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Effect of radius versus rotation speed in artificial gravity

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Abstract. Artificial gravity by centrifugation can lead to perceptual disturbances in the form of motion sickness and/or misperception of motion during head movements, but the degree of perceptual disturbance during centrifugation in 0-g has not been thoroughly investigated. It is known that during whole-body on-axis yaw rotation in 0-g, head movements in pitch and roll cause very little disturbance, despite significant disturbance in 1-g. Therefore, 1-g experimental results do not apply directly to 0-g without further analysis.

A modeling approach was used here to predict disorienting effects in 0-g and 1-g environments, with different rotation speeds, centrifuge radii, and directions of head movement. The results were based upon investigation of the stimulus itself, in the form of angular and linear accelerations, and their consequences due to linear-angular interactions in three dimensions.

The results explain known differences in 0-g and 1-g, for head turns toward and away from the direction of motion, and for head movements on- and off-axis. Additional predictions include an increase in perceptual disturbance with the magnitude of the gravito-inertial acceleration (GIA), therefore an increase off-axis, but a decrease in 0-g. Also predicted is that head-movement direction makes a difference, with rotation outward relative to the centrifuge axis causing the least disturbance.

Keywords: Model, self-motion, perception, vestibular

1. Introduction

In a 0-g environment, centrifugation can provide artificial gravity as a possible countermeasure to the adverse effects of weightlessness. However, head turns during centrifugation are considered likely to cause perceptual disturbances in the forms of motion sickness and/or illusory motions. These undesirable side effects have been studied mostly in a 1-g environment, for obvious practical reasons. Therefore, it is necessary to extrapolate 1-g results to the 0-g environment. It is also beneficial to consider the effects of rotation speed and radius, with special focus on a 0-g environment.

Careful prediction for 0-g is particularly important because the offending motion – head movement about an axis not parallel to the axis of whole-body rotation – has been found to cause surprisingly little motion sickness in a 0-g environment when the rotation is essentially on-axis [11,12,28]. By this result alone, motion sickness in artificial gravity would not be predicted. However, centrifugation introduces a confounding factor, a linear centripetal acceleration. Because linear-angular interaction is important in the perception of motion, this linear vector is a crucial component for reliable prediction of perceptual disturbances in 0-g.

Historically, only the angular vectors were analyzed in order to understand illusory motion upon head movements during rotation. The classic explanation of this “vestibular coriolis” or “cross-coupling” effect in the absence of vision involves consideration of the stimulus to the semicircular canals; of course, the effect arises from the laws of physics, and is the same regardless of the mechanism of acceleration detection. In particular, if an object such as a head is rotating, then upon tilt or turn about a second axis, an angular acceleration arises about yet a third axis. The direction of this third axis is

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given by the right-hand rule as the cross product of the first rotation vector with the second rotation vector. For example, an upright subject rotating counterclockwise (axis upward) who tilts the head rightward (axis forward) will experience a pitch-forward angular acceleration stimulus (axis leftward). (The classic vestibular explanation shows that the vertical canals are thus stimulated.) Indeed, experimental work shows that upon head movements while rotating, subjects typically experience perceptual disturbances in the form of illusory motion and/or motion sickness [13,15,29]. The magnitude of the angular acceleration is the magnitude of the cross product, so greater rotation speeds or faster head movements cause greater accelerations. As expected, greater rotation speeds have also been found to cause greater perceptual disturbances [25,26].

The classic angular-vector explanation fails, however, to explain more sophisticated experimental results. Among those results are the findings that an accelerating on-axis rotation leads to a smaller effect [15], a decelerating on-axis rotation leads to a greater effect [15], a 0-g environment leads to very little effect [11,12, 28], clockwise and counterclockwise head turns lead to different magnitudes of effect [18], and pitch-down head movements are less provocative off-axis, while pitch-up head movements are more provocative off-axis [39]. Clearly, the laws of physics governing these motions do not consist solely of the angular vectors; linear vectors also play an important role. For example, the accelerating- and decelerating-rotation results have been analyzed in terms of a conflict between the linear gravity vector and the final angular acceleration vector, which is least aligned with the gravity vector if the rotation is decelerating [15]. This explanation was also tested by modeling the entire three-dimensional consequences of the linear-angular interactions [24], showing that a decelerating rotation leads to the greatest head-movement-induced sensory conflict arising directly from the physics of the motion.

Whereas simpler vestibular stimuli have traditionally been analyzed by hand, these more complex stimuli require three-dimensional computer analyses that include all three degrees of freedom of both linear and angular accelerations, as well as all linear-angular interactions in three dimensions. Through such computer simulations, a surprising number of experimental results can be explained by the physics of the stimulus alone. For example, computer modeling has revealed an asymmetry between the physics of clockwise versus counterclockwise head movements during rotation [23], an asymmetry reported experimentally in human perception [18]. More precisely, during clockwise centrifuge rotation, supine subjects with head toward center reported greater illusory motion during counterclockwise, i.e. leftward, head yaw than during clockwise head yaw. At first glance, the physics of the two movements would seem symmetric because the angular vectors are symmetric. However, computer simulation [23] has shown that during clockwise centrifuge rotation, counterclockwise head yaw gives a greater effect than does clockwise head yaw due to the pattern of linear-angular interaction between the directions of the pitch angular acceleration and the gravito-inertial acceleration (GIA, i.e. sum of the linear acceleration and an earth-upward acceleration vector associated with reactionary forces due to the presence of gravity). One consequence of the modeling is the realization that when rotating off-axis, previously-thought symmetric head movements are in fact asymmetric; direction of head movement is a relevant variable.

Additional experimental results have also been explained through three-dimensional modeling of the physics consequences of the stimulus. In a centrifuge with fixed carriage, the quicker change in perceived tilt during deceleration than during acceleration [6, 10] can be explained by the three-dimensional consequences of the accelerations themselves [21]. In a centrifuge with carriage that tilts with the GIA, the greater pitch sensation during deceleration than during acceleration [16] can be similarly explained by a model of the physics [22]. The experimental finding that rotation speed is a greater factor in perceptual disturbances than is tilt-arm length when tilting away from the axis of rotation [25,26] can also be explained by the three-dimensional physics of the stimulus [24].

For coriolis cross-coupling conditions, a quantitative measure of potential perceptual disturbance is the magnitude of the illusory motion predicted by the physics of the stimulus. Not surprisingly, this magnitude has been found to correlate with experimental findings of perceptual disturbances. Important are both the angular component, measured precisely by the Twist Factor, and the linear component, termed the Stretch Factor. These factors represent the magnitude of predicted illusory angular and linear motion, respectively, and can be interpreted as the magnitude of vestibular-proprioceptive conflict. The precise method of computation of the Twist and Stretch Factors is given in the Methods section below.

The inclusion of all linear-angular interaction has made it possible to distinguish between different conditions that have the same rotation speed, and to in-

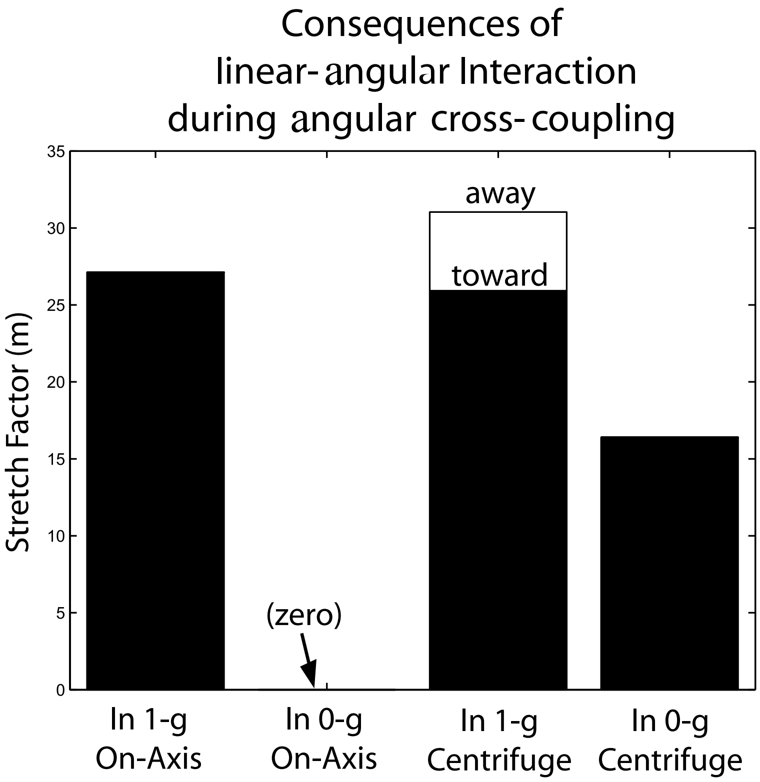

Fig. 1. Stretch Factor arising from head movements under different conditions [23]. All four conditions had 126.9°/s whole-body rotation with a 90° head movement in 1 s orthogonal to the axis of rotation, causing angular cross-coupling. Two gravitational environments were tested: 1-g and 0-g. For each gravitational environment, on-axis rotation was tested with the head movement about a horizontal axis, and 1-m radius centrifuge rotation was tested with the subject considered supine, head toward center, with a yaw head movement. The Stretch Factor was reported at the 3 s point, meaning that the calculation included 1 s of head movement plus 2 s subsequent to the movement, based upon modeling of the physics of the motion. In the 1-g centrifuge condition, different results arose depending upon whether the head movement was toward or away from the direction of motion (Fig. 2). The Stretch Factor is discussed in the text, and is defined formally in the Methods section.

vestigate the effects of including or excluding gravity. In conditions with the same rotation speed, the Stretch Factor distinguishes conditions by measuring the different linear magnitudes of illusory motion, thereby providing a prediction of the magnitude of perceptual disturbance. Figure 1 shows the Stretch Factor in certain coriolis cross-coupling conditions, including that of a centrifuge in 0-g. Predicted, based upon the strong connection between the Stretch Factor and known experimental results, is that perceptual disturbances in a centrifuge in 0-g will be weaker than in 1-g, but will be stronger than those on-axis in 0-g [23].

The significance of the linear vector raises a number of questions. How can the results of experimental research in 1-g be extrapolated to a 0-g environment? What effect does the radius – or, more relevantly, the magnitude of centripetal acceleration – have on the consequences of the stimulus? Does the answer differ between a 1-g environment and a 0-g environment where the orthogonally-directed linear gravity vector is missing? If linear acceleration is a factor, then which is a better predictor of consequences when comparing across all conditions: the centripetal acceleration or the total GIA?

The present paper investigates the effects of centrifuge radius and rotation speed on the acceleration stimulus and its consequences, due to physics, during head movements in both 1-g and 0-g environments. The focus is on short time frames, before perceptual effects such as decay of perceived velocities are significant. Therefore, the primary computations model the pure physics of the stimulus without such decay; additional computations that use perception-related time constants of decay are mentioned in the Discussion. Because the direction of head movement matters, different body orientations and head-movement directions were tested. Further verification of the model was done by comparison with known experimental results [39] in 1-g for pitch head movements on- versus off-axis.

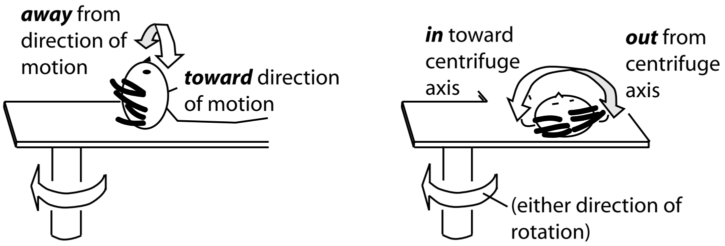

Fig. 2. Illustration of "away", "toward", "in", and "out" head movements.

2. Methods

2.1. Motions

Head movements in a rotating centrifuge were considered under a variety of conditions. All conditions used a 60° head movement with sinusoidal angular velocity profile lasting 1 s, about an axis through the head. Varied were the following.

(1) Gravitational environment and head-movement direction (Fig. 2) (six conditions): 1-g toward, 1-g away, 1-g in, 1-g out, 0-g toward/away, 0-g in/out.

The two different gravitational environments were implemented by the presence of a constant gravity vector in 1-g, and the absence of that vector in 0-g. Head movement directions (Fig. 2) were toward and away from the direction of motion, and in and out from the centrifuge axis. Although Fig. 2 displays a supine subject making yaw head turns, a subject could be oriented otherwise, making pitch or roll head turns about the toward/away or in/out axes. However, because the focus of the present research was to identify differences caused specifically by the physics of the stimulus, the results are most meaningful when comparing like movements, yaw to yaw, or pitch to pitch, etc., so the same type of head movement is considered to take place about both axes. Also notable is that in 0-g, the absence of a vertical direction extinguishes the difference between "toward" and "away" and between "in" and "out", so there are just two 0-g conditions of head movement, "toward/away" and "in/out".

(2) Centrifuge rotation speed (five conditions): 30°/s, 60°/s, 90°/s, 120°/s, 150°/s.

(3) Centripetal acceleration (eleven conditions): 0.0 g, 0.1 g, 0.2 g, 0.3 g, 0.4 g, 0.5 g, 0.6 g, 0.7 g, 0.8 g, 0.9 g, 1.0 g.

Centripetal acceleration was chosen, in place of radius, as an independent variable because the two are directly related when rotation speed is fixed, and acceleration is the stimulus to the sensors. The radius for each run was adjusted in accordance with the rotation speed in order to achieve the required centripetal acceleration. At the highest rotation speed of 150°/s the radii ranged from 0.0 m to 1.4 m, and at the lowest rotation speed the radii ranged from 0.0 m to 35.8 m. The head and body location were considered to be such that the approximate center of linear acceleration detection was located at the given radius; this detection of linear acceleration can arise from a combination of vestibular and extra-vestibular graviceptors [34].

2.2. Computational implementation

To investigate the consequences of the stimulus in each condition, the full three-dimensional laws of physics were implemented, including all linear-angular interactions. Because there is necessarily a one-to-one relationship between motions and their patterns of linear and angular accelerations, when given a set of initial conditions, it was possible to uniquely compute the motion that would be associated with the stimulus for each head movement. (This focus on physics contrasts with that of perceptual models that mix external physics with physiological properties. However, both the present approach and those of many models, e.g. [4, 9,30,40], keep track of computations in a manner sometimes termed an "internal model.") The initial conditions used were those of a typical subject's perception preceding the head movement. In particular, to match the subjective experience, the simulations began with a "perception" of orientation in which the GIA was vertical. In other words, taken into account before the head movement were known properties of perception: the tendency to feel tilted according to the GIA and the tendency to feel stationary despite the continuing constant-velocity rotation. These properties apply to long-term stimuli such as during the constant-velocity portion of the centrifuge run, and can therefore be used to set the perceptual conditions before the shorter-time-frame head movement.

The physics equations follow, but the general idea can be illustrated by examples. One classic example is that of deceleration from clockwise on-axis rotation without vision: During constant-velocity rotation there is a perception of stationarity. Upon deceleration, a counterclockwise acceleration is imposed on the subject. By the laws of physics, the motion associated with stationarity followed by counterclockwise acceleration is counterclockwise rotation. Therefore, counterclockwise rotation would be reported by the model. In fact, this is also what human subjects report (reviewed in [14]). Another example involves a centrifuge in which the carriage tilts with the roll tilt of the GIA: During constant-velocity centrifuge rotation, seated subjects facing the direction of motion feel upright because the GIA is oriented vertically through the body. Upon centrifuge deceleration, an approximately pitch-forward angular acceleration is imposed on subjects, while the GIA, which has magnitude greater than 1-g, remains body-vertical. By the laws of physics, the motion associated with this pattern of accelerations would be a forward pitch motion with ascent from the earth [22]. Therefore, this pitch motion with ascent would be reported by the model. In fact, this motion is what subjects experience at the beginning of the deceleration [16].

It is worth noting that the physics analysis is most applicable to stimuli over short time frames, before the well-known physiological time constants have a significant effect. For investigation over longer time frames, many models include both the underlying physics and time constants, as noted in the Discussion. Although the current model allows for the use of these time constants, the present focus is on the short-term effects of the stimulus itself, so the bulk of the simulations were performed with the unadulterated laws of physics. The physics analysis gives the immediate consequences of the stimulus itself.

The model of the laws of physics used head-coincident coordinates in which velocities and accelerations were given in a coordinate system coincident with the head but temporarily fixed relative to the earth or other surrounding reference so that non-zero velocities could be specified [20]. This method was designed to match the subject-based experience in which the sensors move with the subject. The standard head coordinate axes were used [19], with x noseward, y leftward, and z head-upward. The transformation from head-coincident coordinates to earth-fixed (or other reference) coordinates was given by the 3-by-3 matrix S with rows ${}^h\vec{i}_E$, ${}^h\vec{j}_E$, and ${}^h\vec{k}_E$, representing the earth's $\vec{i}$, $\vec{j}$, and $\vec{k}$ vectors (in the x, y, and z directions) in head-fixed coordinates. The equations were

$$\frac{d\,{}^h\vec{i}_E}{dt} = {}^h\vec{i}_E \times {}^h\vec{\omega}$$

$$\frac{d\,{}^h\vec{j}_E}{dt} = {}^h\vec{j}_E \times {}^h\vec{\omega}$$

$$\frac{d\,{}^h\vec{k}_E}{dt} = {}^h\vec{k}_E \times {}^h\vec{\omega}$$

$$\frac{d\vec{r}}{dt} = {}^E\vec{v}$$

$$\frac{d\,{}^h\vec{\omega}}{dt} = {}^h\vec{\alpha}$$

$$\frac{d\,{}^E\vec{v}}{dt} = S\,{}^h\vec{A} - {}^E\vec{g}$$

with pre-superscripts indicating head-coincident (h) or earth-fixed (E) coordinates, and $\vec{\omega}$, $\vec{r}$, $\vec{v}$, $\vec{\alpha}$, and $\vec{A}$ being angular velocity, linear position, linear velocity, angular acceleration, and GIA, respectively, and $\vec{g}$ being the earth-upward vector due to the presence of gravity. For the zero-g runs, the magnitude of $\vec{g}$ was taken to be that of the centripetal acceleration because subjects were considered to use the GIA during constant velocity as the indicator of vertical.

Of the variables, the inputs to the model were the accelerations, ${}^h\vec{\alpha}$ and ${}^h\vec{A}$. All other variables had their values computed by the model over time, beginning with initial values as described previously. The output of each run was three-dimensional motion information in the form of the above variables, including position, velocity, angular velocity, and orientation including not only vertical but also compass direction.

In addition, three-dimensional graphical output was implemented based upon the ongoing position and orientation information. The graphical output displayed the motions that were associated with the patterns of accelerations imposed upon the subject. These motions could be interpreted as the motions perceived by a perfect processor of acceleration information, given the initial perception of non-rotation.

The computational software and the three-dimensional graphics software were developed in Matlab (The MathWorks, Inc., Natick, Massachusetts, USA). The simulations were performed in Matlab on a Macintosh computer with dual PowerPC processor. All simulations were also tested with veridical initial conditions in order to confirm the reliability of the software.

2.3. Measures

To compare the magnitudes of the consequences of the stimuli from different head movements, two numerical measures were used, the Twist Factor and the Stretch Factor. These have units of angle and distance, respectively, and are "factors" in the sense of being factors likely to contribute to perceptual disturbance. For head movements in a centrifuge, both factors are based upon a comparison between the actual head movement (with accelerations that are "expected" to be sensed) relative to the body, and the computed motion above (which matches the accelerations that are actually sensed, and is therefore the head motion indicated by the acceleration stimulus). These two motions are different because the head movement takes place in an acceleration/orientiation environment that is not veridically perceived by the subject just prior to the head movement.

The Twist Factor is the accumulated angle through which the computed stimulus-associated motion proceeds differently from the actual head movement relative to the body. To calculate the Twist Factor for a computed motion, first calculated was a time series of three-dimensional orientations of the computed motion relative to the actual head orientation (relative to the body). Then calculated was the magnitude of the angle through which this orientation rotated in 3-D from one time step to the next; time steps of 0.1 s were used here. The Twist Factor at any given time is the sum of these "unexpected" rotation angles up to that time. In other words, the Twist Factor is essentially the total unexpected angular stimulus.

The Stretch Factor is the accumulated distance that the computed stimulus-associated motion proceeds differently from the actual head movement relative to the body. Because the head movements studied here involved no linear motion relative to the body, the Stretch Factor was the length of the path followed by the computed motion. The Stretch Factor was also computed by integrating with a time step of 0.1 s. In summary, the Stretch Factor is essentially the total unexpected linear stimulus.

Both the Twist Factor and the Stretch Factor have other, equivalent, interpretations. They give the magnitude of the illusory portion of the motion associated with the stimulus. They also give a measure of vestibular-proprioceptive conflict, as elaborated upon in the Discussion.

Technically, the Twist and Stretch Factors are nondecreasing functions of time, because they are cumulative measures of how the computed stimulus-associated motion proceeds differently from the actual head movement relative to the body. Here, the focus was on short time frames, for which the physics of the stimulus itself is most meaningful. Therefore, for the present purposes the Twist and Stretch Factors were calculated and reported at the 2 s point, the result of integration over the 1 s head movement plus 1 s following the head movement.

3. Results

3.1. Three-dimensional displays

Three-dimensional displays showed the consequences of the linear-angular interactions for each condition. Figure 3 illustrates a representative set of three-dimensional results, for a rotation speed of 120°/s and centripetal acceleration of 0.5 g. The display compares the effects of 1-g and 0-g environments and the effects of the head-movement direction. Only the first 2 s are shown, that is, 1 s during the head movement plus 1 s following the head movement, to stay within the short time frame in which the laws of physics are most applicable, before physiological time constants become significant factors. Again, the goal is to give an estimate of the immediate and potentially disorienting consequences of the stimulus itself. As measures of the magnitude of potentially disorienting components, the Twist and Stretch Factors are shown for each condition.

The results can be summarized as follows. The angular stimulus causes a corresponding translational effect, because the tilt associated with the angular stimulus leads to a misalignment of the perceived vertical with the GIA. This translational effect is measured by the Stretch Factor, which turns out to be the relevant measure because the Twist Factor is identical for all conditions. The Stretch Factor gives results distinguishing the different conditions. One result is that 1-g conditions have greater Stretch Factor than do 0-g conditions. In addition, "1-g in" has greater Stretch Factor than "1-g out", while "1-g away" has slightly greater Stretch Factor than "1-g toward". The least Stretch Factor in 1-g is that of "1-g out". In 0-g, "0-g toward/away" has a significantly greater Stretch Factor than "0-g in/out". In summary,

1-g $>$ 0-g,
1-g in $>$ 1-g out,
1-g away $\geqslant$ 1-g toward,
1-g toward/away/in $>$ 1-g out,
0-g toward/away $>$ 0-g in/out.

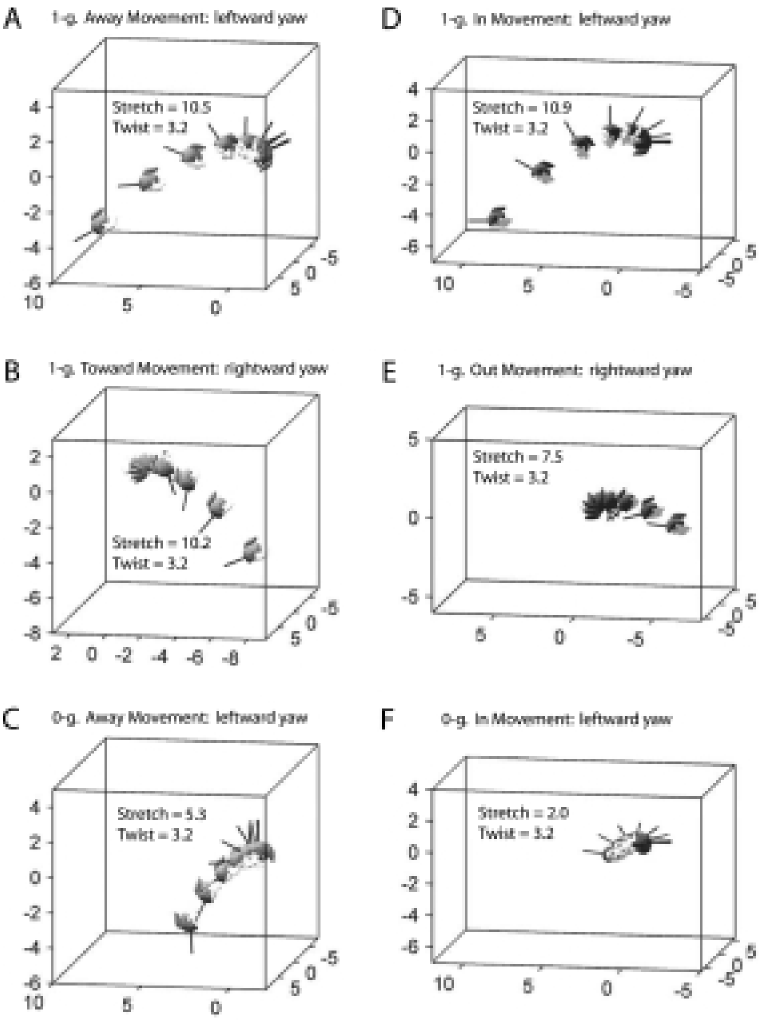

Fig. 3. Three-dimensional output of simulations, displayed in freeze-frame manner with a head shown every 0.25 s, for a total of 2 s of motion. Initial locations are all (0,0,0), and the numbers on the axes indicate meters of movement in the three directions. A "z-axis" is shown out the top of the head to facilitate display of orientation, and heads are five times normal size. All simulations are for clockwise centrifuge rotation speed 120°/s and centripetal acceleration 0.5g (therefore, at radius 1.1 m), and show the motion associated with the accelerations arising from the indicated head movement of 60° yaw. Also indicated are the Stretch Factor, in meters, and the Twist Factor, in radians, at the 2 s point, i.e. as cumulative measures over the motion shown. (A) In 1-g, subject supine, head toward center, turning the head leftward in yaw. The actual centrifuge axis would be to the right. The initial orientation for the simulation, partially visible at (0,0,0), is pitch back, based upon typical subjective interpretation of the GIA as vertical. Upon leftward yaw, the motion associated with the accelerations is of pitch and motion forward, as shown. (B) Centrifuge conditions as in A, with centrifuge axis to the right, and initial conditions identical (though hardly visible) to those in A, but with ensuing rightward instead of leftward yaw. The motion associated with the accelerations is of backward pitch and motion. (C) Similar conditions to A, but in a 0-g environment, where the initial orientation is upright because of the interpretation of the GIA as vertical. The actual centrifuge axis would, therefore, be horizontally-oriented above the subject in the figure. Upon leftward yaw, the motion associated with the accelerations is of pitch and motion forward, but of smaller extent than that in A. Note: In 0-g, Toward and Away are the same, as discussed in the text, so C serves to display the results of 0-g Toward Movement, as well. (D) In 1-g, subject supine with left ear initially oriented toward centrifuge axis, turning the head leftward in yaw. The actual centrifuge axis would between the viewer and the figure. The initial orientation for the simulation, partially visible at (0,0,0), is supine but with slight rightward turn, based upon typical subjective interpretation of the GIA as vertical. Upon leftward yaw, the motion associated with the accelerations is of pitch and motion forward, as shown. (E) Centrifuge conditions as in D, with centrifuge axis between the viewer and the figure, and initial conditions identical (though hardly visible) to those in E, but with ensuing rightward instead of leftward yaw. The motion associated with the accelerations is of backward pitch and motion. (F) Similar conditions to D, but in a 0-g environment, where the initial orientation is right-ear-down because of the interpretation of the GIA as vertical. The actual centrifuge axis would, therefore, be horizontally-oriented above the subject in the figure. Upon leftward yaw, the motion associated with the accelerations is of pitch forward making a small circle in the horizontal plane, with very little linear motion. Note: In 0-g, In and Out are the same, as discussed in the text, so F serves to display the results of 0-g Out Movement, as well.

3.2. Effects of radius and rotation speed

Ranges of radius and rotation speed were tested for the six gravitational and head movement conditions. As described in the Methods section, centripetal acceleration was used as the independent variable in place of radius. Each combination of centripetal acceleration, rotation speed, gravitational environment, and head movement direction produced three-dimensional output, from which the Twist and Stretch Factors were computed.

As expected, the Twist Factor depended only upon rotation speed, and was independent of radius, gravitational environment, and head movement direction. The values were as follows for the five different rotation speeds.

30°/s: Twist Factor 0.79 rad (45°)
60°/s: Twist Factor 1.58 rad (91°)
90°/s: Twist Factor 2.37 rad (136°)
120°/s: Twist Factor 3.17 rad (181°)
150°/s: Twist Factor 3.96 rad (227°)

The Stretch Factor provided the most information distinguishing the conditions, with results shown in Fig. 4A and 4C. Besides the observations discussed in Section 3.1 above, several other results arose, as elaborated here.

The Stretch Factor generally increased with centripetal acceleration, independent of rotation speed, as seen by the mostly positive slopes of the curves. The exceptions were the “1-g out” conditions, for which the Stretch Factor first decreased with increasing centripetal acceleration, before increasing at greater centripetal accelerations. The result that can be stated from the generally positive slopes is that radius does have an effect, independent of rotation speed. In other words, for identical rotation speeds, the potentially disorienting consequences of the physics are greater for head movements at a large radius than for those at a small radius.

Also notable is that the Stretch Factor increased with rotation speed, as seen by the fact that curves for greater rotation speeds are higher on the graph. This result is not immediately intuitive, because the Stretch Factor is a linear factor, while the rotation speed is angular. However, further consideration elucidates the result: A greater rotation speed causes the perceived vertical to move more quickly out of alignment with the GIA, leading to a stronger potentially disorienting effect of the linear stimulus, causing a greater Stretch Factor.

A related result is that for identical centripetal accelerations, the Stretch Factor was smallest during rotation at the largest radius, i.e. with the lowest rotation speed. In fact, both the Stretch Factor and the Twist Factor decreased with increasing radius when rotation speed was adjusted to keep centripetal acceleration constant.

3.3. Centripetal acceleration versus GIA

The Stretch Factor results were plotted, in addition, with GIA in place of centripetal acceleration on the horizontal axis (Fig. 4B and 4D). These plots gave a means to determine which correlated better, centripetal acceleration or GIA, with the potentially disorienting effects of the stimulus.

The result was that the GIA, rather than the centripetal acceleration, clearly correlated better with the Stretch Factor across conditions. In particular, the plots in Fig. 4B and 4D show a more uniform increase with GIA than do the plots in Fig. 4A and 4C with centripetal acceleration. The significance of this result is that the Stretch Factor is related more closely not to the radially-directed component of linear acceleration, but to the magnitude of the total linear stimulus to the sensors, and that this is a basic trend that covers both 0-g and 1-g conditions.

3.4. Comparison of radius and rotation speed

The classic angular-only analysis has now been augmented by linear-angular results that radius is a significant factor for the physics consequences of the stimulus. From this realization arises the question: How do the effects of radius and rotation speed compare?

The Twist Factor increases only with rotation speed, but the Stretch Factor increases with both rotation speed and radius, or more closely, with the GIA (Fig. 5). The underlying data show that the Stretch Factor increases more with GIA than with rotation speed. For example, for all six conditions, 1-g toward, 1-g away, 1-g in, 1-g out, 0-g toward/away, and 0-g in/out, the Stretch Factor increases by a factor of 1.7 ± 0.1 as the rotation speed doubles from 60°/s to 120°/s at a fixed centripetal acceleration of 0.4 g, while the Stretch Factor is increasing at the (greater) rate of 2.4 ± 0.4 per doubling of GIA in the 0.4 g to 0.8 g centripetal acceleration range (with associated GIA calculated in the standard way) at a fixed rotation speed of 60°/s.

Thus, the simulations show that the potentially disorienting effects from physics increase significantly with both rotation speed and GIA.

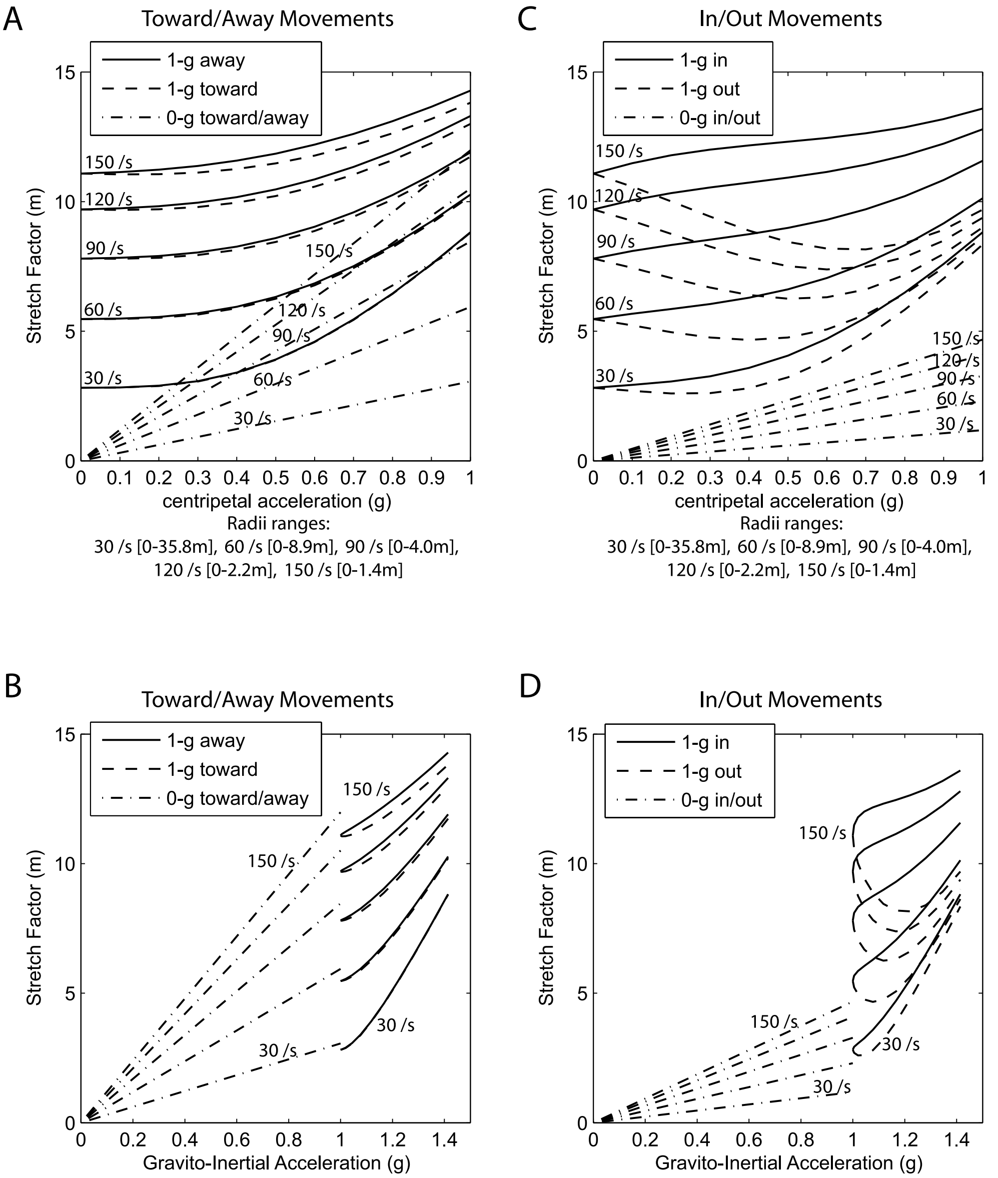

Fig. 4. Stretch Factor as a function of centripetal acceleration (A,C) and GIA (B,D) for head movements in a centrifuge in the six gravitational/head-direction conditions and five rotation speeds. (A) Head movements toward and away from direction of motion. A curve is shown for each rotation speed, as indicated, for each gravitational and head-direction condition, using solid, dashed, and dash-dot curves as indicated in the legend. For the centripetal acceleration range 0g to 1g shown, the radius range depended on rotation speed, and is indicated below the graph. (B) Same data as in A, graphed as a function of GIA instead of centripetal acceleration. The rotation speeds are the same as in A; 30°/s and 150°/s are labeled. (C) Head movements in and out from the centrifuge axis. The curve-labeling convention is the same as in A. (D) Same data as in C, graphed as a function of GIA instead of centripetal acceleration. The rotation speeds are the same as in C; 30°/s and 150°/s are labeled.

3.5. Further model verification

Besides past testing with experimental data [21–24], the modeling approach was further compared with experimental findings that perceptual disturbances were greater during off-axis than on-axis rotation for head movements "in", but were less during off-axis than on-axis for head movements "out" [39]. Indeed, while the Twist Factor remained constant for on-axis and off-axis rotation, testing showed that differences in the Stretch Factor aligned with the experimentally-determined perceptual disturbances. As seen in the 1-g curves in Fig. 4C, a comparison of on-axis (0 g) with off-axis (slightly greater than 0g) shows that "1-g in" move-

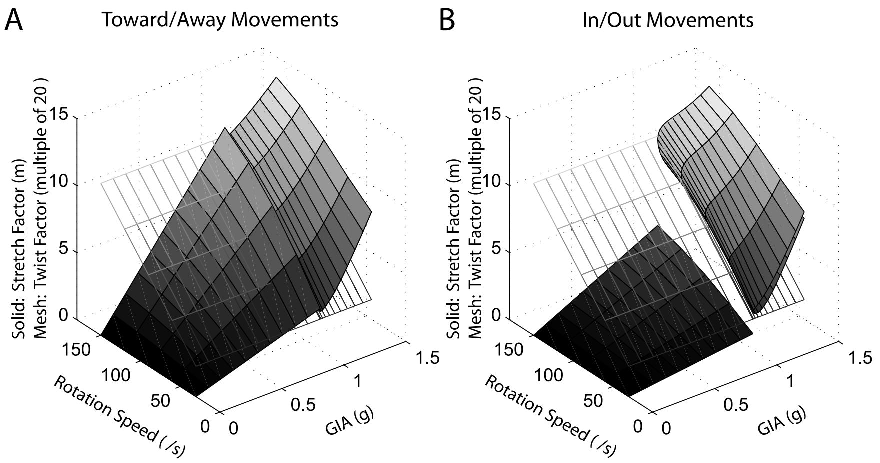

Fig. 5. Stretch and Twist Factors as functions of rotation speed and GIA. The solid surfaces show the same Stretch Factor data displayed in Fig. 4B and 4D. The mesh surfaces show the Twist Factor, scaled by a factor of 1/20° for ease of display on the same graph. The magnitudes of the Stretch and Twist Factors cannot be directly compared because their units of measure are different. Instead, the relative shapes and directions of slope are the relevant features of the graphs. (A) Results for head movements toward and away from the direction of motion. The right side of the solid graph has two close layers, for "1-g away" and "1-g toward" as in Fig. 4B; the underneath, hidden, layer corresponds to the dashed curves in Fig. 4B. (B) Results for head movements in and out from the centrifuge axis. The right side of the solid graph has two layers, for "1-g in" and "1-g out" movements as in Fig. 4D.

ments have greater Stretch Factor off-axis, while "1-g out" movements have smaller Stretch Factor off-axis. Further details of comparison with experimental data are in the Discussion.

4. Discussion

The potentially disorienting consequences of the physics of the three-dimensional stimuli from head movements are shown here to depend upon radius and rotation speed, as well as the direction of head movement. These disorienting effects as measured by the Stretch Factor are approximately proportional to the GIA, and differ depending on the direction of head movement. While the Twist Factor, as a measure of angular disorientation, can distinguish between motions with different rotation speeds, the Stretch Factor serves especially to distinguish between motions with identical rotation speeds. In 1-g, head rotation outward from the axis has the smallest Stretch Factor, while head rotation away from the direction of motion has greater Stretch Factor than head rotation toward the direction of motion. In 0-g, rotation inward/outward has smaller Stretch Factor than rotation toward/away. When different radii are considered, the GIA rather than the centripetal acceleration correlates best with the Stretch Factor across the set of all 0-g and 1-g conditions. In addition, for identical centripetal accelerations, the Stretch Factor decreases with radius, as does the Twist Factor. The Stretch Factor, along with the Twist Factor, gives a measure of the disorientating information from the stimulus itself, based upon the laws of physics, including all linear-angular interactions in three-dimensions.

The measures presented here are grounded in the laws of physics in the same way that classical analyses of misperception of self-motion are based upon physics, and these measures have been found to align with subjective perceptual disturbances in the forms of misperceived motion and motion sickness. Past research has shown that the Stretch Factor agrees with subjective reports [15] upon head movements during accelerating and decelerating rotation [24], with subjective reports [25] when tilting about a long or short tilt arm [24], with subjective reports [11,12,28] in 0-g [23], and subjective reports [18] upon clockwise versus counterclockwise head movements [23]. The latter two results are elaborated upon in the present research, with comparison between 0-g and 1-g apparent in Figs 3 and 4, and comparison between clockwise and counterclockwise head movements displayed as head rotation "toward" and "away" from the direction of motion, also in Figs 3 and 4. The resulting physics-based differences between "toward" and "away" show that rightward and leftward head yaw head movements are physically asymmetric when the body axis is aligned radially in a rotating centrifuge, indicating that experiments must control for head movement direction.

An additional comparison was performed here, with experimental results for head movements inward and outward from the rotation axis. Experimentally, motion sickness ratings have been found to be most often greater off-axis than on-axis for pitch head movements inward, but usually less off-axis than on-axis for pitch head movements outward [39]. Subjects always faced away from the axis in the off-axis experimental condition, so the outward rotations were always pitch-down and the inward rotations were always pitch-up. Therefore, to compare with the present modeling results, pitch-down movements on-versus-off axis were compared separately from pitch-up movements on-versus-off axis. (An experimental finding that pitch-down movements were generally more provocative than pitch-up movements cannot be explained by the physics, and may be a physiological effect due to a physiological asymmetry.) The off-axis centripetal acceleration in the experiment was 0.084 g, with a 60°/s rotation at 0.75 m radius. Therefore, the relevant curves in Fig. 4C are the 60°/s curves for "1-g out" and "1-g in" at centripetal accelerations of 0 g and approximately 0.1 g. Observation of the data in Fig. 4C shows that the Stretch Factor matches the experimental results on motion sickness ratings, of an increase off-axis for inward head movements (pitch-up in the experiment) and a decrease off-axis for outward head movements (pitch-down in the experiment). In other words, the predictions of the model match the experimental findings. Interestingly, when the experimental analysis combined both directions of head movement, a statistically significant difference was not found on- versus off-axis [39]; from a physics standpoint, combining both directions of head movement is equivalent to averaging the lower and higher curves, "1-g out" and "1-g in" in Fig. 4C. In summary, once again, the head movement direction is found to matter, as hinted by experimental results and as shown by the laws of physics as investigated here.

4.1. Zero-g

Predicted for 0-g is an increase in perceptual disturbances with increasing radius, independent of rotation speed. The centripetal acceleration, or GIA, is the crucial factor, with the Stretch Factor doubling when centripetal acceleration increases from 0.5 g to 1.0 g. This result gives additional insight into parameters relevant for artificial gravity. While rotation speed is often thought to be the relevant parameter when considering perceptual disturbances upon head movements, the present work shows that linear acceleration, or more specifically the magnitude of the GIA, is also likely to affect the magnitude of perceptual disturbances.

The radius effect is less likely to be discovered in 1-g experiments. The GIA has been found here to be the most relevant linear factor, but the magnitude of the GIA, as compared to the centripetal acceleration, changes less significantly with radius in 1-g than in 0-g. Therefore, when considering perceptual disturbances as a function of radius, experimental results from a 1-g environment do not apply directly to a 0-g environment. This fact is illustrated in Fig. 4A, where the 1-g curves showing Stretch Factor as a function of centripetal acceleration are relatively flat compared to the 0-g curves, especially for centripetal accelerations of 0.5 g or less. To experimentally discover in 1-g the effects predicted for 0-g, much greater centripetal accelerations would be required.

4.2. Meaning of the Twist and Stretch Factors

The Twist and Stretch Factors are objective physics-based measures of the stimulus. They allow the investigation of complex motions in the same way that simple motions are typically investigated: a larger magnitude stimulus typically produces a larger magnitude perceptual effect. Technically, the Twist and Stretch Factors measure the amount of "unexpected" perceived motion by a perfect processor of acceleration information. An example of unexpected motion would be the pitch stimulus originating from cross-coupling upon head roll during upright on-axis rotation; the nervous system does not expect to receive a pitch stimulus upon head roll. One interpretation of the Twist and Stretch Factors is of sensory conflict: Upon head movement, the linear acceleration and (zero) angular acceleration stimuli to the trunk remain constant, while neck proprioception indicates that the head is rotating relative to the trunk; however, the linear and angular sensors in the head indicate that the head is moving in a completely different direction than that given by the trunk-neck system. In other words, there is a vestibular-proprioceptive sensory conflict. Thus, the Twist and Stretch Factors can be interpreted as measuring the amount of purely physics-induced vestibular-proprioceptive conflict.

The sensory-conflict concept is consistent with that of other models of motion sickness [1,3,36]. The main difference is that the present results are based solely upon measures of the physics of the stimulus, and hold regardless of the values of physiological time constants in other models. However, even other models use the laws of physics as a necessary foundation. The vertical vector (e.g. [1,3,4]), for one, is of the same type as that from the subject orientation in the present model, and can be seen to rotate during centrifuge deceleration, for example, whether the model includes physiological parameters [4] or not [21].

In the present work, the Twist and Stretch Factors cover all directions of motion in three dimensions. It is entirely possible that such measures could be refined further with respect to specific predictions, e.g. for motion sickness, by a giving a weighted measure of the Twist and Stretch Factors that might also depend upon the direction of motion. Here, the measures are unweighted to reflect the physics of the motion. As such, these measures have been found to agree with the relative perceptual disturbances for head movements during rotation in the experimentally tested environments. These results accomplish the scientific goal of Occam's Razor, to give the most straightforward explanation possible for phenomena.

Because the present research focuses on the immediate effects of the stimulus itself, physiological time constants are not necessary in the simulations, but the question may still arise whether the addition of well-known physiological properties could affect the results. One established property is that the perception of angular velocity reduces over time, after an angular acceleration stimulus. Similarly, the perception of linear velocity reduces over time after a linear acceleration stimulus. In addition, the perception of orientation changes in such a way that the GIA is interpreted as the direction of vertical. Each of these properties can be described by time constants implemented by transfer functions, in terms of differential equations, or by feedback loops in three-dimensional models [2,4,8,9,17,24,27,30–33,37, 38,40]. The results of the present paper were additionally tested by inclusion of these time constants in the model. Used were time constants of 20 s, 0.5 s, and 5 s for angular, linear, and tilt, respectively, as described above. The Twist and Stretch Factors were again calculated at the 2 s point, i.e. as cumulative measures over the 1 s head movement plus 1 s subsequent to the movement, for all of the gravitational, head-direction, rotation speed, and centripetal acceleration conditions. The outcome upon inclusion of time constants was a reduction in the Twist and Stretch Factors across all conditions. This reduction is not surprising considering that the angular and linear time constants have the effect of reducing the modeled perceived velocity and thereby the Twist and Stretch Factors (which, in effect, model the consequences of subjects' nonveridical perception of the initial conditions). The more relevant outcome for the present research was that the relative values in comparing conditions showed exactly the same patterns as with pure physics. In other words, physiological factors did not change any of the results.

4.3. Implications for experimental research

The most obvious implications for experimental research are the need to control for head-movement direction, and the identification of a likely GIA effect. While several experimental results confirm that subject reports align with the modeling results, additional experimental research could assess the relationship between subject reports and the modeling results for a wider range of parameter values, especially for different radii. Again, 1-g experiments would not be expected to give perceptual differences as strong as those predicted for 0-g, but the trends could be tested in 1-g if the chosen ranges of parameters are wide enough.

One set of conditions suggested by the present results for experimental testing is that of a range of different radii for a fixed rotation speed. Such experiments in 1-g could help tune the predictions for 0-g, keeping in mind that *GIA*, not centripetal acceleration, has been found to be the relevant factor in the physics of the motion. In 1-g, the range of radii would have to be large enough to give a wide range of GIA, e.g. 1.0–1.4 g as indicated in Fig. 4B and 4D, not just a range of centripetal acceleration. In addition, similar head movement directions would need to be compared, as is clear from Fig. 4.

Also open to experimental investigation is the issue of perceptual scaling of $\vec{g}$ according to the gravitational environment. The current model uses scaling based upon an evaluation of existing research, but existing research is sparse, and further experimental research would allow the modeling to be further tuned. For the 1-g environment, the model currently uses a magnitude of 1g for the nervous system's understanding of gravity. This is the most natural assumption, but must be used with care. For example, it is known that during constant velocity centrifugation, subjects do not typically report linear motion, despite the greater-than-1g GIA. In isolation, this fact might seem to imply that the nervous system scales its interpretation of $\vec{g}$. However, further research has shown that upon subsequent motion, the nervous system seems *not* to scale its interpretation of $\vec{g}$, an implication of studies that include subject reports of ascent upon centrifuge deceleration [16] and greater cross-coupling effects in a greater-than-1-g environment [7,28]. Because the current research is on "subsequent" head movements rather than steady-state conditions, the 1g magnitude is used in the model for the 1-g environment. Additional studies could strengthen our understanding of the nervous system's treatment of a GIA greater than 1g. At the same time, for the 0-g environment, the model currently scales the interpretation of gravity to match the direction and magnitude of the GIA. This choice is based upon a trend beginning over the first couple of weeks in a 0-g environment [5, 35]. In a sense, subjects may begin to use the GIA in a centrifuge as a gravity vector. In addition, evidence for magnitude scaling comes from previous modeling and experimental results that explain the 0-g versus 1-g differences in coriolis cross-coupling effects on-axis [11, 12,23,28].

4.4. Conclusion

To understand the physics of complex stimuli, three-dimensional modeling is required. Such modeling can help lead to interpretation of experimental results, and can make predictions about environments that are difficult to examine experimentally. Reciprocally, experimental results feed into modeling research. With interplay between experimental work and modeling research, scientists can accomplish the best prediction and understanding of the 0-g environment.

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References

[1] W. Bles, Coriolis effects and motion sickness modelling, *Brain Research Bulletin* **47** (1998), 543–549.
[2] J. Borah, L.R. Young and R.E. Curry, Optimal estimator model for human spatial orientation, *Annals of the New York Academy of Sciences* **545** (1988), 51–73.
[3] J.E. Bos and W. Bles, Modelling motion sickness and subjective vertical mismatch detailed for vertical motions, *Brain Research Bulletin* **47** (1998), 537–542.
[4] J.E. Bos and W. Bles, Theoretical considerations on canal-otolith interaction and an observer model, *Biological Cybernetics* **86** (2002), 191–207.
[5] G. Clément, S.T. Moore, T. Raphan and B. Cohen, Perception of tilt (somatogravic illusion) in response to sustained linear acceleration during space flight, *Experimental Brain Research* **138** (2001), 410–418.
[6] I.S. Curthoys, The delay of the oculogravic illusion, *Brain Research Bulletin* **40** (1996), 407–412.
[7] P. DiZio, J.R. Lackner and J.N. Evanoff, The influence of gravitoinertial force level on oculomotor and perceptual responses to coriolis, cross-coupling stimulation, *Aviation, Space, and Environmental Medicine* **58** (1987), A218–A223.
[8] J. Droulez and C. Darlot, The geometric and dynamic implications of the coherence constraints in three-dimensional sensorimotor interactions, in: *Attention and Performance,* M. Jeannerod, ed., Lawrence Erlbaum, Hillsdale, NJ, 1989, pp. 495–526.
[9] S. Glasauer and D.M. Merfeld, Modelling three-dimensional vestibular responses during complex motion stimulation, in: *Three-dimensional Kinematics of Eye, Head and Limb Movements,* M. Fetter, T. Haslwanter, H. Misslich and D. Tweed, eds, Harwood, Reading, 1997, pp. 387–398.
[10] A. Graybiel and R.H. Brown, The delay in visual reorientation following exposure to a change in direction of resultant force on a human centrifuge, *The Journal of General Psychology* **45** (1951), 143–150.
[11] A. Graybiel, E.F. Miller II and J.L. Homick, Individual differences in susceptibility to motion sickness among six Skylab astronauts, *Acta Astronautica* **2** (1975), 155–174.
[12] A. Graybiel, E.F. Miller and J.L. Homick, Experiment M131. Human vestibular function, in: *Biomedical Results from Skylab,* (Section II), R.S. Johnston and L.F. Dietlein, eds, NASA SP-377, US Government Printing Office, 1977, pp. 74–103.
[13] J.J. Groen, The problems of the spinning top applied to the semi-circular canals, *Confin Neurol* **21** (1961), 454–455.
[14] F.E. Guedry, Jr., Psychophysics of vestibular sensation, in: *Handbook of Sensory Physiology,* Volume VI, H.H. Kornhuber, ed., Springer, Berlin, 1974, pp. 3–154.
[15] F.E. Guedry Jr. and A.J. Benson, Coriolis cross-coupling effects: disorienting and nauseogenic or not? *Aviation, Space, and Environmental Medicine* **49** (1978), 29–35.
[16] F.E. Guedry, A.H. Rupert, B.J. McGrath and C.M. Oman, The dynamics of spatial orientation during complex and changing linear and angular acceleration, *Journal of Vestibular Research* **2** (1992), 259–283.
[17] T. Haslwanter, R. Jaeger, S. Mayr and M. Fetter, Three-dimensional eye-movement responses to off-vertical axis rotations in humans, *Experimental Brain Research* **134** (2000), 96–106.
[18] H. Hecht, J. Kavelaars, C.C. Cheung and L.R. Young, Orientation illusions and heart-rate changes during short-radius centrifugation, *Journal of Vestibular Research* **11** (2001), 115–127.
[19] W.C. Hixson, J.I. Niven and M.J. Correia, *Kinematics Nomenclature for Physiological Accelerations,* Monograph 14. Pensacola, Naval Aerospace Medical Institute, Florida, 1966.
[20] J.E. Holly, Subject-coincident coordinate systems and sustained motions, *International Journal of Theoretical Physics* **35** (1996), 445–473.
[21] J.E. Holly, Three-dimensional baselines for perceived self-motion during acceleration and deceleration in a centrifuge, *Journal of Vestibular Research* **7** (1997), 45–61.
[22] J.E. Holly, Baselines for three-dimensional perception of combined linear and angular self-motion with changing rotational axis, *Journal of Vestibular Research* **10** (2000), 163–178.
[23] J.E. Holly, Perceptual disturbances predicted in zero-g through three-dimensional modeling, *Journal of Vestibular Research* **13** (2003), 173–186.

[24] J.E. Holly, Vestibular coriolis effect differences modeled with three-dimensional linear-angular interactions, *Journal of Vestibular Research* **14** (2004), 443–460.

[25] N. Isu, M. Yanagihara, T. Mikuni and J. Koo, Coriolis effects are principally caused by gyroscopic angular acceleration, *Aviation, Space, and Environmental Medicine* **65** (1994), 627–631.

[26] N. Isu, M. Yanagihara, S. Yoneda, K. Hattori and J. Koo, The severity of nauseogenic effect of cross-coupled rotation is proportional to gyroscopic angular acceleration, *Aviation, Space, and Environmental Medicine* **67** (1996), 325–332.

[27] K. Kushiro, M. Dai, M. Kunin, S.B. Yakushin, B. Cohen and T. Raphan, Compensatory and orienting eye movements induced by off-vertical axis rotation (OVAR) in monkeys, *Journal of Neurophysiology* **88** (2002), 2445–2462.

[28] J.R. Lackner and A. Graybiel, The effective intensity of coriolis, cross-coupling stimulation is gravitoinertial force dependent: implications for space motion sickness, *Aviation, Space, and Environmental Medicine* **57** (1986), 229–235.

[29] G. Melvill Jones, Origin significance and amelioration of coriolis illusions from the semicircular canals: a non-mathematical appraisal, *Aerospace Medicine* **41** (1970), 483–490.

[30] D.M. Merfeld, Modeling human vestibular responses during eccentric rotation and off vertical axis rotation, *Acta Oto-Laryngologica,* **S520** (1995), 354–359.

[31] D.M. Merfeld, Modeling the vestibulo-ocular reflex of the squirrel monkey during eccentric rotation and roll tilt, *Experimental Brain Research* **106** (1995), 123–134.

[32] D.M. Merfeld, L.R. Young, C.M. Oman and M.J. Shelhamer, A multidimensional model of the effect of gravity on the spatial orientation of the monkey, *Journal of Vestibular Research* **3** (1993), 141–161.

[33] T. Mergner and S. Glasauer, A simple model of vestibular canal-otolith signal fusion, *Annals of the New York Academy of Sciences* **871** (1999), 430–434.

[34] H. Mittelstaedt, Somatic graviception, *Biological Psychology* **42** (1996), 53–74.

[35] S.T. Moore, G. Clément, M. Dai, T. Raphan, D. Solomon and B. Cohen, Ocular and perceptual responses to linear acceleration in microgravity: Alterations in otolith function on the COSMOS and Neurolab flights, *Journal of Vestibular Research* **13** (2003), 377–393.

[36] C.M. Oman, A heuristic mathematical model for the dynamics of sensory conflict and motion sickness, *Acta Oto-Laryngologica* **S392** (1982), 1–44.

[37] C.C. Ormsby and L.R. Young, Integration of semicircular canal and otolith information for multisensory orientation stimuli, *Mathematical Biosciences* **34** (1977), 1–21.

[38] G. Reymond, J. Droulez and A. Kemeny, Visuovestibular perception of self-motion modeled as a dynamic optimization process, *Biological Cybernetics* **87** (2002), 301–314.

[39] P.D. Woodman and M.J. Griffin, Effect of direction of head movement on motion sickness caused by coriolis stimulation, *Aviation, Space, and Environmental Medicine* **68** (1997), 93–98.

[40] L.H. Zupan, D.M. Merfeld and C. Darlot, Using sensory weighting to model the influence of canal, otolith and visual cues on spatial orientation and eye movements, *Biological Cybernetics* **86** (2002), 209–230.