correspond to Latin Square at the Left.

			Trial					
			1		2		3	
Latin Square	Order	Subject	L - R	R - L	L - R	R - L	L - R	R - L
O CCW CW	I	1	70.2	70.4	63.0	61.0	58.7	63.3
CW O CCW	II	2	64.5	65.9	65.6	65.2	65.0	61.8
CCW CW O	III	3	65.8	65.3	65.0	66.0	66.0	65.4
O CCW CW	I	4	66.8	68.9	66.4	68.8	58.1	59.6
CW O CCW	II	5	66.4	66.9	67.9	69.4	67.2	68.0
CCW CW O	III	6	68.9	69.1	69.1	70.6	67.3	68.1
O CCW CW	I	7	68.1	69.3	69.4	69.0	67.7	68.4
CW O CCW	II	8	70.5	71.6	69.4	66.6	65.4	65.1
CCW CW O	III	9	68.9	68.6	67.6	69.4	67.2	68.3
O CCW CW	I	10	73.1	72.8	70.8	69.7	68.8	71.2
CW O CCW	II	11	70.9	71.0	71.0	70.7	68.1	67.2
CCW CW O	III	12	72.4	69.2	66.1	68.4	67.9	69.4
O CCW CW	I	13	71.6	71.9	69.9	68.9	67.9	69.8
CW O CCW	II	14	70.9	71.9	70.6	70.6	70.2	71.0
CCW CW O	III	15	59.2	62.4	60.8	60.5	61.2	63.4
O CCW CW	I	16	71.6	72.6	71.8	70.8	69.9	70.6
CW O CCW	II	17	70.8	70.3	70.1	68.9	69.4	69.1
CCW CW O	III	18	70.4	70.5	71.7	71.9	72.1	72.5
O CCW CW	I	19	72.4	72.7	70.3	70.9	70.3	70.5
CW O CCW	II	20	70.3	71.9	70.3	71.3	71.1	69.4
CCW CW O	III	21	71.2	71.7	71.6	70.0	69.5	69.5
O CCW CW	I	22	70.6	71.2	70.8	69.6	69.8	70.5
CW O CCW	II	23	72.6	70.3	70.7	71.4	70.1	70.9
CCW CW O	III	24	69.4	72.6	68.0	67.6	66.6	68.6
O CCW CW	I	25	72.1	71.3	71.4	72.1	71.7	69.6
CW O CCW	II	26	72.3	70.6	69.7	70.0	69.9	69.8
CCW CW O	III	27	71.1	72.6	71.6	70.5	70.8	71.6
O CCW CW	I	28	70.8	70.9	70.4	70.5	70.8	69.8
CW O CCW	II	29	71.9	71.0	71.6	71.8	71.0	71.5
CCW CW O	III	30	69.6	70.3	70.8	69.7	69.4	70.2

APPENDIX

TABLE A II

Mean Turning Sensation Phase Lag in Degrees for a Sinusoidal Acceleration Superimposed on a Constant Velocity Rotation on CCW to CW and CW to CCW Transitions of Rotation Direction. All Entries Correspond to Latin Square at the Left.

Latin Square	Order	Subject	CCW→CW	CW→CCW	CCW→CW	CW→CCW	CCW→CW	CW→CCW
O CCW CW	I	1	74.1	71.9	77.0	70.2	73.4	80.0
CW O CCW	II	2	57.1	67.9	60.4	67.2	69.5	61.9
CCW CW O	III	3	79.3	68.6	76.4	91.5	90.1	84.0
O CCW CW	I	4	84.8	89.6	109.1	75.0	75.7	101.5
CW O CCW	II	5	82.8	84.1	99.9	99.9	77.8	86.0
CCW CW O	III	6	72.0	72.0	68.2	68.2	70.0	70.0
O CCW CW	I	7	84.2	84.2	80.0	70.2	69.4	75.0
CW O CCW	II	8	64.4	77.3	67.9	67.2	75.2	58.6
CCW CW O	III	9	74.0	65.0	60.5	81.6	79.5	83.7
O CCW CW	I	10	66.1	64.7	72.5	60.6	60.8	64.3
CW O CCW	II	11	65.1	74.5	63.1	61.5	68.4	64.9
CCW CW O	III	12	67.4	39.0	50.8	52.3	54.2	50.1
O CCW CW	I	13	66.1	64.2	60.8	60.2	62.0	62.5
CW O CCW	II	14	71.3	78.2	78.0	83.0	96.7	59.7
CCW CW O	III	15	119.5	55.7	58.1	69.5	79.7	68.2
O CCW CW	I	16	68.9	68.6	83.1	66.1	74.1	77.2
CW O CCW	II	17	56.8	78.8	60.2	68.4	64.7	63.4
CCW CW O	III	18	104.0	85.6	85.2	108.4	90.5	96.2
O CCW CW	I	19	90.0	77.0	105.6	93.7	91.2	111.2
CW O CCW	II	20	74.5	86.8	78.9	68.5	83.2	56.0
CCW CW O	III	21	84.5	57.4	59.0	73.1	88.0	83.2
O CCW CW	I	22	59.2	64.0	59.0	44.4	50.0	62.8
CW O CCW	II	23	72.0	73.8	72.5	68.4	78.6	69.9
CCW CW O	III	24	70.1	65.6	66.3	71.8	71.5	70.4
O CCW CW	I	25	85.7	86.6	88.7	82.3	82.0	78.8
CW O CCW	II	26	73.6	78.1	79.9	78.4	87.9	83.8
CCW CW O	III	27	69.8	60.5	59.3	70.7	66.8	69.3
O CCW CW	I	28	61.1	69.3	71.6	58.6	37.2	73.4
CW O CCW	II	29	60.5	77.7	82.4	84.0	92.3	62.7
CCW CW O	III	30	75.4	49.1	46.1	49.2	49.4	52.1

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13. ABSTRACT

Thirty subjects were exposed to a sinusoidal rotation stimulus of 0.025 cps and a peak velocity of 63 deg/sec, which was superimposed on a constant rotational velocity of 153 deg/sec clockwise (CW), 153 deg/sec counterclockwise (CCW), or 0 deg/sec. The phase lag of nystagmus and sensation directional transitions was determined and used to derive a functional index, $2\zeta/\omega_n$, equivalent to the Π/Δ index obtained by conventional cupulometry. Nystagmus-based values were found to be independent of the base velocity and its direction. The phase lag of the CCW-to-CW transition in sensation of turning increased with a CCW offset velocity and decreased with a CW offset. The opposite effect was observed for a CW-to-CCW transition.

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