Spatial Disorientation

THE DYNAMICS OF SPATIAL ORIENTATION DURING COMPLEX AND CHANGING LINEAR AND ANGULAR ACCELERATION

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Abstract — The dynamics of spatial orientation perception were examined in a series of experiments in which a total of 43 subjects were passively exposed to various combinations of linear and angular acceleration during centrifuge runs. Perceptual effects during deceleration were much stronger than effects during acceleration. The dynamics of spatial orientation perception differed substantially from changes in the vestibulo-ocular reflex (VOR). VOR was fairly well predicted by a current model, but our experiments revealed perceived change in attitude (roll, pitch, yaw tilt position in space) and perceived angular velocity in space that was not reflected by parallel changes in the plane or magnitude of the VOR. This series of experiments establishes several facts concerning spatial orientation perception beyond the predictive domain of any current model. New concepts are needed and several are suggested to deal with changing reactions to complex combinations of linear and angular accelerations.

Keywords — spatial orientation; perception; VOR; models; dynamics.

In activities of every day life, dynamic spatial orientation during whole body movement relative to the earth depends upon continual subconscious integration of information from a number of sensory systems in relation to intended goals in paths of movement. Most voluntary whole-body motions relative to the earth are complex. Walking often involves curvilinear paths of body movement, while gaze is changed by head turns, all while the trunk is displaced up and down by each step. Most movement generates complex combinations of linear and angular acceleration of the head, and the reactions that serve to improve the control of movement are the product of a) processes inherent in initiating intended paths of movement and b) changing combinations of sequential inputs from several sensory systems during the movement. Understanding reactions to motion demands some focus on reactions to sequences of changing combinations of motion stimuli. This paper focuses on reactions of subjects passively exposed to a complex but controlled stimulus that involves changing patterns of angular and linear accelerations.

The stimulus was an angular velocity profile similar to that employed in centrifuge runs to train pilots on methods to maintain consciousness during exposure to high head-to-
seat inertial forces. The carriage holding the subject swings relative to the direction of gravity to maintain constant alignment of the head and body with the vector resultant of the centripetal and gravity vectors. The complexity of the stimulus sequence in runs like these is attributable to the change in plane of the head relative to the rotating structure during angular accelerations and decelerations of the centrifuge together with the change in the 'gravito-inertial' force magnitude. Tilting the head relative to the plane of rotation yields canal stimulation from cross-coupled angular velocities and from angular acceleration of the centrifuge (1). Spatial orientation during constant velocity centrifuge rotation has been studied in some detail. Under 'steady state' conditions, a directionally fixed resultant linear vector is incorrectly perceived as "vertical," the "oculogravic illusion," and if the directionally fixed linear vector increases in magnitude, subjects perceive a change in the direction of "vertical" that appears to be related to the component of the linear vector that "lies in the shear plane" of the otolithic membranes (2, p 95f). However steady state conditions do not prevail in centrifuge runs used in G-tolerance training; direction and magnitude of linear and angular accelerations change continually throughout the acceleration and deceleration.

The general plan was to obtain data from a series of experiments in order to 1) confirm or deny anecdotal information indicating that deceleration of a centrifuge run generates substantially greater magnitude spatial orientation dynamics than is experienced during the acceleration; 2) evaluate whether or not this difference is present even when low magnitude angular accelerations are used in the profile; 3) evaluate how different head and body configurations relative to the centrifuge alter any differences between effects from the onset and offset accelerations; 4) compare perceptual dynamics with the temporally concomitant vestibulo-ocular reflex (VOR), and 5) determine whether or not differences between acceleration and deceleration responses might be related to differences in rates of change of magnitude of linear and angular vectors and their directions relative to one another throughout the periods of stimulation.

**Approach**

Our centrifuge runs differed from conventional G-tolerance training runs in that we employed very low onset rates (angular accelerations) in attaining the maximum angular velocity necessary to produce the desired force level (2 to 3 g-units in our experiments). Low onset rates were advantageous in providing time for subjects to observe changes in reactions during the continually changing stimulus sequence. We also employed angular accelerations of identical magnitude in starting and stopping rotation of the centrifuge, because our main objective was to compare reactions generated by the acceleration and deceleration portions of the stimulus profile.

Observations were made during four series of centrifuge runs in which subjects were instructed prior to the runs to report changes in spatial orientation perception with emphasis on comparison of perceptions during the angular accelerations and decelerations of the runs. In the first and second series, subjects could not report during the runs because they were occupied with other tasks. These subjects reported and were interviewed after the runs. In the third and fourth series, subjects responded during the runs and were also interviewed immediately after the runs. Descriptions during postrun discussion were aided by subjects' moving a small manikin in space to illustrate the dynamics of their perceptions of linear and angular motion and position relative to the earth. All subjects were fully informed prior to runs of the actual motions and G-levels they would experience and were told that motions perceived might differ from the actual motion of the device.

In the first series, subjects were occupied with a brightness discrimination task (not part of this report) during 2 and 3 Gz exposures. To accommodate the vision research effort, angular accelerations used to attain the G-levels were very low in magnitude, only 3.3°/s². Subjects were positioned in forward-facing tan-
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gential heading. In the second series, the primary object was to measure the vestibulo-ocular reflex (VOR) during runs to the 3 Gz exposure level. In this series, subjects were positioned in forward-facing tangential heading during some runs and in backward-facing tangential heading in other runs. In a third series, subjects were positioned in a centripetal heading relative to the centrifuge and experienced 2-Gz acceleration levels. In a fourth series, subjects were given three runs in a supine body configuration, so that they experienced increases in force-levels along the x-axis, referred to as Gx. Different configurations of the subject in different series are illustrated in Figure 1, where axes are defined as in Hixson and colleagues (3).

Subjects

Series 1

The subjects were military personnel in good health between the ages of 20 and 30 years. Most were student aviators in the US Navy training program. A total of 21 subjects participated in 48 centrifuge runs in Series 1.

The configuration of the subject relative to the centrifuge was forward-facing tangential heading (configuration 1 in Figure 1) in all runs of this series. The linear acceleration levels were 2.0 and 3.0 g-units directed along the z-axis of the head and trunk. Some subjects experienced a number of repeat runs at the 3 Gz levels. This is the only series in which subjects viewed a small head-fixed display.

Subjects could not be asked to describe spatial orientation perceptions during these runs because they were otherwise occupied with tasks germane to vision experiments. All information on spatial orientation perception from these subjects came from post-run interviews.

Series 2

Subjects in this series were men in good health within the ages of 21 to 24 years. They were student aviators in the US Navy training program. A total of 11 subjects participated in 58 centrifuge runs in Series 2.

The configuration of the subject relative to the centrifuge was either forward-facing or backward-facing tangential heading, configurations 1 and 2, respectively, in Figure 1. Each subject was positioned in each of these configurations in 3 Gz runs.

Subjects could not report perceptual effects during these runs because a bite-board was used to stabilize the head relative to eye-movement recording equipment. The quantified VOR is reported by McGrath (4) and McGrath and colleagues (5). All information on spatial orientation perception from these subjects was obtained during postrun interviews. Subjects were in darkness throughout the runs of this series.

Series 3

Subjects in this series were 4 men and 1 woman in good health, in the age range 21 to 33 years. All were either officers in flight training or officers in the research staff who had flight indoctrination.

The subject was positioned to face in centripetal direction with the interaural axis (y-axis) tangentially aligned relative to the centrifuge (configuration 3 of Figure 1). Each subject received two runs that achieved a 2 g-unit linear vector directed on the subject’s z-axis, that is, two 2 Gz runs. In one run, the initial tangential acceleration was in the positive y-axis direction, and in the other run, the initial tangential acceleration was directed in the negative y-axis direction. Subjects reported perceived spatial orientation throughout the runs of this series and additional information was obtained during postrun interviews. Subjects were in darkness throughout the runs of this series.

Series 4

Subjects were 7 men in good health in the age range 21 to 25 years. All were student aviators in US Navy flight training.
In this series, subjects were placed in supine position, z-axis of the head and trunk radially aligned, feet centripetally directed, and with the right ear (−y-axis) toward the initial tangential vector. Subjects commenced the run with gravity directed along the x-axis, and the Gx vector increased in magnitude as centrifuge angular velocity increased. Each subject received three runs, one at a maximum Gx level of 1.5 g-units, another at maximum 2.0 g-units, and one at a maximum of 3 g-units. Subjects reported spatial orientation perception throughout the runs and additional information was obtained in post run interviews. Subjects were in darkness throughout the runs of this series.

**Centrifuge Angular Velocity Profile**

The centrifuge angular velocity profile used in the runs is illustrated in Figure 2, where a 3 G run is depicted. The rate of change of angular velocity in the up- and down-ramps depicted in Figure 2 is 6.4°/s², which is the angular acceleration and deceleration that was employed in Series 2 and 4. In Series 1, angular accelerations and decelerations were 3.3°/s², while in Series 3, angular accelerations of 8°/s² were employed. These low angular accelerations mean that tangential linear acceleration, the product of the radius (20 ft) times the angular acceleration (expressed in radians/s²), was very low in magnitude in all runs.

The subject's chair was affixed to a carriage that was suspended on a tangentially aligned axis, so that the carriage acted as a 2-pole swing. Thus, the direction of gravity was perpendicular to the bed of the carriage when the centrifuge was stationary; when the centrifuge was rotating, the vector resultant of the centripetal and gravity vectors was perpendicular to the bed of the carriage. As illustrated in Figure 3, the carriage swung through 70.5°
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Figure 2. Ramp angular velocity profile used in counterclockwise centrifuge runs. Rate of change of angular velocity in the up and down ramps depicted was an angular acceleration of 6.4°/s². In Series 1, angular acceleration of only 3.3°/s² required upramp and downramp times of 37 seconds.

In 3 G runs. In 2 G runs and in 1.5 G runs, the carriage swung 60° and 38°. In all runs, the total resultant linear acceleration vector remained fixed in direction relative to the subject throughout the run except for the slight angular displacement due to the tangential acceleration component, less than 5 degrees in Series 3, about 2 degrees in Series 1, and less than 4 degrees in Series 2 and 4. In Series 1, 2, and 3, the linear vector resultant remained

Figure 3. Illustrating in the lower panel the swing of the centrifuge carriage about an axis tangential to centrifuge which maintained a fixed position of the subject relative to the vector resultant of the centripetal and gravity vectors. Configuration 3, not shown in the lower panel, can be envisioned by imagining the configuration 1 subject turned 90° to face centripetally. The upper panel illustrates the slight shift of the total resultant linear vector relative to the subject due to the tangential accelerations during the upramps and downramps.
nearly fixed on the subject's z-axis, and in Series 4, it remained fixed on the subject's x-axis.

Figure 1 illustrates the configuration of the subject relative to the centrifuge at the beginning of runs for the four series of runs. Figure 3 illustrates the essential features of the resultant linear acceleration relative to the subject and to gravity as the centrifuge increased speed to achieve a 3-g resultant acceleration at the subject's head.

**Results**

**Series 1**

Subjects were in forward-facing tangential heading (configuration 1). Each subject was interviewed shortly after completing each centrifuge run. Of 13 subjects who made runs at the 2 Gz level, 12 reported much “stronger” effects during the deceleration. The lone exception was uncertain that differences in magnitude of perceptual effects were present.

Of 7 subjects who made runs at the 3 Gz level, 6 indicated pitch-down attitude positions during deceleration of about 90°, while their estimates of pitch-up during the acceleration were about 10°. The 7th subject said that the attitude change experienced during acceleration was “like the real thing” while the motion experience during the deceleration was confusing, “like it was unreal and only happening in my brain.” This report is particularly noteworthy; spontaneous reports of confusion occurred only during the deceleration in this series and in all other series.

Most of the subjects in the 3 Gz runs of this series made several repeat runs. There was a tendency for the differences in magnitude of acceleration/deceleration perceptual effects to diminish over trials in some subjects but not in others. The difference was never reversed in favor of acceleration, and the difference remained relatively unchanged in most subjects, but when change occurred, it was in the direction of diminution of the acceleration/deceleration difference.

The typical description of the perceived sequence of motion in this series was forward motion followed by a slight pitch-up attitude during acceleration and, during deceleration, pitch-down, frequently as much as 90°. The angular accelerations in this series were only 3.3°/s² for all subjects except one who experienced very low magnitude angular acceleration, 1.3°/s², in the up- and down-ramps. This subject also reported much stronger perceptual effects during deceleration, despite the low angular accelerations.

**Series 2**

Series 2 runs were identical to the 3 Gz runs of Series 1 except that subjects were placed in the backward-facing tangential heading in some trials, in the forward-facing configuration in other trials, and in darkness throughout all trials. The reports of perceptions from subjects in the forward-facing configuration were similar to Series 1. All of the 11 subjects indicated that the perceived spatial orientation change was much greater during the deceleration. Most subjects had 6 trials, 3 forward-facing and 3 backward-facing. Again the acceleration/deceleration difference was sustained over the course of the experiment, but when change occurred in a few subjects, it was in the direction of diminution of the acceleration/deceleration difference.

The backward-facing configuration yielded interesting results. The typical spatial orientation change for this configuration is pitch-forward (forward tilt) toward nose-downward position during acceleration and pitch-up (backward tilt) toward nose-up position during deceleration, the reverse of the pitch change encountered during the acceleration and decelerations of the forward-facing tangential heading. Importantly, the magnitude of the spatial orientation change was still much greater during deceleration, which means that backward tumble and backward pitch change were the strong effects in this configuration, while forward pitch and tumble were the strong effects in configuration 1.

In this series, the reports of pitch change during acceleration were less consistent in the backward-facing configuration than in the
forward-facing configuration. Of the 11 subjects, 4 reported weak pitch-change perceptions during acceleration, but in the pitch-up direction in one or two of the three trials. Because the pitch-change is typically small during acceleration, this inconsistency is only remarkable because no inconsistencies were encountered during forward-facing trials. Three of these subjects spontaneously expressed uncertainty about their memories of the acceleration effects.

During acceleration or early during constant velocity, all subjects reported experiencing increased weight. Later during constant velocity, some subjects report moderation of the feeling of weight increase (compare reference 6) even though the force level remained constant during constant angular velocity. During deceleration all subjects reported a sensation of ascent from the earth during angular change in position. For example, subjects sometimes reported tumbling to a face-down or head-down position while rising (ascending) from the earth. The perception of lift was not indicated in the reports of every deceleration, but considering the complexity of the spatial orientation dynamics, effects may go unreported depending on the subject's conception of priorities in reporting clearly illusory events. As in Series 1, subjects reported confusion and dizziness associated with the deceleration and not with acceleration.

Series 3

Series 3 subjects faced the center of rotation and accelerated with right shoulder leading in one run and with left shoulder leading in another run as the centrifuge increased speed. Thus, they pitched forward through $60^\circ$ as the carriage bed swung on its suspension axis to maintain alignment with the vector resultant of the centripetal acceleration and gravity vectors. In this series the centrifuge angular accelerations and decelerations were $8\%/s^2$, and the 2.0 $G_z$ level was attained. In the configuration of this series, the semicircular canal stimulation was predominantly in the roll plane of the head.

As in the other series, all subjects (5 in this series) indicated much greater change in spatial orientation during deceleration. Because of the orientation of the subject relative to the centrifuge, counter-clockwise acceleration of the centrifuge would be expected to yield a perception of slight left roll tilt (corresponding to slight pitch-up perception in forward-facing tangential heading of configuration 1), whereas clockwise acceleration would be expected to yield a slight roll-right perception (corresponding to the slight pitch-down perceptions of the backward-facing heading of configuration 2). Subjects did not report roll tilts during acceleration, but they reported strong roll perceptions and "cartwheeling" during deceleration. These subjects experienced runs in clockwise and counterclockwise directions, and results were essentially the same except that the direction of roll ("cartwheeling") was reversed during the decelerations, that is, during a counterclockwise run, the deceleration produced perception of rolling ("cartwheeling") right, whereas during clockwise runs, deceleration produced a perception of cartwheeling left.

As the upramp began, subjects reported perceiving slight forward pitch. In maintaining alignment with the vector resultant of the centripetal and gravity vectors, the carriage pitched forward $60^\circ$ relative to the plane of the centrifuge and gravity. However, if alignment with the resultant vector was perfectly maintained, the pitch perception, despite being mild, is remarkable because the $y$-axis semicircular canal stimulation was weak and the otolith stimulus was almost fixed in direction. Some subjects in Series 1 and 2 also reported roll of the centrifuge carriage despite the very weak semicircular canal $x$-axis stimulus (see Figure 5 below). This component of the perception seemed to subside as the resultant force increased.

Series 4

Series 4 subjects were in supine position, z-axis radially aligned with feet toward center of rotation, as runs started. The centrifuge
rotated in counterclockwise direction in all runs. Each subject made one run at each of three G levels, 1.5 Gx, 2.0 Gx, and 3.0 Gx. The following descriptions pertain to the 3 G runs, but perceptual effects were similar in the runs at lower G-levels.

At onset of angular acceleration, subjects perceived rightward motion (turning at a radius) and as the upramp continued, most subjects reported increased pressure and weight on their arms, legs and chest. Only 2 subjects indicated a slight CCW turn or position change about the z-axis (the predominant semicircular canal stimulus was CCW z-axis). Five of the subjects described feeling stationary, supine with nose-up, during most of the constant velocity part of the profile; one felt that his head (and body) elevated about 20 degrees after being at G for a while; and the remaining subject reported that, after being at G for a while, he experienced a new position, with head and body 100 degrees from supine and facing slightly downward, without any recollection of having moved into that position (position "realization" without moving into position is common following recovery from deceleration but unusual during the constant velocity portion of the stimulus profile).

All 7 subjects reported that, as compared with events perceived during acceleration, change in perceived spatial orientation was much greater during deceleration. As in the 3 Gx runs of Series 2, during deceleration, perception of lift (ascent) accompanied complex changes in perceived body orientation. During deceleration, all subjects perceived rotation about the z-axis, which elevated relative to the earth, but the z-axis also tumbled so that 4 of the subjects also experienced inversion or near inversion. One who did not report inversion reported head-up position, which is 90 degrees from the actual supine position relative to the resultant vector. Another reported rotation about the z-axis, which was translating in a cylindrical path, and the path was rising. During the cylindrical excursion, the subject perceived that he was face-up when atop the cylinder and face-down when at its bottom. The final subject reported, "... I came up from who knows where to upright while rotating about my z-axis several revolutions. I was very dizzy and confused." Five of the subjects spontaneously mentioned dizziness and confusion during the deceleration without specific questioning about dizziness. While the dynamics of change in spatial orientation perception during deceleration were very great, the subjects did not appear greatly disturbed by the experience, perhaps less disturbed than other groups that experienced the stimulus profile in other configurations.

Miscellaneous Observations

In the course of the four series of runs, we found a number of instances in which the need for clarification of descriptions provided by subjects became apparent. The reports of dizziness or confusion usually meant that the subject experienced the paradoxical perception of motion (velocity) without appropriate change in angular position. Typically the perception consisted of having pitched forward to a nose-down position relative to gravity but with continuing tumble velocity even though the pitch position remained nose-down. Some subject seemed to experience position change through several revolutions before achieving a more or less stable position, after which tumble velocity continued without further position change. Reports of perceiving a body position relative to gravity without having moved into the position were fairly frequent after runs had stopped. After runs, when, for example, the subject had been sitting upright and stationary for some time, the subject would report feeling upright without experiencing transition from a previously perceived position of substantial tilt. One subject was surprised when the light-proof capsule was opened several minutes after his run was completed because he thought he was positioned nose-down until the door opened. This was exceptional but not singular.

In Series 3 and 4, subjects frequently reported perceived direction of rotation by referring to the leading shoulder. During counterclockwise angular acceleration a report of "moving right" meant perceived motion in
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the direction of the right shoulder. Actually at the onset of these runs, subjects were correctly perceiving turn-at-a-radius. In Series 1 and 2, one subject reported that he was moving upward at the same point in the profile that another subject indicated he was going down. The first felt that he was pitching forward (down) but with the pivot-point of the turn displaced several feet in front of his body (thus moving upward), while the second subject had the same perception but chose different words (moving down) to describe his experience.

Summary of Results

Of the 43 subjects who participated in these experiments, 41 reported that perceptual effects were much greater during deceleration. Of the two differing subjects, one indicated that the perception during deceleration was very confusing and so he felt unable to compare magnitudes because his tumbling experience during deceleration seemed unreal relative to the slight but "real" climb he experienced during acceleration. The only truly discrepant subject had relatively small effects during both acceleration and deceleration and indicated uncertainty about the comparison. Most subjects in all series reported that the perceptions during deceleration were confusing; none reported confusion during acceleration. These data clearly confirm the acceleration-deceleration difference indicated by anecdotal reports from centrifuge aviator training and establish the presence of the difference even when very low magnitude angular accelerations are used in starting and stopping the centrifuge.

Discussion

The different series, served to illustrate that the spatial orientation dynamics during deceleration were strongly influenced by the predominant semicircular stimulation in the configurations of head and body relative to the centrifuge in each series. During acceleration, position information from gravity sensors seemed to dominate the perception, but during deceleration, canal-mediated angular velocity information strongly influenced spatial orientation dynamics.

Stimulation of the semicircular canals during counterclockwise centrifuge rotation with the subject in forward-facing tangential configuration is illustrated in Figure 4. The stimulation was determined by the magnitude of the centrifuge angular acceleration (onset and offset rate in G-tolerance parlance), the change in semicircular canal angular position relative to the centrifuge angular acceleration vector, the angular acceleration due to the product of the instantaneous angular velocity of the centrifuge times the instantaneous angular velocity of the change in angular head position relative to the centrifuge, and the duration of these angular velocity changes (1). The stimulus at the position of the subject’s head was the same for each configuration, but the stimulation to particular axes was determined by head position relative to the stimulus. The stimulus is shown in vectorial representation (obtained by resolving the z- and y-axis components at selected points in time) below the time axis of Figure 4. The resultant angular acceleration vector changes only a little in magnitude (indicated by the length of the arrows at selected times), but changes continually in direction relative to the oval that represents the head. The stimulus for configurations 1 and 2 can be envisioned by imagining the oval as a face for configuration 1 and as the back of the head for configuration 2.

The angular and linear acceleration stimuli remained the same relative to the platform that supported the subject in all configurations, but the different body positions relative to the platform controlled the particular axes of stimulation received by the vestibular system and the particular perceptual effects of the different configurations. In Series 1 and 2, the predominant canal stimulation was in the pitch-plane (y-axis) and the predominant change in spatial orientation was in the pitch plane, with slight pitch-change during acceleration and very strong pitch-change during
Figure 4. Principal angular acceleration components were on two axes during the upramp acceleration (a) and on the same two axes during the downramp deceleration (b). For configurations 1 and 2, principal axes were y and z, and for configurations 3 and 4, principal axes were x and z. Acceleration about the third axis was too low for presentation in this figure. The magnitude and direction relative to the head of the resultant angular acceleration at different points in the stimulus profile is in vectorial representation below the time line. The length of each arrow is proportional to the magnitude of the resultant angular acceleration at a particular time in the ramps of series 2 and 4. The arrow in the rectangular inset is calibration for the angular vectors.
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deceleration. In series 3, the predominant canal stimulation vector was on the x-axis (roll plane) and the predominant spatial orientation change was in the roll plane, with very little perceived roll during acceleration and very strong roll ('cartwheeling') perceived during deceleration. In series 4, the predominant canal stimulation vector was on the z-axis (yaw plane) and the predominant spatial orientation change was in the yaw plane, with slight yaw position change noted by several subjects during acceleration, and strong yaw angular position and velocity noted during the deceleration.

The results from the four series served immediately to answer one question and to raise several others. Prior to the data obtained from configuration 2 runs in which subjects were in "backward-facing" tangential heading, we had considered the possibility that the great acceleration-deceleration difference in configuration 1 might be due to arousal by the deceleration perception, forward-pitch, and diving toward the earth, possibly more threatening than the acceleration perception of pitching up and ascending. The very strong deceleration effects found in the backward-facing configuration show that the perceptual dynamics are dependent on something other than arousal related to fear of falling. Great differences in magnitude and complexity of perceptual dynamics between acceleration and deceleration were present in all series, with deceleration always generating the greater effect. The exposure to the 3 G level (Gz and Gx) yielded more reports of rising from the earth than were noted in the 2 Gz exposures, however, comparison of effects in the same subjects is needed to confirm this difference.

Subjects in Series 4 seemed less disturbed by the deceleration in the 3 Gx runs than subjects in the 3 Gz runs of other series, even though acceleration-deceleration difference was definitely present in the 3 Gx runs. Disturbance here refers to an impression that subjects in this series were relatively calm in reporting their experiences. However, this impression needs verification by using the same subjects in different configurations. Leger (7) reported that a Gx configuration during centrifuge runs was less provocative than the Gz configuration. Possibly the reduced cardiovascular load, the supine position, and dorsal support in the Gx configuration reduces arousal and stress.

Here it is important to note that if the different perceptions in different configurations are considered relative to the motion of the vehicle containing the subject, then the perceptions are similar in the different configurations. For example, the forward pitch and tumble associated with the deceleration in configuration 1 and the backward pitch and tumble associated with deceleration in configuration 2 become nearly identical perceptions of pitch-down attitude and forward pitch velocity of an aerospace craft. This, however, highlights the practical operation significance of differences of perceptual effects in the different configurations. Our results suggest that although predominant effects from the platform viewpoint were similar, differences in magnitude of disturbance may have been present. A closer look using the same subjects over different configurations is therefore of practical significance for pilot configurations in aircraft, apart from G-tolerance considerations.

**Acceleration-Deceleration Difference**

The principal finding of our observations was the acceleration-deceleration difference that was of great magnitude, irrespective of the configuration used, irrespective of the particular spatial orientation perceptions associated with the different configurations, and despite the low magnitude angular accelerations used in our experiments. The difference cannot be accounted for by the explanation of the acceleration-deceleration difference in effects of head tilts when subjects are near the center of rotation (8,1, p 14).

In seeking an explanation of the main finding, the acceleration-deceleration difference in all series, we turn first to the question of the relative magnitudes and directions of canal stimuli during acceleration and deceleration. Figure 4 indicates angular accelerations on the two principal axes during the accelerations and decelerations of the centrifuge and illus-
trates how the resultant vector of the two components changed in magnitude and direction relative to head throughout the upramps and downramps. Because the canals tend to integrate acceleration over time, the accumulated angular velocity provides a better estimate of the sensory message. Figure 5 illustrates the accumulated angular velocity on z and y axes.

![Graph](image)

**Figure 5.** Accumulated angular velocity on the z- and y-axes during forward-facing heading configuration of Series 2. The very low angular velocity of the carriage as it swung about its tangentially aligned bearings, x-axis of the head, is shown.
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in configuration 1 of Series 2. Figure 5 also shows the low angular velocity of the carriage about its tangentially aligned pivotal axis, which is the velocity on the subject's x-axis in Series 2. Comparison of the upper and lower panels of Figure 5 shows that the accumulated velocity on the two principal axes is identical in magnitude though reversed in direction as the acceleration and deceleration terminate. However, there is clearly a difference in the rate of accumulation of angular velocity on the different axes during the course of the acceleration and deceleration. In the following discussion, we will use the term turn-vector for the accumulated angular velocity vector and linear vector for the resultant linear acceleration vector.

We now consider the change in magnitude and direction of the linear vector relative to the magnitude and direction of the turn vector. Figure 6 shows changes in magnitude and direction of the linear vector and of the turn vector relative to the head during the upramps and downramps of counterclockwise runs, and the heads depicted below the turn vectors illustrate the stimuli relative to the head for each configuration. The length of the arrows in Figure 6 represents the magnitude of the vectors, and the disc on the turn vectors is used to illustrate the direction of turn, which is also given by the right-hand rule (point the thumb of the right hand in the direction of the arrow-head and the curl of the fingers shows the direction of turn). At the beginning of the upramp, the linear vector is almost directionally aligned with the turn-vector, which is almost aligned with the z-axis in configurations 1 and 2. At the end of the upramp, the linear vector is very large and it is almost perpendicular to the turn-vector, that is, it is directed almost in the plane of the turn-vector.

Experiments examining the response to stopping off-vertical rotation (9,10) indicate that the turning sensation is suppressed when the linear vector (gravity) approaches alignment with the plane of the turn-vector. From this we might infer that the large linear vector in our centrifuge runs, because it was directed almost in the plane of the turn-vector toward the end of the upramp, suppressed the pitch-up turn sensation that the canals would have otherwise generated.

From experiments dealing with static perception of pitch position when the z-axis of the head remains aligned with linear vectors of different magnitudes (11-15), upramp pitch position perceptions of the amounts reported in our configuration 1 could be attributable to the mechanism inferred in these studies. The mean plane of the utricular otolithic membrane does not lie in the x-y plane of the head, but rather slopes downward about 20 degrees. Thus, increased magnitude of a linear vector aligned with the z-axis produces an increased linear component in the shear plane of the utricular otolithic membrane, which increases the angle of the pitch perception. Correia and colleagues (11) found that increase in pitch perception was not directly proportional to the increase in the shear component, but became progressively less as the z-axis linear vector increased beyond 1.25 g-units. Thus the pitch perception during the upramp of configuration 1 may be primarily attributable to stimulation of the otolith system, which generated the pitch perception and suppressed the perceptual effect of the pitch-plane turn-vector.

In configuration 2, backward facing, the increasing shear as the Gz linear vector increased would tend to produce a pitch-up perception, opposite the pitch-down velocity signal from the canals. It may be significant that in this configuration, subjects were inconsistent regarding pitch during the acceleration.

The results during the downramp are more difficult to "explain." At the beginning of the downramp, the pitch-plane (y-axis) turn-vector increases fairly rapidly (relative to y-axis turn-vector during onset of the upramp acceleration). However, the linear vector is very large, and it lies almost in the plane of the turn-vector. By the reasoning we used for the upramp, perceived pitch-plane tumble velocity should be suppressed by the large linear vector. As the downramp continues, the y-axis turn-vector continues to increase in magnitude, and the linear vector, which remains almost in its plane, should suppress perceived pitch plane tumble velocity. However, our results clearly show that the tumble perception
Figure 6. Vectorial representation of the magnitude and direction of 1) the accumulated angular velocity and 2) the resultant force (in g-units) relative to the head in the different configurations. (Figure continues)
Figure 6 continued.
is suppressed very little during the downramp. The deceleration turn vector dominates angular position and angular velocity perception. Apparently, we must consider other aspects of canal-otolith interaction and how they differ during the upramp and downramp. Obvious differences are the decreasing (as opposed to increasing) magnitude of the linear vector and the relatively fast increase in the y-axis turn-vector early in the downramp. That the linear vector, though large and in the plane of the turn vector, was decreasing in magnitude may be the significant factor or, alternatively, adaptation to high magnitude linear acceleration may reduce the suppressive effects of linear vectors of lesser magnitude, particularly for sustained turn-vectors that are increasing in magnitude.

Theoretical Canal–Otolith Responses

The predicted y-axis canal-mediated response according to Oman’s group (5), shown graphically in Figure 7 and vectorially in Figure 8, peaks at 3.0 g-units (Figure 8) just before the end of the upramp acceleration, while during the downramp deceleration, the canal-mediated y-axis response reaches maximum earlier, after only 12 seconds into the deceleration. The vectorial representation in Figure 8 shows the turn-vector relative to the head and also relative to the linear vector. During the upramp as the turn vector approached maximum magnitude, the linear vector approached maximum magnitude and, also, alignment with the plane of the turn vector. During deceleration, the linear vector had diminished to 1.07 g-units as the turn vector reached maximum magnitude. Perhaps the large linear vector directed in the plane of canal-mediated y-axis response suppressed the angular velocity component of the perception and reinforced perception based on position-sensor input during acceleration, while during deceleration the lesser magnitude linear vector only partially suppressed the angular velocity component, which then altered position perception. This inference is consistent with our data, but the direction of change in $G$ level may be significant. Subtle differences in combinations of canal-otolith input can alter the perception from tilt to linear velocity to some combination of pitch, roll, or yaw position change with linear velocity components in the perception (9).

The utricular otolithic membrane was displaced in the negative x-axis direction during the upramp, achieved maximum displacement when 3 Gz was attained, and remained at this displacement throughout the period of constant velocity (unless vestibular efferents alter cilia stiffness). When the downramp commenced, the rapid drop in magnitude of the linear vector caused a rapid reduction of the shear force that had displaced the membrane and, thus, a relatively fast movement of the utricular otolithic membrane in the positive x-axis direction. This combination of relatively fast translation of the otolithic membrane in the positive x-axis direction, coupled with a fairly fast increase in the y-axis (pitch plane) turn-vector, may also be a factor in the very strong dynamics in the downramp perception. During the upramp, the utricular shear component developed initially due to the tangential acceleration and this displacement was increased by the shear component of the increasing Gz vector, but partially due to the initial displacement of the membrane, the rate of membrane displacement would be more and more slowed by restorative spring action of the otolithic membrane and its embraced cilia. Subtle differences, such as the relative speeds of membrane displacement coupled with different rates of increase in the y-axis turn-vector, may play a role in the very great acceleration–deceleration differences we found in series 1 and 2.

In configurations 1, 2, and 3, stimulation to the otolith system can be briefly summarized as a z-axis vector that changed in magnitude from 1 to 3 g-units during the upramp with less than 4.0 degrees deviation in direction in the pitch plane, while during the downramp, the vector remained almost fixed on the z-axis as it changed in magnitude from 3 to 1 g-units with less than 4.0 degrees deviation in direction in the pitch plane. Assuming that the mean plane of the utricular otolithic membrane slopes down about 20 degrees from
Figure 7. Predicted magnitudes of the turn-vector perception components in configuration 1 of Series 2 during the upramp (a) and during the downramp (b) from a model by Oman (5). The long time constant used was 6.0 seconds and the gain was 1.6 times that used by Oman for predicted VOR. Note the similarity in shape of the curves in this figure and in Figure 5.
the x-y plane of the head, the resultant vector was at an angle of 70 degrees relative to the plane of the utricular membrane, plus or minus 4 degree displacements in the pitch plane of the head due to the tangential vector.

In configuration 4, the resultant vector as the run began was only about 20 degrees displaced from the mean utricular shear plane and was also about 20 degrees displaced from the mean saccular shear plane. In this config-

Figure 8. Magnitude and direction of the resultant angular velocity vector (predicted) and of the resultant force vector (downward directed large stippled arrow) relative to the head during the upramp (a) and downramp (b).
uration, displacements of both utricular and saccular otolithic membranes relative to underlying hair cells was nearly maximum for the static 1 g-unit vector before centrifuge rotation commenced. As the magnitude of the linear vector changed from 1 to 3 g-units, its direction remained almost fixed relative to the otolithic membranes, except for the small tangential acceleration component, and the utricular and saccular displacement undoubtedly increased. Due to the fairly large initial displacement of the otolithic membrane, the rate of displacement would probably be less for configuration 4 than for the other configurations. If subjects in this configuration are relatively undisturbed, which was our impression, the perceptual dynamics during deceleration may be attributable to different otolith dynamics. However, the fact that this configuration also reduces muscle-joint load and cardiovascular load and distributes weight over a large body surface must also be considered.

VOR during Series 2

The VOR does not reflect the acceleration/deceleration difference that is so evident in the dynamics of spatial orientation perception. VOR recorded during Series 2 is described in detail elsewhere (4,5) and is summarized in Figure 9, which shows mean z-axis and y-axis

![Mean SPV (± 1SD), Facing Motion](image)

Figure 9. Mean slow phase velocity of the VOR obtained from 8 subjects in forward-facing tangential configuration of Series 2 by McGrath (4). Actual direction of centrifuge rotation was clockwise. Polarity of slow phase eye velocity indicated according to Hixson and colleagues (3).
VOR from 8 subjects throughout runs from Series 2 with subjects in forward-facing tangential heading. Figure 9 shows that the mean VOR slow phase velocity generated by the acceleration and deceleration did not differ in magnitude.

During the constant velocity portion of the stimulus profile, a sustained upbeating nystagmus, apparently attributable to the “hyper-G” linear vector directed approximately along the z-axis, is present. This L-nystagmus has no apparent perceptual counterpart and is under continuing study (16).

The data we obtained on perception clearly indicate differences between the upramps and downramps, but our procedure did not provide information on the shape of the perceived velocity curve within either the upramp or the downramp. The curves presented in Figure 8 are theoretical and not observed. However, the VOR velocity during the upramps and downramps, shown in Figure 10, corresponds remarkably to the shape of the predicted velocity wave form of Figure 7.

The overall gain of the obtained VOR is low. The predicted perceived velocities in Figure 7 are greater by a factor of 1.6 than predicted VOR velocities. We gave predicted perceived velocity higher gain in Figure 7 based on data (2, p 52 f, 17) implying that velocity information in the perception is accurate (so that gain is 1.0) during short arcs of turn, whereas the model developed by Oman’s group (5) gives a VOR gain of 0.6 early in angular velocity wave-forms. From this reasoning, VOR would be 0.6 of the velocities shown in the first few seconds of the upramps and downramps of Figure 7. However, obtained VOR falls substantially below predicted VOR gain. This is shown in the stippled inset in Figure 11, which compares, in vectorial form, obtained and predicted VOR at 5 seconds into the stimulus. Possibly, the linear vector directed in the plane of the predominant (pitch plane) VOR response suppressed VOR velocity toward the end of the upramp and through much of the downramp. VOR gain at 5 seconds in the upramp was 0.49, but only 0.34 in the downramp, suggesting greater suppression or L-nystagmus counteraction or both in the downramp.

VOR cannot reflect part of the acceleration–deceleration difference that was so prominent in the perceptual dynamics. The perception of attitude (pitch position) during deceleration is paradoxical in relation to the perceived velocity. The VOR cannot reflect pitch position and simultaneously an incongruent pitch velocity. A high-magnitude VOR during deceleration would have been consistent with the idea of a strong canal-mediated velocity component overcoming information from position sensors, but this was not present in the VOR. The low VOR gain at 5 seconds into the downramp may reflect the effect of a relatively fixed and large position signal acting for several seconds in the plane of the canal-mediated response. During the first 5 seconds of the upramp, a smaller position signal was almost perpendicular to the plane of the canal-mediated response. Reduced VOR gain could signify greater discord between angular position and angular velocity signals, which is reflected in paradoxical position–velocity perception during the downramp.

The failure of the VOR to provide evidence of the acceleration–deceleration difference in perceptual dynamics is not the only instance of these two aspects of the overall reaction following different paths. During sustained low-magnitude angular acceleration, perceived turning diminishes before and more than does the VOR (18). Another point of departure was shown in what is now referred as “velocity dumping” (19,20). In man, strong postrotational nystagmus can be substantially suppressed by brief room illumination, and after darkness is restored, VOR slow phase velocity recovers almost to the level of an uninterrupted response and then resumes its decay (21). Perceived turning does not return at all in many subjects and returns very little in others. Dumping of the turn sensation is greater than dumping of nystagmus (21,22). In the present experiments, the perceptual dynamics reveal a dimension in the effects of interaction between position sensors and turn sensors that is not apparent in the oculomotor response.
Figure 10. Mean slow phase velocity of the VOR during the upramp (a) and during the downramp (b). The directions of the responses have been switched to facilitate visual comparison of these data with the predicted z- and y-axis components in Figure 7. Note the similarity of shape of the curves in Figures 7 and 10 but the low gain of the obtained VOR.
Perceived Angular Movement about the Tangential Axis

The carriage that held the subject's chair swung on an axis that was aligned tangentially on the centrifuge, and, thus, the subject maintained almost constant alignment with the vector resultant of gravity and the centripetal vector. As shown in the curve for the x-axis in Figure 5, the angular velocity profile of this
movement, considered alone, was a very weak semicircular stimulus, almost subthreshold. Despite the weak angular vector and the relatively fixed direction of the linear vector relative to the head, subjects in Series 1, 2, and 3 mentioned position change about this axis (x in Series 1 and 2, y in Series 3). Because subjects had been told that this motion of the carriage would occur, expectation may have potentiated this perception (in contrast to the pitch-motion perceptions of Series 1 and 2 and the cartwheeling perceptions of Series 3, which are beyond the repertoire of the centrifuge). However, perceptual potentiation of this component of the overall perception could be preconditioned by the tilt of the body that occurs naturally during curvilinear ambulatory movement; leaning into a turn aligns body components with a mean resultant vector. A particular direction of body tilt could be associated with direction of curvilinear motion. Additional observations under different conditions are needed to clear up such questions.

Reduction of the Acceleration-Deceleration Difference

When the acceleration–difference changed over the course of repeated runs, the change was in the direction of reduction of the difference. If further investigation confirms this possible trend as a reliable effect, the effect may be a form of adaptation dependent on repeated suppression by position sensors of canal-mediated turn perception, similar to the visually induced changes in canal-mediated reactions that have been so vigorously studied over the past 20 years. Though less effective than a fixed visual scene in modifying the VOR, nonvisual position-sensor information does influence the plane and other characteristics of the VOR (23–26) as well as perceptual dynamics. The study of adaptive modulation of spatial orientation dynamics through this interaction awaits a convenient research paradigm like optically-induced modulation of the VOR (compare reference 27).

A Model for Dynamics of Spatial Orientation

The results of this series of observations provide fundamental information that must be handled by any model that purports to predict the dynamics of spatial orientation perception under complex conditions. To simplify the following discussion, we use the term *attitude* to refer to the instantaneous perception of angular position of the body relative to a fixed reference frame, which is usually the earth, and we assume that the head and body are aligned, as in normal upright seated configuration.

For steady state conditions, perceived attitude is determined by the magnitude and direction relative to the head and body of the total resultant linear acceleration, \( A \), including gravity as a component. The direction of this steady-state vector relative to the body can be described according to the projection of \( A \) onto the x, y, and z head axes, employing the nomenclature of Hixson and colleagues (3). As a first approximation, perceived attitude will deviate from level (upright) by the angle by which \( A \) deviates (tilts) from the z-axis, and a first approximation of error in the pilot's perception of aircraft attitude will be given by the angle between \( A \) and the direction of gravity, under static or very slowly changing conditions. Much information is available on attitude perception soon after attaining a steady-state (static) tilt position, how it varies as a function of time in a pitch or roll or other tilt position or under different G-levels with and without visual frames of reference, and how accurately lines can be set to "vertical" from various static or very slowly changing tilt positions. Models are available to deal with attitude perceptions under these static or nearly static conditions.

Models sufficient to predict attitude perceptions under steady state conditions may become part of a more general model that will predict the dynamics of reactions under dynamic conditions, but it is clear that new concepts will be needed. For example, during fairly fast changes in horizontal linear acceleration of the whole body in the earth-horizontal
plane, attitude perception is not influenced by the changing direction of \( A \) relative to the body, rather the perception is horizontal linear velocity of the body and not attitude change. The frequency dependence of the transition from tilt to linear velocity perception is yet to be determined. Evidence can be adduced to support the idea that quick and accurate perception of attitude change depends upon concomitant information from several motion and gravity sensors. When the otolith system receives adequate stimulation without appropriate confirmation from the canals, for example, attitude change perception appears to be very sluggish. An idea that would subsume the results of our centrifuge runs is that a linear vector approximating the magnitude of gravity that is fixed in or near the plane of a turn vector will suppress the turn perception, and the turn vector will not influence attitude (position) perception very much. (More data is needed to say how much.) If the linear vector is directionally fixed in the plane of the turn vector and increasing in magnitude, the canal-mediated turn perception (pitch, roll, or yaw) will be suppressed, and the turn vector will not influence attitude perception very much. If the linear vector is directionally fixed in the plane of the turn vector but diminishing in magnitude from some hyper-G state, the linear vector will not suppress the canal-mediated turn perception, and the turn vector will strongly influence attitude (pitch, roll or yaw) perception. The relative magnitudes of the linear and turn vectors probably determine how much the turn vector alters the attitude perception and how much the linear vector suppresses the turn perception. We introduce these ideas not as carefully derived principles (we are considering others [9]), but as examples of ideas that will have to be incorporated in models that will be sufficient to deal with the dynamics of spatial orientation.

This series of observations has raised a number of questions and also provided insight into a simple approach for revealing large effects. The striking acceleration–deceleration difference is a fact that must be explained by any viable model of the dynamics of spatial orientation perception. The possible amelioration of distressing effects in configuration 4 can be evaluated by using the same subjects to compare several configurations. The possible reduction in the acceleration–deceleration difference over repeated runs can be more fully investigated. If substantial effects exist, statistically significant preponderance in comparisons will emerge. Small effects may be missed, but major effects can be revealed and established as facts that must be adequately subsumed by any model that seeks to predict spatial orientation dynamics. Such simple procedures should not be overlooked in favor of academically acceptable but tedious psychophysical procedures, which can also be blind to important effects. Dynamics of responses to whole-body movement do not permit quick and repetitive stimulus repetition (required by conventional psychophysics) without confounding sequential effects.

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