Tolerance to Vehicle Rotation of Subjects Using Turning and Nodding Motion of the Head while Performing Simple Tasks

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Rotation of space stations to provide artificial gravity may be used to combat the effects of long exposure to weightlessness. It has been established that motion of the head out of the plane of vehicle rotation results in nystagmus, visual illusions, sweating, and nausea. Cross-coupled accelerations are induced by these motions and are the cause of these disturbances. In order to obtain quantitative data on the magnitude of these induced cross-coupled accelerations that can be tolerated by man, an investigation was initiated at NASA Langley. The Langley subjects, lying on their backs, feet outward, were inclosed in a small cabin on a simple rotating-vehicle simulator. The subjects were required to move their heads in a specified manner in response to light signals. The head position and rate of motion, as well as reaction time, were recorded. Results have been obtained for cases where the subject is required to make turning and nodding motions of his head. The results indicate that the subjects cannot tolerate the stimulation experienced when nodding as well as they can tolerate the stimulus of the turning-head motion. The toleration to these various stimulations is discussed. Experiments to determine what value of cross-coupled acceleration can be tolerated for the nodding case are also mentioned and referenced.

Nomenclature

$\alpha_{G\theta}$ = cross-coupled angular acceleration (nodding)
$\alpha_{G\psi}$ = cross-coupled angular acceleration (turning)
$\omega_{G\theta}$ = apparent nodding velocity
$\omega_{G\psi}$ = apparent turning velocity
θ_G = apparent nodding displacement
ψ_G = apparent turning displacement
$\dot{\omega}_{h\theta}$ = nodding angular acceleration
$\dot{\omega}_{h\psi}$ = turning angular acceleration
$\omega_{h\theta}$ = nodding velocity of head
$\omega_{h\psi}$ = turning velocity of head
ω_V = vehicle rotational velocity
θ_h = nodding displacement
ψ_h = turning displacement
t = time

Subscripts

lr and ll = right and left lateral canals, respectively
pr and pl = right and left posterior canals, respectively
ar and al = right and left anterior canals, respectively

Introduction

MAN has long been concerned with the effects of rotation on his faculties. He has used rotation for his amusement, for therapy, to create forces to simulate flight conditions, and now in the space age, possibly to create artificial gravity on long-time space missions such as in a manned orbital research laboratory. In rotation, however, certain undesirable effects result which, for long-time missions, can be disquieting if not intolerable. These effects in our mundane activities cause sea and air sickness and, through visual illusions, have caused fatal aircraft accidents. The fundamental physical phenomena involved occur when head or body motions are made while in a rotating environment, resulting in crossed-coupled angular accelerations that are sensed by the semicircular canals shown schematically in Fig. 1. These three canals, although nearly orthogonal to each other, are not aligned with the body's axis. They mechanically sense the angular accelerations, which, through the nervous system and appropriate discrimination, are interpreted by the brain as turning, nodding, or rolling motions. The problems of man's tolerance to the cross-coupled acceleration have been studied extensively by Graybiel et al.[1, 2] and by the present authors.[3, 4] Graybiel has studied these effects for long periods with his subjects normally oriented with their long-body axis parallel to the axis of rotation and has found tolerance levels of 3 to 4 rpm. When attaining artificial gravity by rotation, however, the astronauts will be oriented with their long-body axis perpendicular to the axis of rotation of the vehicle, and this is the orientation examined by the present authors. The experiments of Refs. 3 and 4 have indicated a tolerance to 10 rpm while turning the head from side to side (hereafter this will be called turning). This is, of course, a rather restricted condition in view of the random motions expected in flight and used in Graybiel's work where lower tolerances were indicated. Studies were initiated at Langley to examine nodding motions and combinations of nodding and turning motions with the subjects oriented with their long-body axis perpendicular to the axis of rotation as done in Refs. 3 and 4. Some initial results of these studies are presented herein.

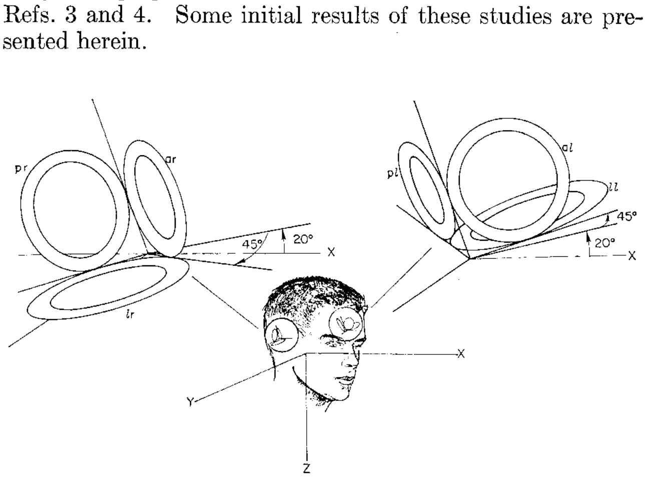

Fig. 1 The semicircular canal system.

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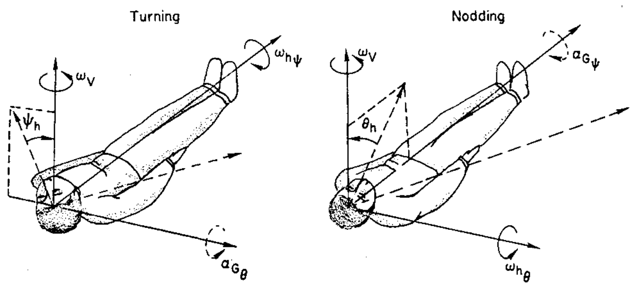

Fig. 2 Motion definitions for both the head-turning and head-nodding motions (also see section on symbols).

Head Motion and Semicircular Canal Stimulation

To the subject visually isolated in a rotating environment, the cross-coupled angular accelerations are only apparent, as the visual environment does not have a corresponding rotation. This disparity of sensory cues is the basic cause for visual illusions and nystagmus, which can lead to a state of disorientation and possible nausea.

The conditions of cross coupling for turning and nodding are shown in Fig. 2. For the turning motion, $\omega_{h\psi}$ is perpendicular to ω_V, the angular velocity vector of the vehicle. The cross-coupled acceleration experienced is perpendicular to both of these vectors and basically represents a nodding motion depending on the head position ψ_h so that

$$\alpha_{G\theta} = \omega_V \omega_{h\psi}$$

The portion of this acceleration sensed as a nodding motion is $\cos\psi_h\alpha_{G\theta}$, and as a rolling head motion, $\sin\psi_h\alpha_{G\theta}$. For the nodding motion, $\omega_{h\theta}$ is perpendicular to ω_V, and the cross-coupled acceleration that is experienced is perpendicular to these two vectors and basically represents a turning motion depending on the head position θ_h so that

$$\alpha_{G\psi} = \omega_V \omega_{h\theta}$$

That portion of the acceleration sensed as a turning motion is $\cos\theta_h\alpha_{G\psi}$, and as a rolling head motion, $\sin\theta_h\alpha_{G\psi}$.

This discussion has dealt basically with the apparent head motions experienced. It is of interest to examine the effects of these cross-coupled accelerations as compared with normal head motions. Consider further the stimulation of each of the semicircular canals. As noted previously, the canals are orthogonal to one another, but are tilted back so that the lateral canals are from 15° to 30° up in the front,[5] and the anterior and posterior canals, as indicated by their names, are turned somewhere from 35° to 65° about a near-vertical axis as shown in Fig. 1. For convenience, some calculations have been made assuming a 20° tilt back and a 45° rotation, respectively, for the factors listed previously.

With these assumptions, the following components of acceleration exist at each of the six canals when the subject normally turns his head:

$$\left.\begin{aligned} \dot\omega_{lr} &= 0.9397\dot\omega_{h\psi} & \dot\omega_{ll} &= 0.9397\dot\omega_{h\psi} \\ \dot\omega_{pr} &= -0.2418\dot\omega_{h\psi} & \dot\omega_{pl} &= -0.2418\dot\omega_{h\psi} \\ \dot\omega_{ar} &= 0.2418\dot\omega_{h\psi} & \dot\omega_{al} &= 0.2418\dot\omega_{h\psi} \end{aligned}\right\} \quad (1)$$

When he normally nods his head,

$$\left.\begin{aligned} \dot\omega_{lr} &= 0 & \dot\omega_{ll} &= 0 \\ \dot\omega_{pr} &= 0.7071\dot\omega_{h\theta} & \dot\omega_{pl} &= -0.7071\dot\omega_{h\theta} \\ \dot\omega_{ar} &= 0.7071\dot\omega_{h\theta} & \dot\omega_{al} &= -0.7071\dot\omega_{h\theta} \end{aligned}\right\} \quad (2)$$

and when he normally rolls his head,

$$\left.\begin{aligned} \dot\omega_{lr} &= 0.3420\dot\omega_{h\phi} & \dot\omega_{ll} &= 0.3420\dot\omega_{h\phi} \\ \dot\omega_{pr} &= 0.6645\dot\omega_{h\phi} & \dot\omega_{pl} &= 0.6645\dot\omega_{h\phi} \\ \dot\omega_{ar} &= -0.6645\dot\omega_{h\phi} & \dot\omega_{al} &= -0.6645\dot\omega_{h\phi} \end{aligned}\right\} \quad (3)$$

Figure 3 shows schematically the anterior and posterior canals as if viewed from above. The small arrows or vectors indicate the direction of that component of the angular acceleration which is perpendicular to each canal and which each canal experiences and presumably would sense. According to Löwenstein and Sand,[6] however, nervous responses to acceleration are transmitted from only some canals during any given motion, whereas others are not affected or are inhibited. It is not fully evident what would cause such inhibition, for under the conditions of rolling and turning, the anterior and posterior canals are stimulated in a like

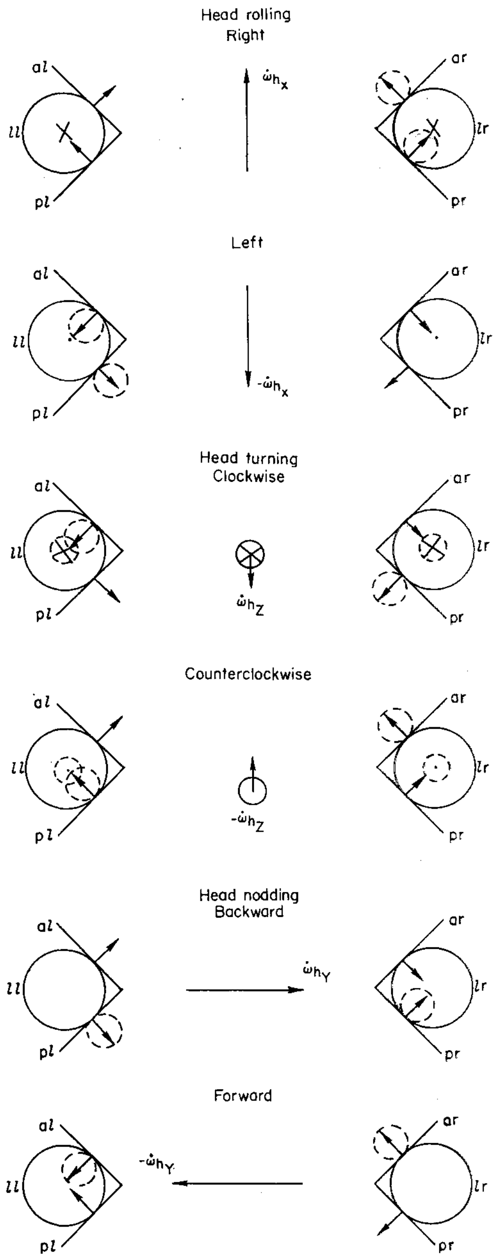

Fig. 3 Vectorial representation of the stimulation of the semicircular canal system for various head motions (vectors are perpendicular to plane of canals. Circled vectors indicate responsive canals according to Löwenstein and Sand.[6])

manner. Reference 6 notes, however, that, for these conditions, different canals or their signals are inhibited. The only difference that exists between these conditions of stimulation is that the lateral canals have a greater stimulation than the vertical ones in the turning case, and a lesser stimulation in the rolling case. This difference could be a signal or trigger for the inhibition.

In comparison to the simple results of individual head motions just discussed, consider the same head motions, but in a rotating environment. For these cases, the subject is assumed to be oriented as in Fig. 2, and the motions are considered as acting separately. The angular acceleration experienced by each canal in the rotating environment is the sum of the direct angular acceleration indicated in Eqs. (1–3) and the component of the vector product of the vehicle rotational rate and the head motion rate. The components of acceleration at each of the six canals for head turning are

$$\left.\begin{aligned}
\dot{\omega}_{lr} &= -0.3420\sin\psi_h\omega_V\omega_{h\psi} + 0.9397\dot{\omega}_{h\psi}\\
\dot{\omega}_{ll} &= -0.3420\sin\psi_h\omega_V\omega_{h\psi} + 0.9397\dot{\omega}_{h\psi}\\
\dot{\omega}_{pr} &= (-0.6645\sin\psi_h - 0.7071\cos\psi_h)\omega_V\omega_{h\psi} - 0.2418\dot{\omega}_{h\psi}\\
\dot{\omega}_{pl} &= (-0.6645\sin\psi_h + 0.7071\cos\psi_h)\omega_V\omega_{h\psi} - 0.2418\dot{\omega}_{h\psi}\\
\dot{\omega}_{ar} &= (0.6645\sin\psi_h - 0.7071\cos\psi_h)\omega_V\omega_{h\psi} + 0.2418\dot{\omega}_{h\psi}\\
\dot{\omega}_{al} &= (0.6645\sin\psi_h + 0.7071\cos\psi_h)\omega_V\omega_{h\psi} + 0.2418\dot{\omega}_{h\psi}
\end{aligned}\right\} \quad (4)$$

and for head nodding are

$$\left.\begin{aligned}
\dot{\omega}_{lr} &= (0.3420\cos\theta_h - 0.9397\sin\theta_h)\omega_V\omega_{h\theta}\\
\dot{\omega}_{ll} &= (0.3420\cos\theta_h - 0.9397\sin\theta_h)\omega_V\omega_{h\theta}\\
\dot{\omega}_{pr} &= (0.6645\cos\theta_h + 0.2418\sin\theta_h)\omega_V\omega_{h\theta} + 0.7071\dot{\omega}_{h\theta}\\
\dot{\omega}_{pl} &= (0.6645\cos\theta_h + 0.2418\sin\theta_h)\omega_V\omega_{h\theta} - 0.7071\dot{\omega}_{h\theta}\\
\dot{\omega}_{ar} &= -(0.6645\cos\theta_h + 0.2418\sin\theta_h)\omega_V\omega_{h\theta} + 0.7071\dot{\omega}_{h\theta}\\
\dot{\omega}_{al} &= -(0.6645\cos\theta_h + 0.2418\sin\theta_h)\omega_V\omega_{h\theta} - 0.7071\dot{\omega}_{h\theta}
\end{aligned}\right\} \quad (5)$$

For the case of head rolling about an axis parallel to the axis of vehicle rotation, the vector product of the vehicle rate and the head rate is zero, and the total angular acceleration at the canals is the same as that indicated in Eq. (3).

By comparison, it is evident that the stimulation in a rotating environment is much more complex than in simple normal conditions. In head turning, as has been noted before, a stimulation (for $\psi = 0$) that is sensed as nodding exists. In head nodding, the lateral canals are stimulated whereas they are unaffected in normal nodding; thus a turning sensation is experienced when nodding.

Table 1 Subjects used in nodding tests

Subject	Age	Flight experience	Previous rotational experience
1	22	None	None
2	45	None	None
3	43	Flight engineer World War II	Limited Centrifuge
4	21	None	None
5	26	None	None
6	28	None	None
7	21	None	None
8	22	None	None
9	42	Air Force pilot World War II	Subject in tests of Refs. 3 and 4

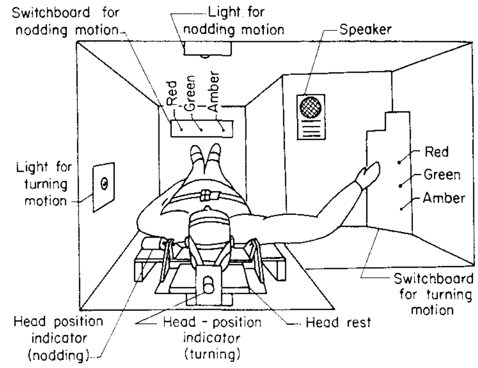

Fig. 4 Internal features of rotating vehicle simulator.

Test Equipment and Technique

In order to examine the effects of kinds of stimulation just discussed, a simple rotating-vehicle simulator was used at the Langley Research Center. Subjects were lying on their backs, enclosed in a small cabin with their feet 15 ft from the center of rotation. The centrifugal force was felt on the soles of their feet as it would in a rotating space station.

The internal features of the rotating simulator are shown in Fig. 4. The subject's task was to observe the lights either on his left or over his head which were controlled by the experimenter located externally from the simulator. The color of the lights was varied by the experimenter, and the subject, upon observing a light of certain color, was required to turn his head to the right or nod his head forward, depending upon the light observed, and then place a probe in an appropriate hole to extinguish the light. Separate head motions were required of the subject, and no simultaneous motions were used. The subjects were asked to accomplish their tasks as rapidly as possible, commensurate with their general feelings at the particular time. The head position and head rate were measured by head-position indicators, which were attached to a harness on the subject's head and to the moving head rest. The moving head rest supported the head by negator springs and allowed nodding motions without the need to hold up the head in the supine position. The time from light activation to light cutoff was also measured. The output of the head-position and head-rate indicators and of the reaction timer was recorded on strip chart recorders from which the data were directly read. Subjective opinions of the subjects were also elicited and recorded during and after termination of the tests.

The results presented herein were for experiments made with nodding motions alone and with combination nodding and turning motions. Nine subjects were used in the nodding experiments and ten were used in the combined motions. The number of subjects is admittedly low, but publication of the data was considered warranted on the basis of the timeliness of the problem. All of the subjects were of general good health with no known vestibular defects. Other data for the subjects are presented in Tables 1 and 2. Of the subjects who participated in the nodding experiments, only one participated in any of the previous experiments.[3, 4] However, three subjects who participated in the experiments of Refs. 3 and 4 also participated in the combined motion experiment. The nodding experiment lasted 1 hr, and rates of rotation of 0, 2, 4, 6, 8, and 10 rpm were used. The combined nodding and turning experiments were run at 10 rpm

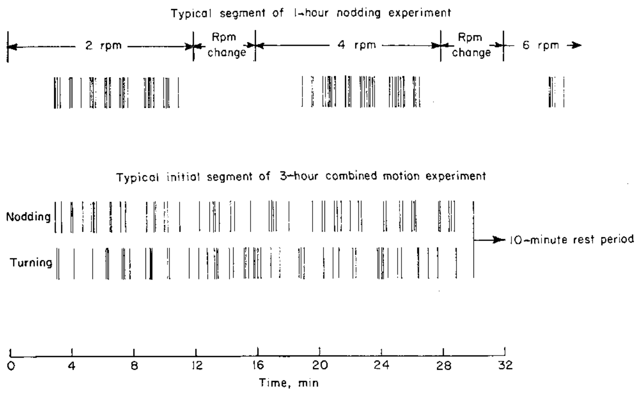

Fig. 5 Time histories of light activations. (Each line indicates activation of light.)

and lasted 3 hr. Figure 5 shows typical initial segments o the time history of light activation for both the nodding-alone experiments and the combined nodding and turning experiments. Each line indicates an activation of the light. For the nodding experiments alone, the light was activated about 32 times for each vehicle rotational rate. The light was activated 160 times during the 1-hr period of the nodding-alone experiment. During the combined nodding and turning motions 500 light activations were made. These were randomly distributed between the nodding and turning motions as shown in Fig. 5. Some motion pictures of eye motions were made to determine qualitatively the motion of the eyes under the conditions of the experiments.

Results and Discussion

For the purpose of correlation with current nodding and combined nodding and turning motions, data from Ref. 4 for turning motions alone are presented in Figs. 6 and 7. The data presented by the solid lines in Fig. 6 show a typical turning-head motion and the apparent cross-coupled nodding motion that is sensed when the turning motion is made while rotating at 10 rpm. It should be noted that the apparent acceleration on the right, $\alpha_{G\theta}$, is about 250°/sec^2 maximum, and occurs in separate increments in contrast to the normal head motion shown on the left, wherein each motion consists of an acceleration followed immediately by one in the opposite direction.

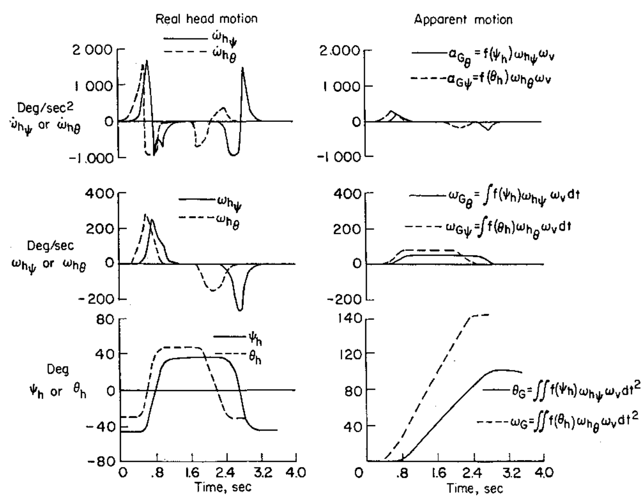

Fig. 6 Typical head motions used and the resulting apparent motion; simulator rate ω_v = 10 rpm. (Solid lines indicate real turning-head motion and apparent nodding motion; dashed lines indicate real nodding motion and apparent turning motion.)

Figure 7 shows a tolerance boundary obtained in Ref. 4 for head turning while rotating. These results show that a cross-coupled acceleration of from 4 to 6 rad/sec^2 (230° to 345°/sec^2) is tolerable at least for 3 hr. These values are appreciably larger than other experimenters have reported.

As noted before, our purpose in this paper is to examine nodding motions and combinations of nodding and turning motions to determine if a similar tolerance exists. A typical nodding motion used by the subjects and the apparent turning motion are shown by dashed lines in Fig. 6. Nodding accelerations shown on the left of Fig. 6 are about the same as those for turning. Maximum values of 1600°/sec^2 were measured while the head was moved a total of 80°. On the right side of Fig. 6 is the apparent turning motion that exists when nodding in a vehicle rotating at 10 rpm. In this motion, the subject experiences cross-coupled angular accelerations of about 300°/sec^2 maximum, which, when integrated, give rise to an apparent velocity of 80°/sec maximum and an apparent turning displacement of 140°.

The results for the 1-hr experiments performed with head-nodding motions alone are shown in Fig. 8. These data, as well as all of the data presented herein, are numerical averages of the data from all of the subjects participating in the experiment. For these tests the subject, as noted previously, was requested to look over his head at a light, the color of which varied. When he saw the light he nodded his head forward about 80°, and placed a probe in the appropriate hole to extinguish the light. The subject's head position, rate of motion, and response time (the time from when the light was turned on until it was extinguished) were recorded. These tests were performed, as previously noted, with vehicle rotations of 0, 2, 4, 6, 8, and 10 rpm with nine subjects.

The average amplitude of head-nodding motions for the subjects at each vehicle rate of rotation is shown by the circles in Fig. 8. The periods of time at each rotational rate are noted by the stepped line. The amplitude of motion ranges from 80° to 90° without a consistent variation with vehicle rate of rotation. As is noted on the figure near the end of the run, one subject dropped out, two others became nauseous, and two became dizzy; these all at 10 rpm.

The average rate of head-nodding motion by the nine subjects is also shown in Fig. 8. The results are shown by circles, and the stepped line indicates the time at each rotational rate as already mentioned. The rates varied between 120° and 140°/sec with the lower rates occurring at the higher rpm. This is apparently a subjective attempt to reduce the cross-coupling effects at the higher speeds. As can be seen in Fig. 8, there is a decrease in response time occurring at the changeover to 6 rpm, the time dropping from 2 to 1.6 sec. The faster response, despite the reduced head rates just discussed, can be explained only by a learning process in directing the probe to extinguish the lights or by the possibility that this task became easier.

In these nodding experiments, contrary to the turning ones reported in Refs. 3 and 4, the subjects reported no fuzziness

Table 2 Subjects used in combined motion tests

Subject	Age	Flight experience	Previous rotational experience
1	30	Research pilot	None
2	28	Light plane pilot	None
3	25	Light plane pilot	None
4	24	None	None
5	26	None	None
6	24	None	None
7	32	None	Subject in tests of Refs. 3 and 4
8	43	None	Subject in tests of Refs. 3 and 4
9	42	Air force pilot World War II	Subject in tests of Refs. 3 and 4
10	26	None	None

of vision, and motion pictures of the eyes showed that no nystagmus existed. Nystagmus was shown to exist in the turning motions of Refs. 3 and 4 and is confirmed by motion pictures. Also, in these nodding experiments, the subjects reported aftereffects causing some discomfort following the experiment. Two subjects who reported nausea during the tests were affected for several hours afterward.

Since most of the subjects tolerated the experience at 10 rpm and because similar experience[3, 4] with turning-head motions showed tolerance and adaptation to 10 rpm, an experiment with combined turning and nodding motions was performed at 10 rpm. These tests were run for 3 hr and consisted of random head motion in turning and nodding in response to lights in both planes. The amplitudes of head motion, the rates of head motion, and the response times were recorded. Ten subjects were used in this experiment. As noted before, none of these subjects had participated in the nodding experiments just discussed. The results are presented in Fig. 9. The data in this figure are for a constant vehicle rate of rotation, and are plotted as a continuous curve based on the average head motions and response of all of the subjects at the time of each light activation.

Figure 9 illustrates the amplitude of head position, showing variations in the amplitude of motion used for both nodding and turning. There was a decrease in turning amplitude during the first hour and an increase thereafter. An increase in nodding amplitude was used during the first $\frac{3}{4}$ hr and a decrease thereafter. Five of the ten subjects, however, dropped out of the experiment within the first 15 min because of nausea. The other subjects completed the entire experiment without any ill effects. Some aftereffects of dizziness during head motions were experienced by each subject for a short duration following the completion of the 3-hr run.

Also shown in Fig. 9 are the rates of turning and nodding motions during these combined motion experiments. There is an increase in the turning rate throughout the experiment which is consistent with the increase shown in Ref. 4 for turning motions alone, although the rates for the current experiment are normally slower than those used in the previous experiments with turning motions alone. The rates of nodding motion remained rather constant after the first $\frac{1}{2}$ hr, and did not differ greatly from the rates for nodding motions alone which were discussed previously.

The response times required to extinguish the lights for the combined experiments (Fig. 9) show decreases in the response to both nodding and turning stimulations. The response times are, however, somewhat larger than those for turning alone in Ref. 4 and for nodding alone. It appears that, although the turning and nodding motions occur separately, that is, one is completed before another is started, the subjects required more time to perform the tasks indicating again a more stressful condition or, at least psychologically, a more complex situation requiring more deliberation and time. The responses are not exceptionally long, however, and are certainly adequate for normal operations.

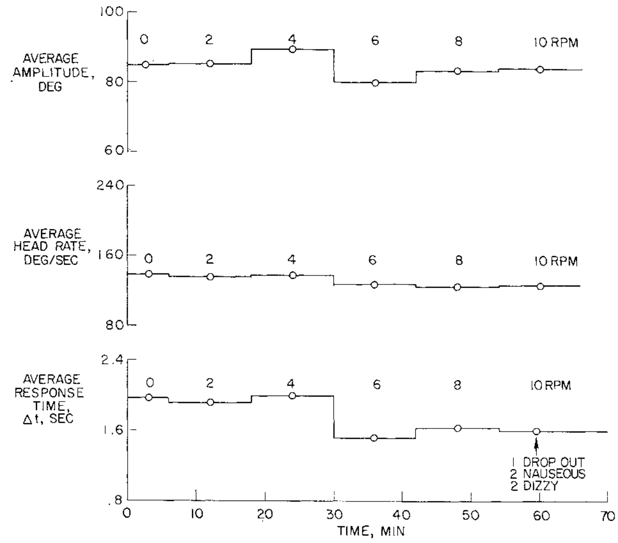

Fig. 8 Head-nodding experiment; average head amplitude, head rate, and response time at various rates of rotation of the simulator.

The general results of these experiments are summed up in Fig. 10, which is a tolerance boundary plot, with head rates of rotation plotted vs vehicle rates of rotation. These boundaries are based on the concept that tolerance or intolerance to such motions is dependent upon the cross-coupled angular accelerations and not specifically upon the rates of rotation that exist. Shown in this figure are boundaries for the separate and the combined motions which represent curves of constant cross-coupled angular acceleration based on the maximum average acceleration that was experienced and tolerated during the experiments. It appears, generally, that man can tolerate and adapt to larger cross-coupled angular acceleration when performing turning motions better than when performing nodding motions. Furthermore, it appears that, even in the combined exposure to nodding and turning, an adaptation to higher cross-coupled acceleration exists, as shown by the somewhat higher values for the 3-hr

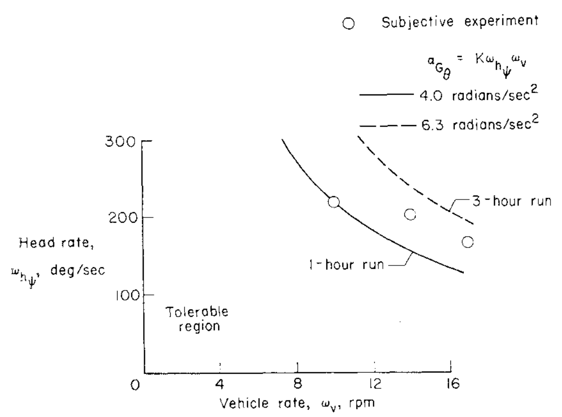

Fig. 7 Tolerance to cross-coupled angular acceleration while turning head.

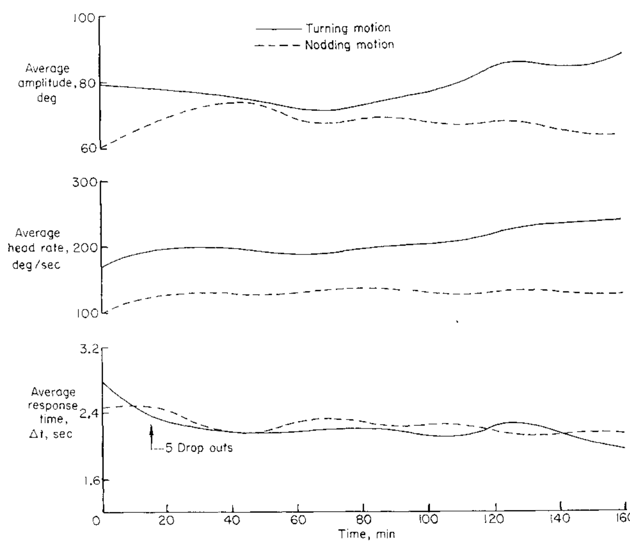

Fig. 9 Combined turning and nodding experiment; average head amplitude, head rate, and response time during combined tests of turning and nodding motion at a rate of rotation of the simulator of 10 rpm.

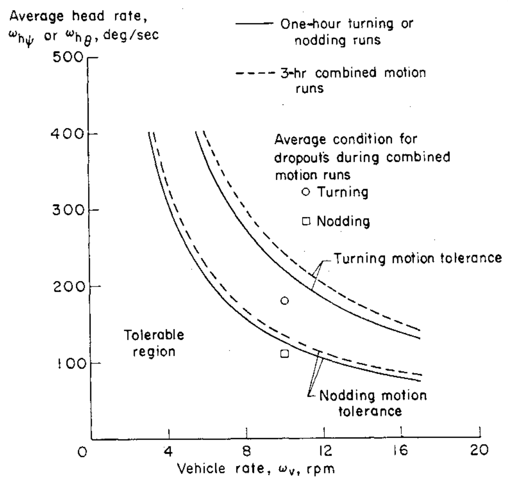

Fig. 10 Tolerance to cross-coupled angular accelerations while turning and nodding head.

run than for the 1-hr runs. Also shown in Fig. 10 are two data points representing the average conditions that existed for the five dropouts in the combined experiment. These data points are plotted at the vehicle rate of 10 rpm and at an average turning-head rate of 180°/sec and at an average nodding-head rate of 110°/sec which are the average rates of the subjects at the time they dropped out of the experiments. Tolerable conditions for these subjects are probably at head rates much lower than for the data points shown. These data are somewhat smaller cross-coupled accelerations than those which exist for the subjects who tolerated the entire experiment. It appears that certain subjects have a marked intolerance to the combined situations, whereas others adapt rather readily.

It should be remembered that these cross-coupled accelerations are in a nodding sense when turning the head and in a turning sense when nodding the head. There is evidence, therefore, of a greater sensitivity to cross coupling that affects the lateral semicircular canals than to cross coupling that affects the vertical (anterior and posterior) canals. This is evidenced by the dropouts, the aftereffects, and the somewhat slower head rates used in these cases. The lack of nystagmus when the cross coupling is in the lateral plane and its presence when in the nodding direction, however, are not fully understood. In normal examinations of disorientation, as elicited on a Barany chair, nystagmus is readily obtained by appropriate stimulation of the lateral semicircular canals. The nausea and dizziness so obtained are, however, like that obtained in the present experiments.

In the present investigation, it was assumed that the semicircular canals respond only to angular acceleration, yet they do not respond effectively to gravity or other linear accelerations. It should be pointed out, however, that any difference in the density of the cupula and the endolymph that surrounds it would allow the canals to be stimulated to some extent by linear accelerations. However, insufficient information is available in this regard and, as pointed out in Ref. 7, the canals are not considered to be efficient detectors of linear acceleration. The otolith system, however, is responsive to the combined g and centrifugal force field, which is recognized by the subjects. Similarly, Coriolis accelerations caused by total movement of the head would be sensed by the otolith system and could have some effect on the response of the subject. Whether the stimulation of the otolith system contributed to the intolerance to the motions of some of the subjects is not known.

It would appear that experiments of the kind reported here and in Refs. 3 and 4 may well be used as a selection test of persons who may not be prone to motion sickness, and who may tolerate rotation in space vehicles. The data also indicate that, if one is careful not to elicit cross coupling in the lateral semicircular canals, adaptation to rotation may be obtained more readily and by more people.

Concluding Remarks

The effects of rotation, as may be used in space vehicles to obtain artificial gravity, may be quite varied among persons having normal semicircular canal systems. Some subjects were tolerant of rates of rotation of 10 rpm and would probably adapt for long time periods; others, however, were very intolerant of these conditions when combined motions of the head were used. The results of the experiments reported herein indicate a greater sensitivity to cross-coupled angular accelerations when they occur so as to be sensed by the lateral semicircular canals. Adaptation to rotation would be more readily obtained, therefore, if the head could be moved so as not to stimulate the lateral canals by cross-coupled accelerations. Further study and collaboration of these phenomena should be obtained however. The kinds of experiments reported herein may be useful as a selecting test of persons who may not be prone to motion sickness.

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