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Group mean estimates of subjective angular displacement obtained from 40 naval flight students were approximately accurate for stimulation of both horizontal and vertical canals. Significant individual differences were found within the group. From the responses obtained, mean estimates of vestibular system parameters were calculated. The method appears to be a reliable and practical means of measuring the $K_s \frac{\theta}{\Delta}$ parameter which has not been assessed in the past due to lack of a suitable method. The theoretical basis of the method is discussed.

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A COMPARISON OF SUBJECTIVE RESPONSES TO SEMICIRCULAR CANAL STIMULATION PRODUCED BY ROTATION ABOUT TWO AXES *

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SUMMARY PAGE

THE PROBLEM

The problem is to find a few response parameters, measured by procedures practical for clinical use, which would be sufficient to describe the dynamics of individual vestibular reactions. A practical procedure has been developed for obtaining reliable measures of sensation associated with semicircular canal stimulation. Theoretically these measures can be used along with measures of nystagmus to estimate several vestibular response system parameters relevant to the clinical assessment of pilot vertigo. In this experiment, responses produced by stimulation of the horizontal semicircular canals are compared with those produced by stimulation of the vertical canals.

FINDINGS

Group mean estimates of subjective angular displacement obtained from 40 naval flight students were approximately accurate for stimulation of both horizontal and vertical canals. Significant individual differences were found within the group. From the responses obtained, mean estimates of vestibular system parameters were calculated as follows: $\frac{\Pi}{\Delta} = 16.0$ sec and $K_s \frac{\theta}{\Delta} = 19.9$ sec for stimulation of horizontal semicircular canals, and $\frac{\Pi}{\Delta} = 7.2$ sec and $K_s \frac{\theta}{\Delta} = 10.5$ sec for the stimulation of vertical semicircular canals. These values are consistent with results obtained by other methods, and in this way the results support the validity of this procedure for the assessment of vestibular function. The method appears to be a reliable and practical means of measuring the $K_s \frac{\theta}{\Delta}$ parameter which has not been assessed in the past due to lack of a suitable method. The theoretical basis of the method is discussed.

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The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

INTRODUCTION

In recent experiments it was found that men were able to make consistent estimates of angular displacement when they were rotated passively through short arcs about an Earth-vertical axis. The vestibular stimuli comprised a sequence of triangular waveforms of angular velocity, varying in wavelength and temporally separated from one another. The mean displacement estimates made by a group of subjects using a particular reporting method (12) were nearly accurate; however, there were significant individual differences within the group which appeared to have high test-retest reliability (18). Purposely excluded from the test situation were visual and auditory cues to relative motion between the man and the Earth and otolith cues from reorientation relative to gravity. Since these sources of sensory information were absent, it is reasonable to assume that the semicircular canals were the primary source of information for the judgments of angular displacement.

There are theoretical as well as practical reasons for using displacement judgments in combination with other responses generated by the triangular waveform stimulus to assess vestibular function. The theoretical justification is based upon the fact that such stimulus-response relationships can be predicted from the torsion-pendulum model proposed by van Egmond, Groen, and Jongkees (3,5) and, insofar as the model is appropriate, these relationships provide a means for measuring parameters of individual sensations which are not assessed by nystagmus measures alone. The practical justification derives from the fact that these measures can be accomplished quickly and reliably and from indications that sensation measures may be more relevant than nystagmus measures to the clinical assessment of pilot vertigo (1,12).

The present experiment was undertaken to extend application of triangular waveform procedures to evaluation of responses produced by stimulation of the vertical semicircular canals and to compare these responses with those produced by stimulation of the horizontal canals in the same set of subjects. Although the main experimental results described herein are sensation measures obtained during triangular waveforms of angular velocity, this paper includes consideration of the assessment of both sensation and nystagmus.

METHOD

SUBJECTS

Forty U. S. Navy and Marine officers awaiting flight training served as subjects. All had passed standard Navy flight physical examinations without signs of vestibular disorders.

APPARATUS

The rotation device was a Stille-Werner RS-3 rotator fitted with a rectangular platform upon which a subject could be positioned on his side or seated upright near the center of rotation.

PROCEDURE

Two groups of twenty subjects were selected. Subjects in the first group were tested in complete darkness to prevent their use of visual cues, but no effort was made to eliminate auditory or cutaneous cues. The second group was also tested in complete darkness and, in addition, auditory cues were minimized by applying wide-band noise through audiometric earphones, and cutaneous cues were minimized by encapsulating the subject to reduce air currents.

With the exceptions just noted, the procedure was the same for both groups. Two series of stimuli were presented to each subject. As illustrated in Figure 1, subjects were seated upright in one series with the z-axis* and the axis of rotation in alignment to stimulate the horizontal canals; in another series subjects were positioned right-side-down with the y-axis* and the rotation axis in alignment to stimulate the vertical canals. Half of the subjects were tested in the seated position first and half were tested in the right-side-down position first.

Each series consisted of twenty triangular waveform stimuli. Two accelerations were used, 10 and 15 deg/sec^2, and each was combined with five stimulus durations to give ten displacements that ranged from 90 to 495 deg. Each of the ten displacements was given in both the clockwise and counterclockwise direction. Order of presentation of stimuli within series was scrambled, but was the same for each subject. A 30-sec rest period was allowed between stimuli.

Judgments of angular displacement were reported verbally in degrees. Subjects were instructed to make retrospective judgments; i.e., to delay judgment until apparent displacement was complete. Instructions were specific in this regard to avoid concurrent velocity estimates which, according to earlier studies (11, 12, 18), yield systematic underestimation of larger displacements (cf. 12).

RESULTS

Mean subjective displacement judgments (ψ_s) were approximately correct throughout the range of stimuli under all conditions of the experiment, as shown in Figure 2. For purposes of making statistical comparisons, the slope of the best-fitting straight line through paired values of estimated and actual angular displacement was calculated, using a least squares criterion, for each subject under each condition of the experiment. These slopes were then used as data for an analysis of variance test of statistical significance between experimental conditions. The results of this analysis are as follows:

1) Subjects underestimated the larger angular displacements to a greater extent during y-axis rotation than during z-axis rotation. This difference was small but statistically significant at $p < 0.01$.

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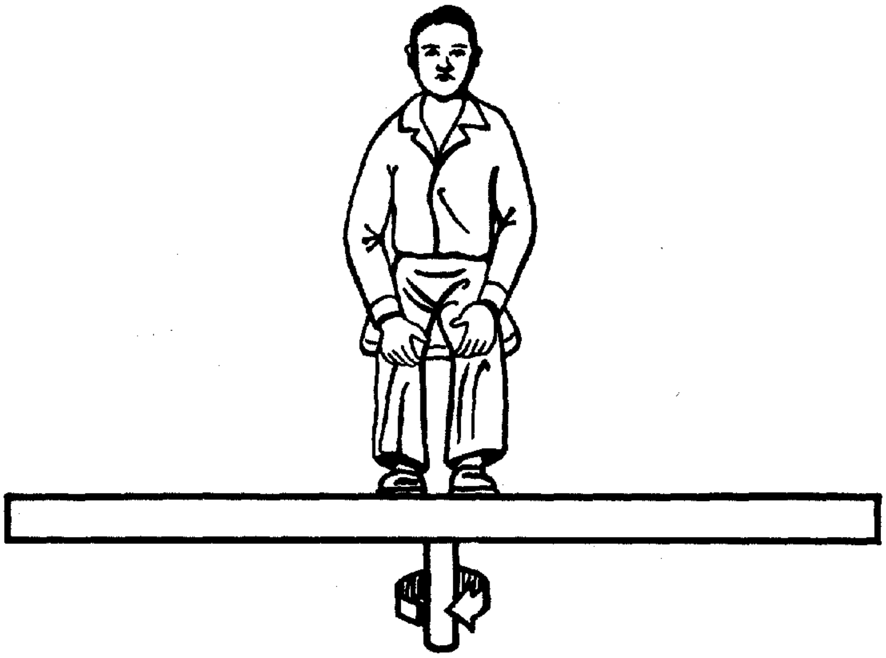
* The nomenclature system proposed by Hixson *et al.* (14) is used here.

Z - AXIS
ROTATION



Y - AXIS
ROTATION

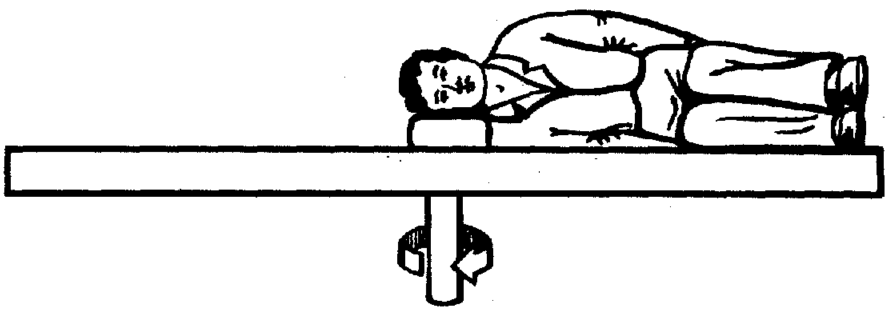


Figure 1

Position of subject: seated upright with z-axis and axis of rotation in alignment (upper), right-side-down with y-axis and axis of rotation in alignment (lower)

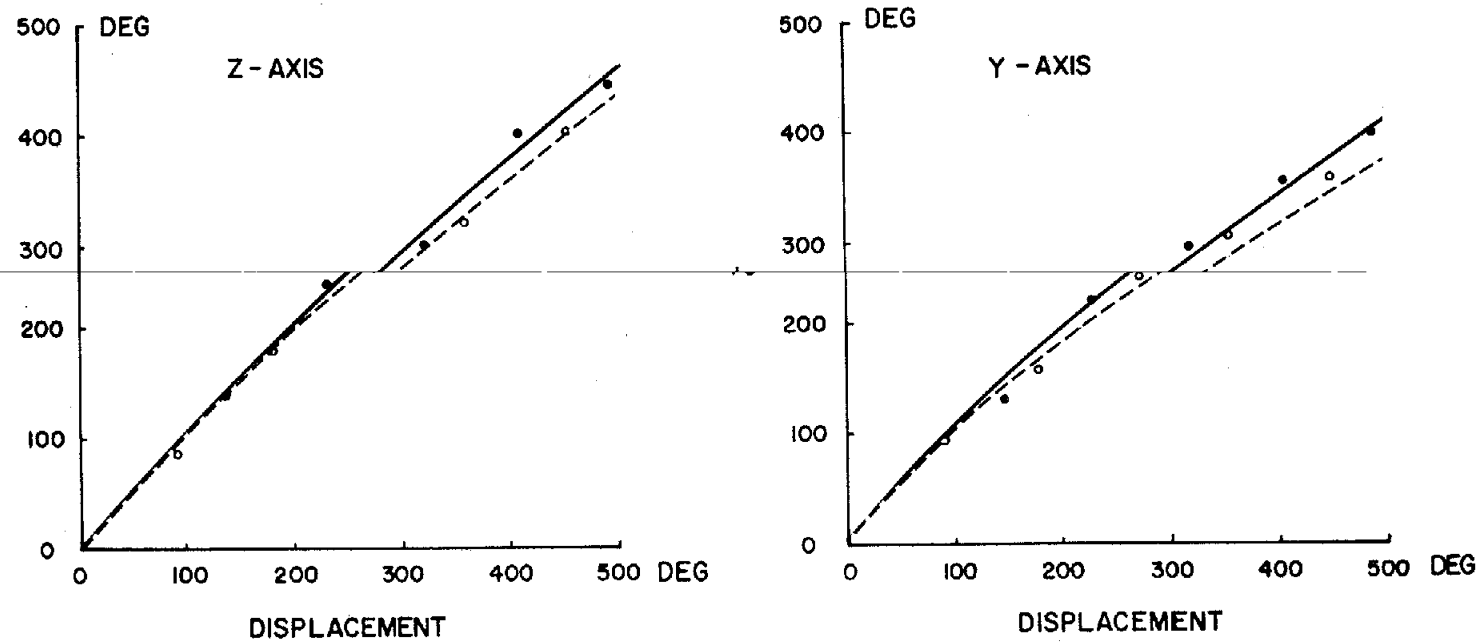


Figure 2

Mean angular displacement (ψ_s) estimates when subject is rotated about his z-axis and about his y-axis. Solid lines and solid circles indicate predicted and obtained results, respectively, for $\alpha = 15$ deg/sec^2. Dashed lines and open circles indicate predicted and obtained results, respectively, for $\alpha = 10$ deg/sec^2. Predicted curves were derived from equation (4) in Discussion section.

2) Subjects made slightly smaller estimates of the larger displacements with the 10 deg/sec^2 stimuli than with the 15 deg/sec^2 stimuli. The difference was not statistically significant in the present sample, but it was also observed in a previous experiment (12). A difference of the magnitude found here was expected on the basis of theoretical considerations discussed below.

3) The presence of extraneous cutaneous and auditory cues did not significantly affect displacement judgments. However, between-subjects differences were large, so a large between-groups difference would be required for statistical significance. Hence, the possibility remains that a reliable difference might be found if the comparison were based upon data from one group of subjects tested under both conditions.

4) No significant difference was found for direction of rotation about either axis. This result is of some interest because several experiments (7, 9, 13) have shown a pronounced difference in the magnitudes of upbeating and downbeating nystagmus produced by angular acceleration of equal magnitude but opposite direction when the acceleration exceeded a certain magnitude or when visual suppression of nystagmus was present. Although the present experiment involved neither the requisite stimulus magnitude nor visual suppression, the data were examined for a directional difference on the hypothesis that sensation might prove more sensitive than nystagmus. The hypothesis was not confirmed.

Large differences were found between individuals as illustrated by the results of two subjects shown in Figure 3; one subject (PE) overestimated and the other (KI) underestimated actual displacement. Although conspicuous differences existed between them, it is apparent that each of these individuals gave consistent responses. In this respect they were typical of most subjects in the sample. Correlations between actual and perceived displacement for individual subjects ranged between .46 and .99 with a mean of .89. Subjects in a previous experiment (18) had indicated perceived displacement by use of a pointer on a dial, and their judgments were more consistent than those obtained in this experiment. In the earlier study mean correlation between perceived displacement and actual displacement was .94. A Mann-Whitney U Test indicated that the difference between the distribution of correlation coefficients in the two experiments was statistically significant ($z = 6.28$, $P < .00006$).

Individual subjects tended to give similar judgments for rotation about both the y- and z-axes, i.e., a subject who gave large estimates for z-axis stimuli also tended to give large estimates for y-axis stimuli. Slopes of best-fitting straight lines were calculated for each subject for each axis of rotation. The slopes for the two axes were significantly correlated ($r_{yz} = .62$, $n = 40$), a result which may indicate that individuals tend to have "matched sets" of canals, but which may also be indicative of some kind of central nervous system gain factor that operates to produce the same gain for an individual irrespective of the source of the sensory signals.

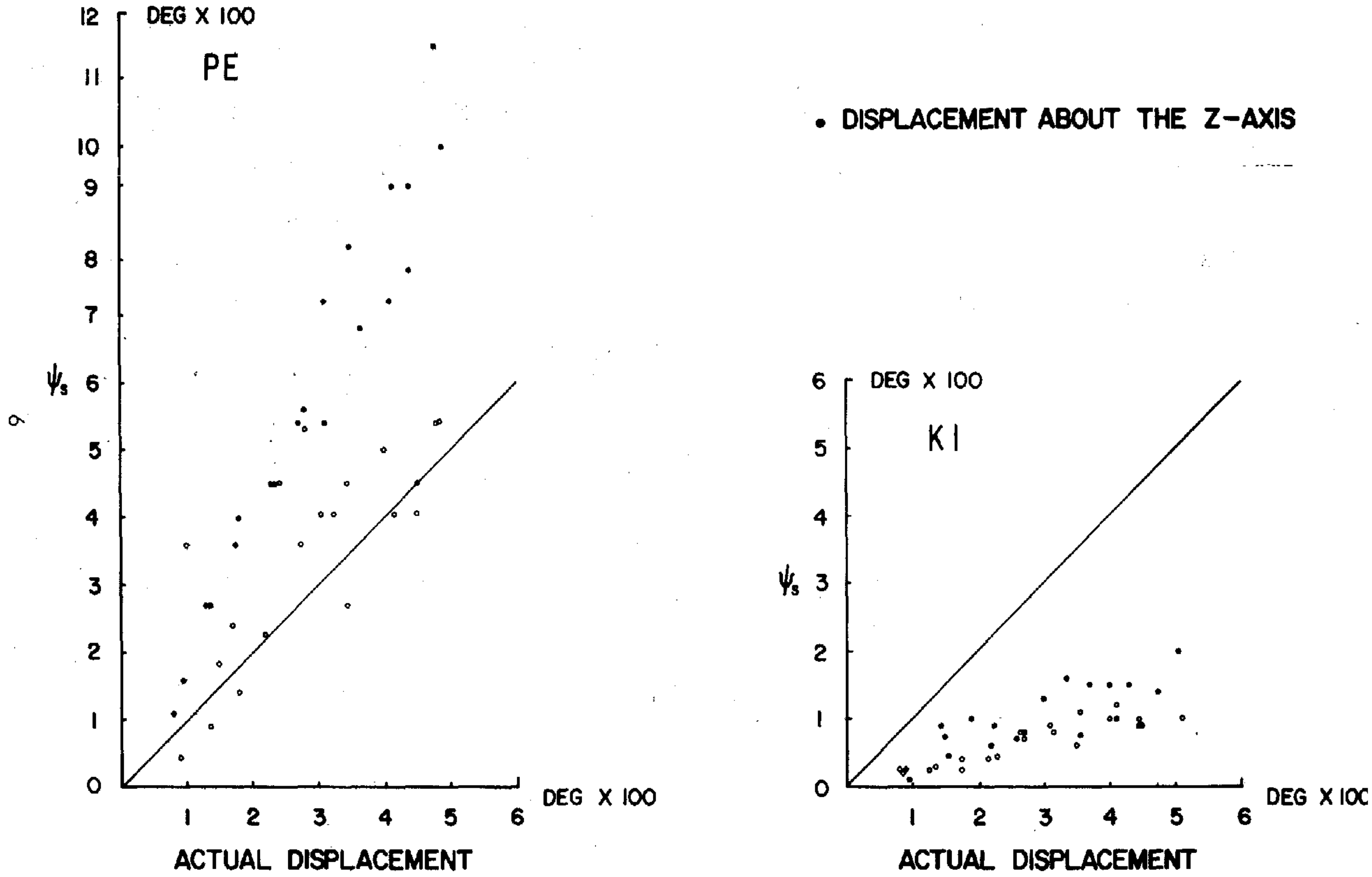


Figure 3

Mean angular displacement (ψ_s) estimates from subjects PE and KI

DISCUSSION

The results of the present study, as well as previous results (11, 18), illustrate that man can integrate the available sensory information provided by triangular waveform stimuli to give approximately accurate and consistent estimates of subjective angular displacement (ψ_s) when he makes retrospective judgments. However, the subjects in this experiment made less consistent judgments than did those in a previous experiment (12, 18), and perhaps this was due to a slight difference in procedure. In the present experiment subjects were tested in complete darkness and they reported their estimates verbally. In the earlier study (18) the interior of the capsule was dimly illuminated, and estimates were made by manual displacement of a pointer on a circular dial marked off in angular units. The illumination alone may have provided a perceptual aid to consistent reporting insofar as it provides a visible frame of reference for estimating angles, but the presence of the dial may have also have aided judgments by permitting the subject to match a perceived angle rather than having to convert perceived displacement into units of angular measure. It is also possible that subjects in the dark tended to round off estimates to familiar large angular units such as 360 deg. In any case, testing in the dark is advantageous in that it permits the simultaneous recording of nystagmus, but this procedure appears to reduce the reliability of subjective angular displacement judgments.

A typical stimulus profile used in this experiment is illustrated in Figure 4. As inferred from evidence supporting the torsion pendulum analogy proposed by van Egmond et al. (3), cupula deflection during this stimulus is approximated by the curve shown in Figure 4C. If it is assumed that subjective angular velocity ($\dot{\psi}_s$) and nystagmus slow phase velocity ($\dot{\psi}_n$) are proportional to cupula deflection for this type of stimulus, then in accordance with equations developed in previous papers (10, 12), these response measures should be predicted by

$$\dot{\psi}_s = \alpha\, K_s \frac{\theta}{\Delta}\left[\left(2 - e^{-\frac{\Delta}{\Pi} t_1}\right) e^{-\frac{\Delta}{\Pi} t_2} - 1\right] e^{-\frac{\Delta}{\Pi} t_\omega} \qquad (1)$$

and

$$\dot{\psi}_n = \alpha\, K_n \frac{\theta}{\Delta}\left[\left(2 - e^{-\frac{\Delta}{\Pi} t_1}\right) e^{-\frac{\Delta}{\Pi} t_2} - 1\right] e^{-\frac{\Delta}{\Pi} t_\omega} \qquad (2)$$

where $K_s \frac{\theta}{\Delta}$, $K_n \frac{\theta}{\Delta}$, and $\frac{\Pi}{\Delta}$ are parameters of the response system (cf. 10, 12), and t_1, t_2, and t_ω are measures of time during their respective time epochs T_1, T_2, and T_ω (see Figure 4).

The maximum apparent displacement occurs theoretically at or very near the point in the T_2 epoch when the cupula crosses the zero baseline. The inverval between the onset of T_2 and the point of reversal (t_r) is given by

$$t_r = \frac{\Pi}{\Delta} \ln\left(2 - e^{-\frac{\Delta}{\Pi} t_1}\right) \qquad (3)$$

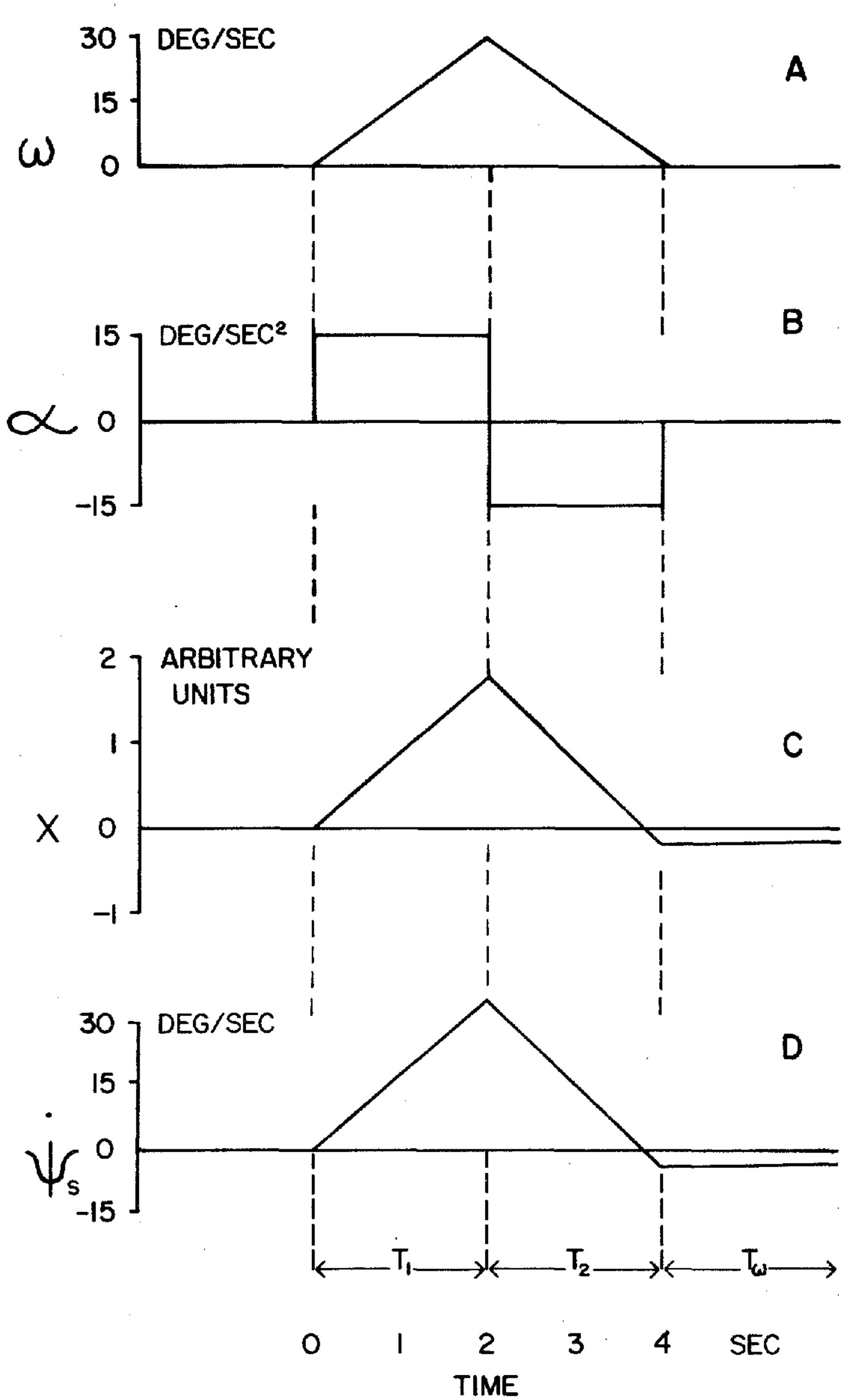


Figure 4

A typical stimulus used in this experiment and theoretical response. (A) stimulus angular velocity, (B) stimulus angular acceleration, (C) cupula displacement, (D) subjective angular velocity

When subjective angular velocity, given by equation (1), is integrated over the interval $(T_1 + t_r)$, we obtain for subjective angular displacement (ψ_s) the equation

$$\psi_s = \alpha K_s \frac{\theta}{\Delta}\left[T_1 - \frac{\Pi}{\Delta}\ln\left(2 - e^{-\frac{\Delta}{\Pi}T_1}\right)\right] \qquad (4)$$

or

$$\psi_s = \alpha K_s \frac{\theta}{\Delta}\left(T_1 - t_r\right) \qquad (4a)$$

One primary purpose of this study was to compare judgments (ψ_{s_y}) obtained during the y-axis series with those (ψ_{s_z}) obtained during the z-axis series. Characteristics of responses elicited by stimulation of the horizontal and vertical canals have been reported to differ in several respects. For example, differences have been noted in response decay following angular impulses (15) and in stimulus-response phase relations during sinusoidal oscillation (9). For these situations, a reasonable mean estimate of $\frac{\Pi}{\Delta_z}$ for responses to horizontal canal stimulation appears to be about 16 sec*, whereas a reasonable mean estimate for $\frac{\Pi}{\Delta_y}$ from vertical canal responses is about 7 sec. Equation (4) provides a close fit to the mean z-axis data obtained in this experiment, using the values of $\left(K_s\frac{\theta}{\Delta}\right)_z$ = 19.9 sec and $\frac{\Pi}{\Delta_z}$ = 16.0 sec that were used in the earlier study (12). The predicted values of ψ_{s_z} for 10 deg/sec^2 (dashed line) and 15 deg/sec^2 (solid line) stimuli are shown in Figure 2 (z-axis).

To predict the ψ_{s_y} results we can use the $\frac{\Pi}{\Delta_y}$ value of about 7 sec as determined from these other procedures, but it is also necessary to estimate a value for $(K_s\frac{\theta}{\Delta})_y$. Nystagmus slow phase velocity approaches a maximum during prolonged constant angular acceleration, and this maximum differs for y- and z-axis stimulation. These maxima provide estimates of $K_n \frac{\theta}{\Delta}$ for both horizontal and vertical nystagmus and, by the data of Collins and Guedry (2), the ratio of $(K_n \frac{\theta}{\Delta})_y$ to $(K_n \frac{\theta}{\Delta})_z$ is 0.53. Assuming that the ratio of $(K_s\frac{\theta}{\Delta})_y$ to $(K_s\frac{\theta}{\Delta})_z$ is also 0.53, the value of $(K_s\frac{\theta}{\Delta})_y$ would be 0.53 (19.9 sec) or 10.5 sec. When values of $(K_s \frac{\theta}{\Delta})_y$ = 10.5 sec and $\frac{\Pi}{\Delta_y}$ = 7.2 sec are used in equation (4), an excellent fit to the ψ_{s_y} data is obtained as shown in Figure 2 (y-axis). Thus it appears that reasonable average estimates of $\frac{\Pi}{\Delta}$ and $K_s\frac{\theta}{\Delta}$ are, respectively, 16.0 sec and 19.9 sec for the z-axis and 7.2 sec and 10.5 sec for the y-axis. Moreover, because the values of parameters used in equation (4) are consistent with those found by other methods, the results offer support for the validity of this procedure in the assessment of vestibular function.

There is a noteworthy difference in the subjective aftereffects of z- and y-axis triangular waveform stimuli. Figure 5 illustrates that, as the triangular waveform stimulus ends, the subject should have an experience of rotation in reversed direction because the cupula overshoots its rest position. Subjects were asked to ignore this "overshoot" effect and to estimate only displacement in the initial rotation direction. The accuracy of the mean judgments suggests that subjects followed these instructions fairly well, but

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* However, past estimates of $\frac{\Pi}{\Delta_z}$ may have been low due to adaptation effects (16).

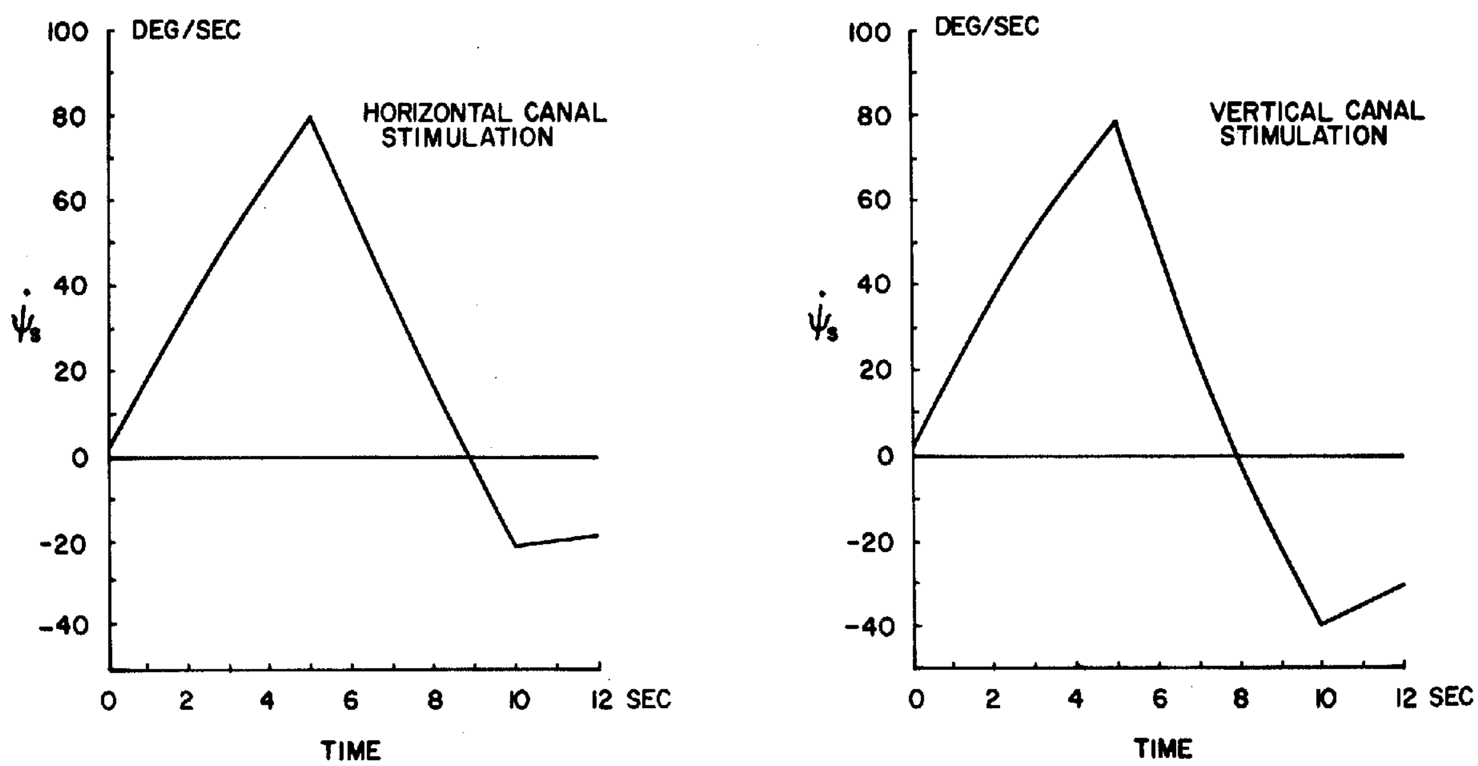

Figure 5

Theoretical subjective angular velocity calculated from equation (1) when $\alpha = 15$ deg/sec^2, $t_1 = t_2 = 5$ sec, and values of $\frac{\Pi}{\Delta}$ and $K_s \frac{\theta}{\Delta}$ appropriate for the horizontal canals (z-axis rotation) and vertical canals (y-axis rotation) are used there were spontaneous reports that the reversed motion seemed stronger during y-axis stimulation. When values of $K_s \frac{\theta}{\Delta}$ and $\frac{\Pi}{\Delta}$ appropriate for the horizontal and vertical canals are inserted into equation (1), $\dot{\psi}_s$ curves shown in Figure 5 are generated. Note that a stronger reversed effect ($-\dot{\psi}_s$) is predicted for vertical canal stimulation (y-axis rotation) even though approximately equivalent ψ_s estimates are predicted for the two axes. Thus, another aspect of the results is apparently consistent with theoretical expectations, and an additional study (4) will explore this and other points in more detail.

Mean values of $K_s \frac{\theta}{\Delta}$ and $\frac{\Pi}{\Delta}$ have been used to fit the mean results in the present experiment, but it is feasible to determine these values for individuals. In practice, $\frac{\Pi}{\Delta_z}$ and $\frac{\Pi}{\Delta_y}$ could be determined for individuals from nystagmus data. This could be done by measuring t_r responses to triangular waveforms (cf. 13) or by several other procedures (6, 10, 17). The $K_s \frac{\theta}{\Delta}$ and $K_n \frac{\theta}{\Delta}$ values can be determined for individuals by fitting to the obtained ψ_s or ψ_n data points a curve generated by equation (4) utilizing previously determined $\frac{\Pi}{\Delta}$ values. Alternatively, a curve generated by equation (4a) could be fitted to the data, in which case two response measures, ψ and t_r, would be substituted into the equation to generate the curve and determine $K\frac{\theta}{\Delta}$. The latter method is feasible when nystagmus is measured, since both measures can be taken from the same record (cf. 12). It would be less feasible to determine t_r and ψ_s from subjective data in a single trial because the divided attention involved in reporting a stop and estimating displacement could detract from the accuracy of the reports. However, for measures of responses to stimulus wavelengths used in these experiments, it is probably feasible to determine t_r from nystagmus data while obtaining subjective estimates of ψ_s. This would permit estimates of $K_s \frac{\theta}{\Delta}$ and $K_n \frac{\theta}{\Delta}$ from one sequence of stimuli. For longer wavelengths than those used in the present experiment, it is likely that adaptation effects would alter t_r, especially in subjective responses (cf. 8, 16, 19).

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