THREE-DIMENSIONAL BASELINES FOR PERCEIVED SELF-MOTION DURING ACCELERATION AND DECELERATION IN A CENTRIFUGE

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Abstract — Three-dimensional motion trajectories were computed, representing the motions that would be perceived by a perfect processor of acceleration information during the acceleration and deceleration stages of a centrifuge run. These motions serve as “baselines” for perceived self-motion in a centrifuge, and depend on the initial perception of orientation and velocity immediately preceding the acceleration and immediately preceding the deceleration. The baselines show that a perfect processor of acceleration information perceives self-motion during centrifuge deceleration significantly differently from self-motion during centrifuge acceleration, despite the fact that the angular accelerations have equal magnitude (with opposite direction). At the same time, the baselines can be compared with subjects’ reported perceptions to highlight limitations of the nervous system; limitations and peculiarities of the nervous system are identified as deviations from a baseline. As a result, peculiarities of the nervous system are held responsible for any perception of pitch or roll angular velocity or change in tilt of the body-horizontal plane of motion during the centrifuge run. On the other hand, baselines explain perception of tilt position during deceleration, linear velocity, possible lack of significant linear velocity during deceleration, and yaw angular velocity, including on-axis angular velocity during centrifuge deceleration. The results lead to several experimental questions.

Introduction

A subject’s perceived self-motion does not always match the subject’s actual motion. However, many motion misperceptions by subjects in the dark are easily explained by the laws of physics, assuming that one takes into account the state of the vestibular system (or the perception) immediately prior to the motion of interest.

A simple example is that of (mis-)perceived clockwise rotation during deceleration from counterclockwise constant velocity on-axis rotation in the dark. First, it is well-known that a subject on a chair rotating at constant velocity in the dark will feel stationary despite the continuing rotation (reviewed in (1)), because over the long time scale of sustained rotation, the vestibular system has reached a steady state that lacks any indication of angular velocity. For the laws-of-physics analysis, the subject is replaced during constant velocity rotation by a perfect processor acceleration information that also has the perception of being stationary. Then if the constant velocity rotation is followed by deceleration (that is, oppositely directed acceleration) to a stop, the laws of physics predict that the processor will have a perception of rotating in the opposite direction (Figure 1). This prediction is based on two pieces of information: (i) the initial perception (in this case, of being stationary) and (ii) the succeeding acceleration (in this case, a clockwise yaw angular acceleration).
In effect, the perceived motion shown in Figure 1B resulting from the actual motion of Figure 1A, forms a “baseline” for our expectations. It is the motion that would be reported by a perfect processor of acceleration information, assuming that the processor begins with an initial perception of “stationary”. If a subject reports the motion shown in Figure 1B, we are not surprised (2). If a subject reports the motion shown in Figure 1B but with decreasing intensity, we use that decrease in intensity to draw conclusions about the nervous system’s time constants of decay of angular velocity perception (reviewed in (1)). If a subject reports a completely different motion from that shown in Figure 1B, we label the perception as an anomaly, at the least, and might even suspect a vestibular disorder.

$Laws of Physics in Three Dimensions$

For more complicated motions as well, it is possible to calculate the perception predicted by the laws of physics alone (that is, the motions that would be reported by a perfect processor of acceleration information, assuming that the processor begins with initial perception matching the subject’s), thus distinguishing those aspects of perception that are straightforward—predicted by the laws of physics—from those that are peculiar to the nervous system.

It is important for calculations in three dimensions to include (i) the fully three-dimensional initial perception, that is, perceived orientation relative to the earth, perceived angular velocity (possibly zero) in three dimensions, and perceived linear velocity (possibly zero) in three dimensions, and (ii) the succeeding forces and torques in three dimensions, as given by the angular acceleration and the resultant linear acceleration, which includes the “pseudo-acceleration” due to the gravitational field. The three-dimensional motion that would be reported by a perfect processor of acceleration information is completely determined by initial conditions (i) and accelerations (ii).

This point is worth emphasizing especially with regard to the resolution of actual linear acceleration and orientation relative to the earth. For a perfect processor of acceleration information, if the initial accelerations are resolved (which they are by (i)), then the accelerations continue to be resolved throughout the movement. Of course, Einstein’s Principle of Equivalence implies that a linear accelerometer cannot tell the difference between the effects of the earth’s gravitational field and an actual linear acceleration. This means that perceived linear acceleration cannot be unambiguously resolved into components representing orientation and actual acceleration, at least in certain cases: (1) a processor of acceleration information has not been given initial conditions (that include orientation) by an independent source, (2) the processor has been given initial conditions, but is not a perfect processor, as in the case of human perception that is initialized by vision but that does not perfectly integrate acceleration information in the dark, or (3) the processor has been given initial conditions but does not receive all six dimensions of acceleration information—all three of angular and all three of linear. The latter case would occur, for example, if a perfect processor of acceleration information were given initial conditions of “upright and stationary,” but were only given linear acceleration information, without the accompanying angular acceleration information. Any ensuing forward linear acceleration, for example, would be am-

Figure 1. Actual motion versus perceived motion predicted by the laws of physics, illustrated by the simple case of on-axis rotation with a vertical axis, top view. (A) Actual motion: rotating counterclockwise, then decelerating (= accelerating clockwise) to a stop. (B) Perceived motion: stationary, then accelerating into a clockwise rotation.
Three-Dimensional Baselines

ambiguous because without information about pitch acceleration (and thus calculated velocity and position), the processor would not detect whether the perceived linear acceleration was due to an actual forward acceleration or to a backward pitch motion possibly accompanied by actual acceleration.

On the other hand, full information in three dimensions about perceived resultant linear and angular acceleration, accompanied by initial conditions that include orientation, allows a perfect processor of acceleration information to keep orientation and actual linear acceleration resolved throughout the entire motion. Einstein’s Principle of Equivalence does not prevent the resolution of linear accelerations in this case.

The motion reported by a perfect processor of acceleration information matches the actual motion only if the initial perceived motion matches the initial actual motion. “Initial” refers the time immediately preceding the specific motion of interest, at which point the processor is given initial conditions matching a subject’s perception. Often, the specific motion of interest is immediately preceded by a non-stationary steady motion for which a subject’s (and therefore the processor’s initial) perception does not match the actual motion. This is the case in the example above (deceleration from constant velocity rotation), where perceived initial conditions are incorrect, so an incorrect motion—completely explained by the laws of physics—is reported.

Acceleration and Deceleration in a Centrifuge

The present paper focuses on acceleration and deceleration in a centrifuge, where linear and angular accelerations take place concurrently, raising a number of difficult issues (3). These motions are a prime candidate for application of theory because the availability of experimental data is at an early stage; a few studies have been done and many more are possible.

Intriguing perceptions of self-motion arise during acceleration and deceleration in a centrifuge (3,9–11). A striking result is that perceived self-motion during deceleration is quite different from that during acceleration, despite the fact that the angular accelerations have equal magnitude (with opposite direction). One difference occurs in perceived radius of turn: subjects report that the perceived axis of rotation is displaced from the body during acceleration but is near or through the body during deceleration (3,9). Subjects may also report tilt motion late in the acceleration but early in the deceleration (9). For a centrifuge run in which the carriage tilts to keep the resultant linear acceleration approximately aligned with the subject’s vertical axis, forward-facing subjects report significantly less pitch-up motion during acceleration than pitch-down motion during deceleration (11). The reasons for all of the differences in perceived motion are still under investigation.

Three-Dimensional Baselines

The approach taken in the present paper highlights the full motion predicted by the laws of physics, showing all degrees of freedom together in a three-dimensional display. Components are extracted when necessary. This contrasts with previous approaches that identify the vestibular endorgans directly involved and carry out calculations for only those sensors or idealizations of them. This second strategy works, for example, in the underlying calculation for Figure 1, using only an idealized semicircular canal in the horizontal plane, and is also used for idealized semicircular canals during the vestibular Coriolis (or “cross-coupling”) effect in which head pitch or roll movement during upright whole-body rotation causes a sensation of tumbling (4,5). However, interactions between linear and angular accelerations can be much more complicated.

A goal of the present research is to identify those perceptions that can be explained by the laws of physics alone. This approach applies Occam’s razor by first giving the most direct explanation for phenomena. As a consequence, peculiarities of the nervous system are also identified. This approach contrasts with modeling approaches that mix the laws of physics with the special properties of the vestibular and nervous systems (for example, 6–8). Because
motion during a centrifuge run has nontrivial interactions between angular and linear accelerations, our understanding of the ensuing perceptions can be aided by explicit knowledge of those perceptions that are fully explained by the laws of physics and those that are not.

Accelerations are incorporated into a baseline, which represents the motion that would be reported by a perfect processor of acceleration (or vestibular) information during the given motion, with specified initial "perceived" conditions. (Although velocity can be transduced by the vestibular system at certain frequencies, acceleration is the stimulus, and all vestibular information is contained in the acceleration information.) By computing baselines for perceived self-motion, three possibilities can result for each component, linear, angular, pitch, roll, and so forth, of the perception, when comparing with subject’s reports:

1. The subject’s perception is matched by the baseline that has initial conditions given by the subject’s initial perception. In this case, the perception is explained directly by the laws of physics.

2. The subject’s perception is matched by a baseline that has initial conditions differing from the subject’s initial perception. In this case, one possible explanation is that the subject’s perceived motion follows from an immediate change in initial perception at the beginning of the motion.

3. The subject’s perception is matched by no baseline for the motion. Since baselines are restricted to those motions mirroring the accelerations of the original motion, it is possible that no baseline matches the perception. In this case, the deviation of the perception from the baseline is identified as a physiological phenomenon open to further investigation.

The present paper establishes baselines for perceived motion during the acceleration and deceleration stages of a centrifuge run in which the human carriage (for example, chair) stays upright on the end of the centrifuge arm. This research leads, in addition, to future research on centrifuge runs in which the human carriage tilts to keep the resultant linear acceleration in the subject’s sagittal plane. Limitations or peculiarities of the nervous system can be identified as deviations from the baseline. Although certain deviations from the baseline might be said to arise from properties of sensor biomechanics, a well-designed nervous system could take into account the properties of the sensors. Therefore, deviations from the baseline are attributed to limitations of the nervous system. Baselines are given here as complete motions, trajectories of a body through space. In this way, the focus is on the full perceived motion of a subject, and motions are displayed graphically as such.

Methods

Motions computed were based upon those of a subject in a 6-m radius centrifuge accelerating counterclockwise to 57°/s (1 rad/s) in 5 s, and decelerating for 5 s to a stop after a period of sustained constant velocity (Figure 2). The subject was assumed to be upright and facing tangentially; however, all calculations presented in this paper hold for a subject in any position relative to the centrifuge arm. See Equations for exact details of the calculations described below.

For the acceleration stage of the centrifuge run, a baseline was computed as the trajectory of a body, with initial conditions given by the

Figure 2. The centrifuge set-up, top view. The subject faces tangentially, with counterclockwise rotation. Acceleration and deceleration are described in the text.
subject's presumed initial perception of being upright and stationary, and with succeeding accelerations equal to those encountered during the centrifuge acceleration. (Since the perceived initial conditions matched the subjects starting position exactly, the baseline matched the actual motion of the accelerating subject.) A perfect processor would register this baseline motion.

For the deceleration stage of the centrifuge run, several baselines were computed under alternative assumptions about the subject's perception of position and velocity preceding the deceleration. Three different alternatives for perception of roll tilt position were used: no tilt, "partial" tilt of 17° (0.3 rad), and "full" tilt of 32° (0.55 rad). Full tilt assumed that the subject perceived earth-upward as the direction of the initial resultant linear acceleration (Figure 3), as is commonly reported during the constant velocity portion of a centrifuge run (reviewed in (1)). Partial tilt assumed that the subject's nervous system interpreted the forces at the beginning of the deceleration as though vertical were tilted only partially toward the resultant acceleration from true vertical.

Two methods for computing perceived acceleration were used: with scaling and without scaling, as explained below. Baselines computed without scaling were computed in the usual way (that used for both the rotation example in the Introduction and the acceleration stage of the centrifuge run): each baseline was...
computed as the trajectory of a body with initial conditions given by the subject's assumed perception of position and velocity before the deceleration, and with succeeding accelerations equal to those encountered by the subject during deceleration of the centrifuge. A perfect processor would register this baseline, given these initial conditions and using the forces (or equivalently, accelerations) on the vestibular endorgans as a motion cue.

For the tilt conditions, baselines were also computed with "scaling" of the perceived resultant linear acceleration. Scaling was motivated by the fact that subjects do not typically report motion in the body's vertical direction prior to deceleration, despite the fact that the resultant linear acceleration (which subjects perceive as partially or completely earth-upward) has magnitude greater than \( g \) \((9.8 \text{ m/s}^2)\). In order for a subject to feel full \( (32^\circ) \) tilt without vertical motion prior to deceleration, the resultant acceleration must be interpreted by subjects as being the “pseudo-acceleration” arising from the presence of gravity. In order for a baseline to have initial conditions matching those of a subject, scaling of the perceived acceleration was necessary; for conditions of tilt, it was assumed that prior to deceleration subjects felt no motion in the body’s vertical direction. Therefore, to match this perception, baselines computed with scaling were computed as above except that linear accelerations were scaled by the factor \( \cos \phi \), where \( \phi \) was the angle of full or partial tilt.

Motion trajectories were calculated using a custom software package developed in C++ for equivalence analysis—the analysis of motions that are perceptually equivalent from the sensory standpoint of a moving subject (12)—using equations developed in (13). Graphics output was programmed in Mathematica (Wolfram Research, Inc., Champaign, Illinois, U.S.A.) and used display files created by the equivalence analysis package.

Global results about baselines were obtained by evaluation of the general mathematical form for the complete family of possible baselines under a given motion as well as by inspection of the individual baselines computed. In addition, the effects of parameter variation were tested by re-computing a baseline with variations in deceleration magnitude and centrifuge radius.

Equations

Calculations for each baseline used an earth-fixed reference frame given by the coordinate system oriented with the stated initial position. Considering the positive \( x \)-axis to be noseward, the positive \( y \)-axis to be leftward from the head, and the positive \( z \)-axis to be head-upward, two sets of calculations were carried out: one for the \( xy \)-plane projection of motion, and one for the \( z \) component of linear motion. In the equations, the following are used:

- \( r \) = radius of the centrifuge, in meters,
- \( \Omega \) = maximum angular velocity of the centrifuge, in rad/s,
- \( g \) = acceleration due to gravity of a free-falling body, in m/s\(^2\),
- \( T \) = total time of acceleration or deceleration, in seconds.
- \( \phi \) = roll tilt angle of initial conditions, in radians.

For the \( xy \)-plane projection calculations, the following two-dimensional vectors are used for linear motion, with pre-superscript \( E \) indicating earth-fixed reference frame:

- \( E_x \) = position, in meters,
- \( E_y \) = velocity, in m/s,
- \( E_a \) = acceleration, in m/s\(^2\),
- \( E_{ag} \) = pseudo-acceleration due to the presence of gravity, pointing away from the earth in m/s\(^2\),
- \( E_A \) = resultant linear acceleration, in m/s\(^2\).

Each of these vectors is a function of time \( t \). The counterclockwise angular position is given as an angle:

- \( \theta \) = angle of counterclockwise yaw rotation (initial angle = 0), in radians.

The angle \( \theta \) is a function of time \( t \).
Three-Dimensional Baselines

For the xy-plane components of the centrifuge acceleration baseline, the equations in (13) can be distilled to

\[ E_{\rightarrow x}(t) = \int_0^t E_{\rightarrow x}(\tau) \, d\tau \] (assuming initial position at the origin)

\[ E_{\rightarrow y}(t) = \int_0^t E_{\rightarrow y}(\tau) \, d\tau + E_{\rightarrow y}(0) \] (with \( E_{\rightarrow y}(0) \) given by initial conditions)

\[ E_{\rightarrow y}(0) = E_{\rightarrow y}(t) - E_{\rightarrow y}(0) \]

\[ E_{\rightarrow y}(t) = E_{\rightarrow y} A(t) - E_{\rightarrow y} (t) \]

\[ E_{\rightarrow y} A(t) = R(\theta(t) \ A(t)) \]

for \( 0 \leq t \leq T \), where

\[ R(\theta(t)) = \begin{pmatrix} \cos \theta(t) & -\sin \theta(t) \\ \sin \theta(t) & \cos \theta(t) \end{pmatrix} \]

\[ E_{\rightarrow y} A(t) = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \]

\[ \theta(t) = \frac{\Omega t^2}{2T} \]

and \( \overset{h}{A}(t) \), with pre-superscript \( \overset{h}{} \) indicating head-coincident coordinates (13), given by

\[ \overset{h}{A}(t) = \begin{pmatrix} \frac{-\Omega r}{T} \\ \frac{\Omega r}{T} \frac{\cos \phi}{1 - \frac{t^2}{T}} \end{pmatrix} \]

The \( z \) component of linear position is given in baselines computed without scaling by double integration of the linear acceleration

\[ \overset{h}{A}(t) = \begin{pmatrix} \frac{-\Omega r}{T} \cos \phi \\ \frac{\Omega r}{T} \cos \phi \left(1 - \frac{t^2}{T}\right) \end{pmatrix} \]

In baselines computed with scaling, the gravity vector \( g \) scaled by the factor \( \cos \phi \) cancels the resultant acceleration \( g \cos \phi \) in the \( z \) direction, so the \( z \) component of linear position is constant, at zero.

Terminology

In certain cases, the distinction between "velocity" and "change in position" is important. For example, an individual can change pitch position from 45° downward (forward) pitch position to 45° upward (backward) pitch position without experiencing any pitch angular velocity—by rotating 180° in yaw. No pitch velocity is necessary to accomplish a change in pitch position. For this reason, the specific terms "position" and "velocity" are used whenever the more general term "rotation" would be ambiguous.

For subject reports of perceived motion, general terms such as "rotation" and "motion" are necessary because the experiments were not specifically designed to distinguish between perception of velocity and perception of change in position. This topic is discussed later in relation to the findings of the present research.

Results

Most of the results concern the deceleration stage of the centrifuge run; calculations for the and on scaling as follows. For calculations without scaling,

\[ \overset{h}{A}(t) = \begin{pmatrix} \frac{-\Omega r}{T} \\ \frac{\Omega r}{T} \frac{\cos \phi}{1 - \frac{t^2}{T}} \end{pmatrix} \]

and for calculations with scaling,

\[ \overset{h}{A}(t) = \begin{pmatrix} \frac{-\Omega r}{T} \cos \phi \\ \frac{\Omega r}{T} \cos \phi \left(1 - \frac{t^2}{T}\right) \end{pmatrix} \]
acceleration stage are straightforward. Figure 4 displays the computed actual motion of a subject during acceleration and deceleration of the centrifuge. For acceleration, the computed baseline for perception was equal to the subject's actual motion (Figure 4A) because the perceived initial position, upright and stationary, matched the subject's actual position. A perfect processor would report this motion.

The baseline for perception during centrifuge deceleration depended on the subject's assumed perception of position and velocity preceding the deceleration. For this reason, a set of baselines was developed to take into account different possible perceptions preceding the deceleration. Each baseline represented the motion registered by a perfect processor of acceleration information, whose initial conditions matched the initial perception of the subject. Because the acceleration information and initial conditions are fully three-dimensional, the trajectory—including orientation relative to the earth—is completely determined in three dimensions (as discussed in the Introduction).

The first baseline was computed with initial conditions given by the widely reported perception of being tilted during the constant velocity portion of a centrifuge run (reviewed in (1)). Perceived angle of tilt approximates the off-vertical angle of the resultant linear acceleration (Figure 3); presumably, the resultant linear acceleration is interpreted by the subject as a gravity signal and is perceived to be earth-vertical.

The resulting baseline with tilted initial position is shown in white in Figure 5A, computed using the scaling method to reflect the lack of head-upward velocity perception by subjects during the constant velocity portion of a centrifuge run. The top view in Figure 5A shows two separate motions: the acceleration baseline in gray and the deceleration baseline in white (with tilted initial conditions); each starts at position (0,0,0). The acceleration baseline, taken from Figure 4A, arcs forward and to the left, while the deceleration baseline slips to the right. The side view in Figure 5A shows the same two baselines, each starting at (0,0,0). The acceleration baseline moves to the left while the deceleration baseline moves diagonally down to the right.

The deceleration baseline displayed in white in Figure 5A is the perceived motion during centrifuge deceleration, as predicted by laws of physics alone, assuming that the initial perception is of full (32°) tilt and that perceptions of linear acceleration are scaled accordingly. The difference between the baselines for acceleration and deceleration is striking. Notable is that the deceleration baseline does not consist of movement about a radius in the manner of the acceleration baseline. In addition, the deceleration baseline includes rightward movement down a slope while rotating.

Figure 5B uses the same initial conditions of tilt as Figure 5A, but the trajectory was computed by the basic method without scaling. The resulting deceleration baseline, shown in white, includes rightward movement but not movement down a slope.

Alternative baselines arose from alternative assumptions about perception preceding the
Figures 5. Baselines for subject perception during centrifuge deceleration, shown in white, if the subject starts with a feeling of full (32°) tilt, displayed along with the baseline for acceleration in gray to compare. In each of (A) and (B), top and side views are shown, the starting position for each baseline is (0,0,0), the motion in gray arcing to the left is the acceleration baseline, and the motion in white progressing to the right is the deceleration baseline. In this figure and in Figures 6 and 7, polyhedra indicate the subject’s position every 0.5 s. (A) Baseline for deceleration in white, computed with scaling according to tilt. (B) Baseline for deceleration in white, computed without scaling. In both (A) and (B), the white polyhedra as shown in the side view are sloped at the same angle at each time step, indicating that there is neither roll nor pitch velocity. However, the roll and pitch tilt positions change with the orientation of the polyhedra, as seen from the top view in combination with the slope shown by the side view.

centrifuge deceleration. Since forces on the body preceding the deceleration do not exactly match the forces that would be experienced in a tilted position, additional sets of initial conditions were investigated. The nervous system’s interpretation of the initial forces could differ from that described above in a number of ways, including degree of tilt, magnitude of linear acceleration scaling, or sense of velocity.

Figure 6 displays motions in white computed with different assumptions about the nervous system’s interpretation of the conditions at the
start of the deceleration. In each part of Figure 6, the top view and side view include the acceleration baseline in gray from Figure 4A for comparison with the deceleration baseline displayed. Both the acceleration baseline and the deceleration baseline shown in each view start at (0,0,0).

Figures 6A and B assume initial perceived tilt of 17°, with and without scaling of linear acceleration, respectively. This reduced tilt would reflect a possible sudden shift in the nervous system’s interpretation of tilt position due to the stimulus at the start of the centrifuge deceleration. The resulting baselines shown in white in Figures 6A and B progress leftward, backward, and upward before curving rightward and, in Figure 6A, returning downward.

Figure 6C assumes no initial perception of tilt. The resulting deceleration baseline progresses considerably leftward while rotating.

Most significant from Figure 6 are the differences in lateral movement between Figure 5,
Three-Dimensional Baselines

Figure 7. Additional baselines for subject perception during centrifuge deceleration, shown in white, along with the acceleration baseline in gray (arching forward and to the left). Each motion starts at (0,0,0). (A) Same as in Figure 6A, but with initial forward velocity of 1.3 m/s. (B) Same as in (A) except without scaling. In both (A) and (B), the white polyhedra as shown in the side view are sloped at the same angle at each time step, indicating that there is neither roll nor pitch velocity. However, the roll and pitch tilt positions change with the orientation of the polyhedra, as seen from the top view in combination with the slope shown by the side view.

Figures 6A and B, and Figure 6C. The baselines of Figure 5 shown in white have mostly rightward movement, those of Figures 6A and B have much less lateral movement, and that of Figure 6C has substantial leftward movement. Also noteworthy is the variation in earth-vertical movement between conditions.

A pair of additional baselines is displayed in white in Figure 7. These two motions correspond to an initial perception of 17° tilt, as in Figures 6A and B, but with initial forward velocity of 1.3 m/s. One might argue that the nervous system of a subject moving in a centrifuge could be in a state that includes an unreported and unperceived impression of forward motion. While this issue is necessarily vague, such possibilities cannot be eliminated in the development of baselines for perception.

Global results on baselines for perception during centrifuge acceleration and deceleration include those summarized in Table 1, as well as additional observations based upon inspection of the mathematical form for the motion trajectories. Results obtained from the computed baselines were found to hold across the range of possible baselines:

<table>
<thead>
<tr>
<th>Type of movement</th>
<th>Does not</th>
<th>Does</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Yaw</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Yaw rotation</td>
<td>Yes, always clockwise</td>
<td>Yes, always clockwise</td>
</tr>
<tr>
<td>b. Change in yaw position</td>
<td>Yes, always clockwise</td>
<td></td>
</tr>
<tr>
<td>2. Roll</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Roll rotation</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>b. Change in roll position</td>
<td>Yes, if initial position is tilted</td>
<td>Yes, if initial position is tilted</td>
</tr>
<tr>
<td>3. Pitch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Pitch rotation</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>b. Change in pitch position</td>
<td>Yes, if initial position is tilted</td>
<td>Yes, if initial position is tilted</td>
</tr>
<tr>
<td>4. Lateral motion</td>
<td></td>
<td></td>
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<tr>
<td>5. Forward/backward motion</td>
<td></td>
<td></td>
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<tr>
<td>6. Body-vertical motion</td>
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</table>

Table 1. Global Results on Baselines for Perception During Deceleration

Baselines include the type of movement (yes/no/details) if the initial state of the nervous system "does not"/"does" include an impression of linear velocity:
(1) No deceleration baseline is the mirror image of the acceleration baseline.

For deceleration:

(2) The overwhelming majority of possible baselines exclude angular velocity about a fixed radius.
(3) On-axis angular velocity is approximated by certain basic baselines (such as those shown in Figure 7).
(4) Any direction of linear velocity as well as both small and large linear excursions can occur in a baseline, depending on which assumption is followed about the nervous system's initial state.
(5) The smallest linear excursion occurs in those baselines that assume initial position of partial tilt. The resulting linear movement is then significantly less than in the acceleration baseline for 5 s of motion.

These results identify both (a) perceptual phenomena that are explained by the laws of physics, those matching (1) through (5) and Table 1, and (b) perceptual phenomena that are peculiar to the physiology, those not matching the baselines.

Finally, the effect of parameter variation on a basic baseline was tested. As shown in Figure 8, changing the magnitude of deceleration changed the linear excursion and speed of rotation, but did not change the general direction of motion of the baseline tested (that of Figure 5A). In addition, baselines for centrifuges of different radii were similar to that for a 6-m radius centrifuge, with the only differences occurring in the linear components of motion: smaller radii centrifuges had baselines progressing more forward, but with less total linear excursion. The baselines all rotated clockwise and moved rightward:

**Discussion**

The present research shows that fundamental laws—the laws of physics—suffice to predict and explain that perceived self-motion during centrifuge deceleration differs significantly from that during centrifuge acceleration, despite the fact that the angular acceleration profiles are identical. In other words, no peculiarities of the nervous system need to be hypothesized in order to explain an acceleration–deceleration difference, other than habituation to constant-velocity rotation. However, perceived self-motion may include components that indicate peculiarities of the nervous system, and the present techniques help identify those components. The
form of self-motion reported by a perfect processor of acceleration information is illuminated by the three-dimensional display of motion, incorporating all components (x, y, and z) of both linear and angular motion. Each three-dimensional motion displayed represents a "baseline", a possible perceived motion as predicted by the laws of physics, and perceptions differing from the baseline arise from limitations or peculiarities of the nervous system. A perfect processor would register motion matching a baseline, assuming that it used forces (or equivalently, accelerations) on the vestibular end-organs as a motion cue and that its initial perception matched the subject's initial perception. Thus, results about the physiology can be identified as deviations from the baseline. For 5 s of acceleration in a centrifuge, a single baseline was computed, matching the subject's actual motion because the initial perception of position was assumed to be accurate. For 5 s of deceleration in a centrifuge, several different baselines were computed under different assumptions about the initial perception of position and velocity.

Comparison with Experimental Data

The present results agree with the experimental finding that acceleration and deceleration are perceived differently by subjects (3,9,11). Because the availability of subject reports is at an early stage, the present work will help to interpret future reports of perceived self-motion in a centrifuge. Known perceptions include those of a clockwise turn with the axis of rotation away from the body during acceleration, but with the axis of counterclockwise motion near or through the body during deceleration (3,9). Centrifugal tilt change is reported during acceleration, with tilt returning to vertical during deceleration (9). However, the exact time course of tilt perception was not reported in (9), so it cannot be compared to the 5 s of motion studied here. Although perception of pitch motion is reported in (10) and (11), those studies use different variations of centrifuge motion. Cohen, Crosbie, and Blackburn (10) follow acceleration immediately by deceleration while the subject's carriage also rotates, on-axis with a vertical axis, on the centrifuge arm. Guedry, Rupert, McGrath, and Oman (11) have the subject's carriage swing on the centrifuge arm in order to keep the resultant linear acceleration approximately aligned with the subject's rostro-caudal axis.

The experimental results of most relevance here are those in which the centrifuge has a human carriage that is fixed upright. For such a centrifuge, subjects report off-axis rotation during acceleration and near- or on-axis rotation during deceleration (3,9). This component of the computed baseline for acceleration (Figure 4A) is consistent with subjects' reports because it shows off-axis rotation, using initial conditions given by the subjects' initial perception. The deceleration perception of off-axis rotation is explained directly by the laws of physics.

On the other hand, the deceleration perception is not matched by the baselines (Figures 5A and B) that have initial conditions given by the subjects' reported initial perception, which leads to the question: Is near- or on-axis rotation perception matched by any deceleration baseline? The answer is "yes", the baseline in Figure 7A approximates on-axis rotation. As discussed in the Introduction, this means that one possible explanation for the perception is that there occurred an immediate change in initial perception at the beginning of the motion. One principle of self-motion perception is that the initial perceived motion profoundly affects the ensuing perception during complex motion (14). In this case, the beginning of the motion would have been accompanied by the immediate perception of a 1.3-m/s forward velocity and a 17° tilt position.

Change in centrifugal tilt is also reported during both acceleration and deceleration (9). For acceleration, neither roll velocity nor change in roll tilt position are matched by a baseline, meaning that a phenomenon particular to the physiology is responsible; a perfect processor of acceleration information would use all dimensions of information, including that from the vertical semicircular canals, to detect that no roll movement has occurred. For deceleration, on the other hand, a change in roll tilt position is matched by the baseline (Figure 5) that has ini-
tial conditions given by the subjects’ reported initial perception. In fact, change in roll tilt perception is matched by most baselines. Perceived change in roll tilt position during deceleration is explained directly by the laws of physics.

Interestingly, roll tilt velocity is not matched by any deceleration baseline. This raises the experimental issue of separating the two questions: What roll tilt positions do subjects report? What roll tilt velocities do subjects report? The laws of physics alone predict that during deceleration the roll velocity calculated from changes in reported roll tilt position will exceed the perceived roll velocity reported by the subject.

Components of Motion

Centrifuge deceleration has included subject reports of rotation and tilt; future studies are possible in which the subject’s task is to report magnitude and direction of pitch, lateral movement, body-vertical movement, or other components of motion. The present research not only serves to interpret existing reports, but is available to help analyze future reports. Explained by a baseline for perceived self-motion during deceleration of a centrifuge rotating counterclockwise are:

(a) clockwise angular velocity,
(b) in particular, clockwise angular velocity taking place approximately on-axis or while moving linearly,
(c) tilted position,
(d) possible linear velocity in a body-horizontal plane.

Not explained by a baseline for perceived self-motion during centrifuge deceleration are:

(a) pitch or roll angular velocity,
(b) change in tilt of the body-horizontal plane of motion,
(c) body-vertical velocity if the nervous system scales linear acceleration according to tilt.

These basic properties are unchanged by variation in centrifuge radius or magnitude of deceleration, although such variations may alter the direction and speed of motion in the baselines (Figure 8).

Scaling of linear acceleration was introduced into the baselines in order to match the initial conditions as reported by subjects, and baselines were computed in pairs: with scaling and without scaling. Scaling of linear acceleration reconciles the fact that subjects report no body-vertical velocity during constant velocity rotation with the fact that body-vertical velocity is required under the given resultant linear acceleration. Whether the nervous system suppresses a perception of body-vertical velocity by scaling down the sensed linear acceleration, as done for the baselines, is an open question. Perceptions that match baselines computed without scaling, such as those that include body-vertical velocity, would be evidence that the nervous system uses a different mechanism to suppress a vertical motion perception during constant velocity. Perceptions that match baselines computed with scaling would be evidence that the nervous system scales the sensed linear acceleration.

Experimental Questions Raised

The computation of baselines leads to a number of experimental questions. One has already been mentioned: To what extent do subjects report roll velocity during centrifuge deceleration? Evidence for decoupling of position and velocity perception already exists, for example, in the pitch plane (11).

Another experiment is suggested by the intriguing discrepancy in rightward linear motion between the basic (Figure 5) deceleration baselines and subjects’ reports (3,9) of near- or on-axis rotation. The baselines, and therefore the laws of physics, predict a report of velocity away from the centrifuge, so subjects’ reports lacking that velocity are surprising. However, a close inspection reveals that the rightward motion in each baseline is not due to rightward force, but is due to reduction in leftward force. Perhaps the nervous system fails to interpret reduction in force as an opposite acceleration. This possibility leads to experimental questions: If a subject were carried through the motion shown in white in Figure 5A, would the subject perceive rightward motion? Would the subject
have the same perception of on-axis rotation as during the centrifuge deceleration?

A simpler version of the experiment could involve rightward motion down a slope, without rotation. Would a tilted subject without visual or auditory cues who accelerates rightward down a slope by a continuous decrease in leftward force (as opposed to by a rightward or a lack of leftward force) report rightward velocity? The subject's awareness of the experimental conditions would, of course, need to be carefully controlled.

The baselines also suggest that other components of perceived motion are worth specifically investigating. In addition to body-vertical velocity, related to possible scaling as discussed above, other components include lateral velocity, forward or backward velocity, pitch velocity, and pitch position (Table 1).

An additional issue mentioned above is that of initial perception. The baseline of Figure 7A suggests the question: Just as the centrifuge deceleration is beginning, does a subject report forward velocity approximating 1.3 m/s and tilt position of approximately 17°? Practically speaking, it may or may not be possible for a subject to give a clear report of perception immediately as the deceleration begins.

**Further Research**

In addition to full perceptions of self-motion as displayed in three dimensions, eye movements can be addressed with the present approach. Since eye movements are already the focus of many vestibular models, this topic was not highlighted here. Nevertheless, baselines for eye movement can be extracted from the baselines for perception by assuming appropriate compensatory eye movement throughout the motion.

Torsional eye movement, for example, would be absent from every baseline for acceleration and deceleration in a centrifuge, assuming that the nervous system's initial state includes no initial impression of roll angular velocity. Therefore any torsional eye movement appearing during acceleration or deceleration would be due to an oddity of the nervous system, and would warrant further investigation.

A general statement of the present approach is that perceptions aligned with the baseline—
explained by the laws of physics—are not surprising. At the same time, deviations from the baseline might also fail to cause surprise, depending on the type of deviation. For simple motions, one currently expected deviation from baseline is decay of angular velocity perception during an extended period of rotation. A perfect processor acceleration information would register continuing rotation, but subjects are known to deviate from this baseline by reporting decreasing rotation. The deviation from baseline is determined by curves fit to experimental data and by models aimed to mirror the decay, both methods arriving at time constants indicating the speed of decay.

The baselines incorporate the laws of physics alone, in order to give the most direct explanation when possible for perceptual phenomena. For future research, after Occam’s razor gives basic (laws of physics) explanations for perceptual phenomena when possible, a next step would be to add time constants of decay and other properties one at a time. However, it is important to keep track, for any given motion, of the physically determined baseline motion onto which the new properties are being added. The computation of such baselines increases in difficulty with the complexity of the motion, but cannot be ignored.

Conclusion

In summary, the role of physics as a baseline for three-dimensional motion is made explicit, guiding our attention to features of the nervous system and leading to a number of experimental questions toward refining our understanding of the vestibular system: Does the nervous system fail, either partially or completely, to register decrease in force as an acceleration in the opposite direction? What does the nervous system do with the extra magnitude of resultant acceleration while feeling tilted during the constant velocity portion of the centrifuge run? If the nervous system simply adapts, scaling the magnitude down to that of gravity, then a subject carried through the rightward motion displayed in Figure 5A will have the same perception of motion as during a centrifuge deceleration. If, instead, the nervous system feels the tilted position as “suspicious”, then stimulation at the start of the deceleration might cause a jump in perception to one of less tilt; the subject might feel the same during centrifuge deceleration as during the motions shown in white in Figure 6A, 6B, or 7.

Another question that arises: Do different possibilities for direction of actual motion affect subjects’ interpretation of the resulting perception? Specific examples of motions that produce equivalent stimulation of the vestibular sensors are given in this paper, each with a different direction of movement. The motions shown in white in Figures 4B (centrifuge deceleration), 5B (rightward), 6B (curving backward and upward), and 7B (rotating while progressing upward) would be detected by the vestibular system as being exactly the same (assuming that the same initial sustained accelerations were used). If the carriage on the centrifuge arm could tilt and slide rightward, would a subject who was aware of such possibilities report rightward movement during the centrifuge deceleration? The clues provided by the vestibular system only give a range of possible motions from which the nervous system must choose a perception.

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