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Technical Report No. 116

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Do Visual Cues Influence the Perception of Earth Vertical?

Paul MacNeilage[1], *Daniel R. Berger*[2], *Markus von der Heyde*[2], *Martin S. Banks*[1] *& Heinrich H. Bülthoff*[2]

Abstract. Accurate perception of the direction of earth vertical can be achieved by sensing the direction of gravity in body coordinates. This is equivalent to knowing body orientation in world coordinates. There are a number of visual and non-visual cues we can use to estimate earth vertical relative to the body. Non-visual cues include the sensation of gravity and forces due to acceleration, and they can be measured by the somatosensory and vestibular systems. These systems cannot always tell us directly about the direction of gravity because they signal gravito-inertial (GI) force, which is the sum of all forces acting on the body at a given time. For example, if one is accelerating, the GI force is the sum of the force due to acceleration and the force due to gravity. In these situations, the direction of GI force does not indicate the direction of earth vertical, but visual cues may be used to resolve the ambiguity. We conducted an experiment in which the direction of GI force was manipulated by pitching observers (rotation about the body's x-axis) on a motion platform. Their task was to indicate the direction of earth vertical using a pointing device. In some conditions, no visual stimulus was presented. In other conditions, observers were presented with a visual scene depicting acceleration over a flat, textured ground plane. Two cues in the visual display contained information relevant to judging the direction of earth vertical: 1) the location and orientation of the horizon and 2) the rate of acceleration over the ground plane. We present a model of how these visual and non-visual cues might be used to generate an estimate of the direction of earth vertical. Observer responses are compared with the predictions of this model. Results suggest that under the conditions of the present experiment, visual cues had very little effect, and perception of earth vertical was estimated primarily on the basis of vestibular and somatosensory cues.

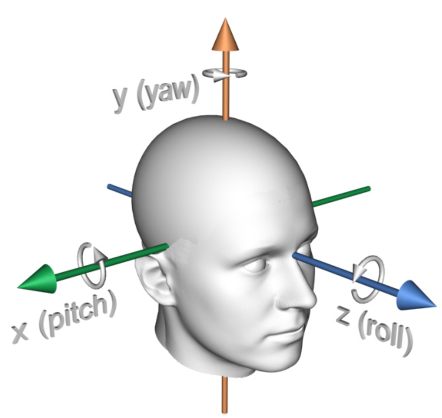

Figure 1: Axes of rotation. Depicted are the body coordinate axes used here and the names for rotations about these axes

1 Introduction

We can estimate the direction of earth vertical from the direction of gravity in body coordinates. This is equivalent to knowing our body orientation in world coordinates. Visual and non-visual cues are both relevant to estimating the direction of earth vertical. Non-visual cues include somatosensory and vestibular sensing of gravity and other inertial forces acting on the body.

The somatosensory system senses gravity through pressure sensitive receptors in the skin. These tell where the weight of the body is supported. The vestibular system senses gravity with the otolith organs in the inner ear. Gravity and acceleration forces are transduced by the hair cells of the otolith organs. These hair cells are covered by a jelly-like substance that contains dense calcium carbonate crystals, called otoliths (ear-stones). Sensory signals are generated when forces acting on the otoliths bend the hair cells. For a more detailed description see Kandel, Schwartz, & Jessell, 2000.

The somatosensory and vestibular systems signal the direction and magnitude of GI force, which is the sum of all forces acting on the body at a given time. Because GI force is the sum of such forces, an infinity of combinations of gravity and inertial acceleration give rise to the same direction and nearly the same magnitude of GI force. We are relatively insensitive to

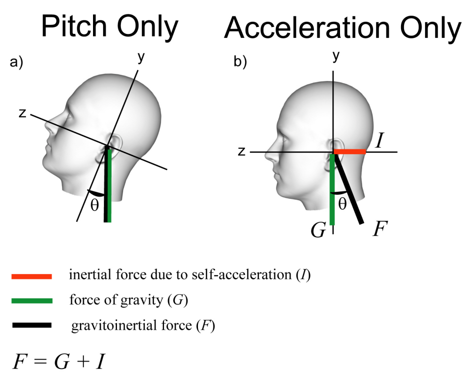

Figure 2: Two situations giving rise to the same direction of GI force relative to the body. This figure depicts two different situations which give rise to identical directions of GI force, despite different body orientations in world coordinates. The angle between the GI force direction and the body's y-axis is theta in both cases. In a) the observer is pitched backwards, while in b) the observer is upright and accelerating forwards. GI force (F) is the sum of gravity (G) and inertial forces due to acceleration (I): $F = G + I$ (all are vectors).

the magnitude of this force when asked to make judgements about the direction of gravity; centrifuge studies applying centripetal force with no visual cues have found that subjects indicate the direction of gravity to be in the direction of the resultant GI force vector, even when the magnitude of the resultant force is significantly greater than the force of gravity alone. This seems to be a prior assumption of the nervous system, that in the absence of visual cues, the direction of gravity is in the same direction as the sensed GI force. In situations where inertial forces other than gravity are present, humans cannot reliably recover the direction of gravity from somatosensory and vestibular signals alone. An illustration of this phenomenon is shown in figure 2.

Visual cues could allow one to disambiguate the somatosensory and vestibular signals. One useful cue for estimating body orientation in world coordinates is the location and orientation of the horizon in body coordinates. For an observer above a completely flat ground plane, earth vertical is perpendicular to the plane specified by the horizon and the observation point, so earth vertical can be determined directly from this horizon cue.

Optic flow is another visual cue that can be relevant to estimating the direction of earth vertical, because it can provide an estimate of inertial forces due to self-motion. Gibson, 1966 noted that direction of self-motion (heading) can be determined from the focus of expansion of the optic flow field. Velocity and acceleration of self-motion can also be determined from the flow field, given that the scale of the scene is known (Longuet-Higgins & Prazdny, 1980). A visual estimate of the magnitude and direction of self-acceleration in body coordinates could in principle be used to estimate the inertial component of GI force. Comparison of this estimate with the sensed GI force would yield an estimate of the remaining gravitational component, and thus an estimate of the direction of earth vertical. Several prior studies (e.g. Royden, Banks, & Crowell, 1992, Crowell, Banks, Shenoy, & Andersen, 1998) have found that visual and extra-retinal cues are combined in the context of self-motion perception, so this hypothesis is not unreasonable.

The aviation literature shows that the perception of earth vertical is subject to large illusions (Gillingham & Previc, 1993). One example is the somatogravic illusion (SG illusion), in which the pilot misperceives the pitch of the aircraft while accelerating: specifically, they perceive the pitch as more upward than it actually is when accelerating and as more downward than it actually is when decelerating. If the pilot attempts to correct for misperceived nose-up attitude, they may steer into the ground. The literature also shows that pilots are generally not subject to the illusion when they can see the ground; clearly visual cues are able to override the somatogravic illusion. It would be extremely valuable to know what visual cues are most effective at breaking the illusion. Such knowledge could be applied to the development of cockpit displays that could prevent pilots from experiencing the SG illusion by displaying appropriate visual cues.

Several prior studies have used the SG illusion to look at the effect of visual cues on the perception of earth vertical. In all of these studies, the direction and magnitude of the GI force was manipulated by placing subjects in a centrifuge. When subjects face the center of rotation, centripetal force due to rotation of the centrifuge alters the experienced GI force. When the subject's head is upright with respect to gravity, the centrifuge creates the same direction and magnitude of GI force as is experienced with upright head and forward acceleration (as occurs in a high-performance take-off). It also creates the same direction of GI force that is experienced with body pitched backwards while not accelerating. These situations are depicted in figure 2. The three studies discussed below presented a centripetal force that caused a rotation in the direction of the GI force equivalent to that experienced during backward pitch of 30 degrees.

Previc, Varner, & Gillingham, 1992 examined the effects of three visual cues: a horizon line, perspective lines in a ground plane, and texture flow in a ground

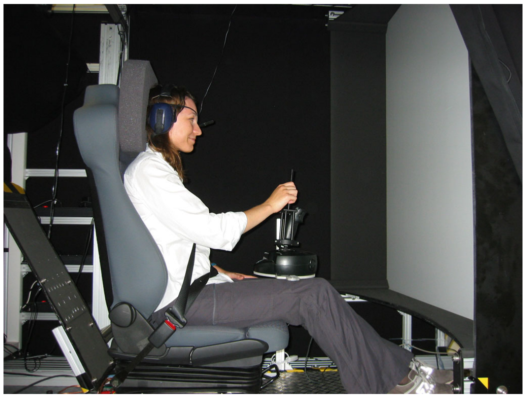

Figure 3: The experimental setup. Movement of the Stewart motion platform generates vestibular and somatosensory stimulation. Visual stimuli are generated by a projector mounted above and behind the observer. Both the projector and the screen are fixed to the platform and therefore fixed with respect to the observer.

plane. The observers' task was to indicate the direction of "down" using a pointer. In the dark, they misperceived the direction of earth vertical and pointed in the direction of the GI force (the vector sum of the gravitational and centrifugal forces). The main question of interest was which visual cues would cause a change in perceived earth vertical. Previc and colleagues found no effect of visual cues: responses with any or all of the visual cues present did not differ significantly from responses in the dark.

Lessard, Mathews, & Yauch, 2000 used the same task (pointing the direction of down). They tested pilots and non-pilots in the dark and in the presence of visual scenes depicting level accelerating flight over level terrain. The visual acceleration was consistent with the simulated inertial force generated by the centrifuge. The visual scenes allowed the pilots, but not non-pilots, to correctly perceive the direction of earth vertical (as evidenced by the fact that their pointing responses were unaffected by the centripetal acceleration). Stated another way, they were able to override the SG illusion with the addition of visual cues consistent with the inertial acceleration in the centrifuge. Lessard and colleagues could not determine which visual cues were responsible for the observed effect.

Tokumaru, Kaida, Ashida, Mizumoto, & Tatsuno, 1998 asked subjects to indicate the location of the "perceived" horizon. There were three conditions: no visual cues, a horizon line, and a constant velocity vection stimulus consisting of vertical lines moving laterally from the center of the screen. Tokumaru and colleagues found that responses were significantly less pitched relative to the no-visual-cues condition (that is, less subject to the SG illusion) when the horizon line, but not the vection stimulus, was present. This result is, however, not surprising because the task was to indicate the location of the horizon and perhaps subjects experienced a rotation of earth vertical, but performed correctly by simply indicating the location of the visible horizon. The failure to obtain a response due to the vection stimulus is also not surprising because their stimulus specified constant velocity rather than acceleration and, as we argued above, the rotation of the GI vector (figure 2) is caused by inertial acceleration.

Together, these centrifuge studies show that some visual cues can influence the perception of earth vertical in some subjects.

In the present study, our primary goal was to determine the effect of optic flow, a vection stimulus, on perception of earth vertical. We used a pure pitch stimulus to produce changes in the direction of the GI force. This is equivalent to the situation depicted in figure 2a, and differs from the centrifuge method described above. There is a small difference in the magnitude of the GI force vector in our technique compared with the centrifuge technique. In our technique, we rotate the GI force vector by pitching the subject; the GI acceleration remains $9.8\ m/sec^2$. With the centrifuge technique, the GI force becomes greater than $9.8\ m/sec^2$. However, this increase would not be detectible for the small deviations from vertical we used in this experiment (Gillingham & Previc, 1993); the two methods generate the same suprathreshold stimulation.

Six pitch angles were used. There were conditions with and without visual stimuli. The visual scene, when present, simulated forward acceleration (when the subject was pitched backwards) or backward acceleration (when the subject was pitched forwards) at a constant height over a textured ground plane. The vertical position of the horizon was constant, but the magnitude of the visually specified acceleration was systematically varied. The observers' task was to indicate the direction of perceived earth vertical by pointing a joystick.

As depicted in figure 2, the GI force vector (F) is the sum of gravitational force (G) and inertial forces due to acceleration (I). We are interested in how visual estimates (denoted by the subscript v) and non-visual or body estimates (denoted by subscript b) of F and I are used to estimate the direction of gravity (G). Non-visual or body estimates are obtained from the vestibular apparatus and somatosensory stimulation.

We assume that $F_b = G_b + I_b$, where F_b, G_b and I_b are vectors and are body estimates of GI force, gravity, and inertial forces due to acceleration, respectively. The variable of interest is G_b, so the above equation can be rewritten as $G_b = F_b - I_b$. The vestibular and somatosensory systems provide estimates of F_b, but not G_b or I_b. Therefore, one cannot determine G_b from vestibular and somatosensory information alone. However, the visual system can provide useful information from which the equation might be solved. The visual acceleration cue, which is the speed over time of the optic flow, indicates the inertial acceleration, I_v. A sensible system could substitute I_v for I_b, which yields $G_b = F_b - I_v$, and hence provides an estimate of the direction of G. The problem is that I_v cannot be measured directly from the optic flow alone because of the scale ambiguity of optic flow. The distance to a scene element and the observer speed through the scene can only be determined to within a scale factor (Longuet-Higgins & Prazdny, 1980). Because of this scale ambiguity, the absolute value of the acceleration can also not be determined directly from optic flow. The scale ambiguity can be resolved if the distance to at least one scene element is known; we will examine the importance of this in future research.

Another potentially useful visual cue is the horizon cue, which is the pitch of the visible horizon in body coordinates, and indicates the direction of earth vertical, G_v. In principle this cue could be used directly to determine the direction of G relative to the body. Thus, there is a variety of ways in which the nervous system could estimate the direction of G relative to the body.

First, if the vestibular and somatosensory systems could sense I_b and F_b independently, G could be estimated directly from these. This method can be mathematically expressed by the equation $G = F_b - I_b$.

However, because the nervous system does not provide an estimate of I_b, the solution to this formula is underdetermined. The fact that the SG illusion exists suggests strongly that the nervous system assumes that G is approximately equal to F_b when no other information (such as the visible horizon) is present:

$$G \approx F_b \tag{1}$$

This is true even if the magnitude of F_b differs significantly from the actual magnitude of G, as shown in centrifuge studies (e.g. Previc et al 1992).

Second, the nervous system could estimate G indirectly by using the acceleration specified by optic flow (I_v) as an estimate of the inertial acceleration I:

$$G = F_b - I_v \tag{2}$$

This method would be subject to error too because of the scale ambiguity of optic flow, which means that I_v cannot be determined directly unless the observer knows the scale of the 3d scene that created the optic flow.

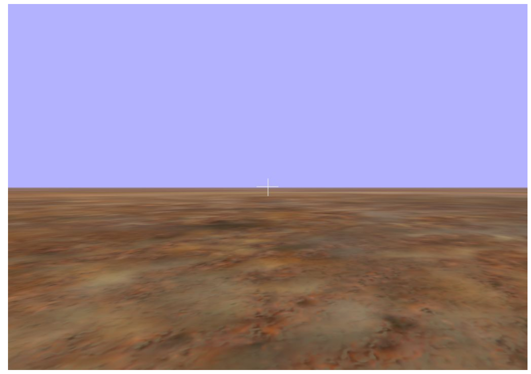

Figure 4: The visual stimulus. The ground plane was constructed using a texture of low-pass filtered random noise patterns, which were mipmapped and interpolated. This texture was duplicated at a number of scales and overlaid in transparency to produce a ground plane that contains a range of spatial frequencies (Berger, 2003).

Third, the nervous system could estimate the direction of G directly from the horizon by assuming it to be perpendicular to the plane specified by the horizon and the observation point. We define G_v as a vector with this direction and a magnitude equal to the known gravitational acceleration of $9.81\ m/s^2$. The estimate would then be:

$$G = G_v \tag{3}$$

This method would be subject to error if the horizon were not a true indicator of earth horizontal (and therefore earth vertical) which would occur with sloped terrain or perhaps with a simulated horizon.

All three methods might exist and might provide different estimates of G. In such cases, the nervous system should use a weighted average of the various estimates to provide the best overall estimate. If the weights were optimal (e.g., Ghahramani, Wolpert, & Jordan, 1997), the combined estimate would be statistically optimal. Thus,

$$G = w_1 F_b + w_2 (F_b - I_v) + w_3 G_v \tag{4}$$

$$w_1 + w_2 + w_3 = 1 \tag{5}$$

The weights in the second equation add to 1 so that the combined estimate is not a biased estimate of the true direction of G.

2 Methods

2.1 Equipment

Experiments were conducted in the Motion Lab (v. d. Heyde, 2001), a distributed virtual-reality envi-

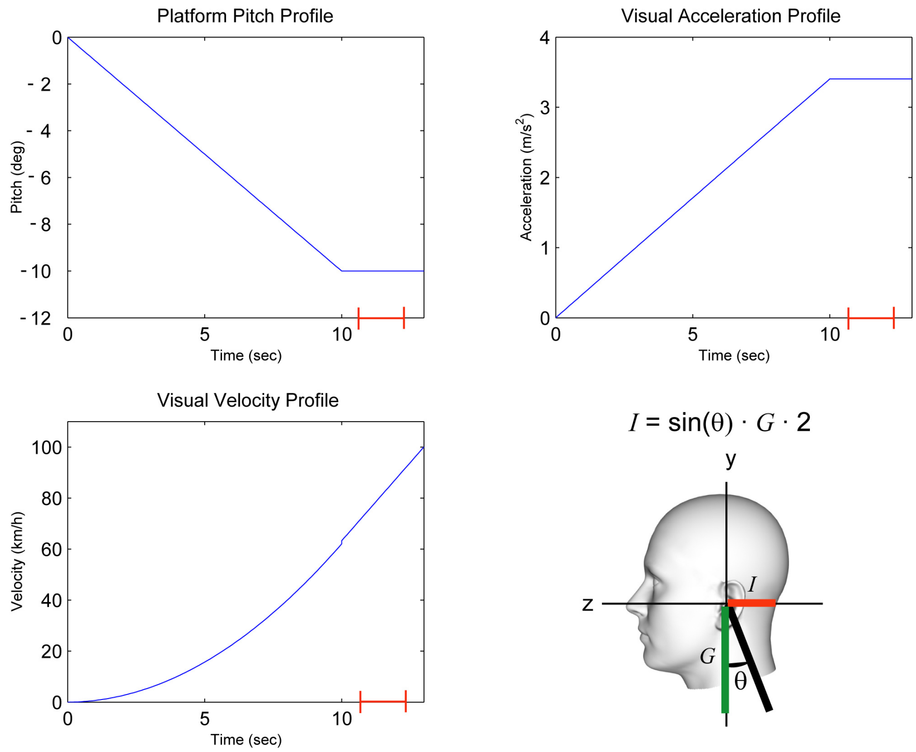

Figure 5: Sample pitch, acceleration, and velocity profiles. The upper left plot shows the pitch profile for a trial in which the platform moves to -10 degrees. The figure and equation in the lower right show how an instantaneous pitch angle θ can be used to derive a corresponding instantaneous inertial force due to acceleration, which we then double. The upper right and lower left plots show the acceleration and velocity profiles derived from the given pitch profile. The red brackets on the x-axes show the interval over which the joystick position was averaged to give the response value for that trial.

ronment that allows simultaneous presentation of stimuli to different senses (figure 3). The Motion Lab contains a six-legged, 6-DOF Stewart motion platform. Observers were seated in the chair on the motion platform with their seatbelt fastened. The visual stimulus was projected onto a flat screen in front of the observer from a projector mounted above the observer's head. The field of view was $86° \times 63°$. Observers wore noise-cancellation headphones to prevent them from hearing noises associated with platform movement; a headrest minimized head movements. The observer's task was to indicate the direction of perceived earth vertical using a joystick. The default position of the joystick was perpendicular to the floor of the platform. The joystick had force feedback, so that it returned to the default position when the subject did not apply force.

2.2 Stimuli

The vestibular/somatosensory stimuli were generated by rotating the platform forward or backward to one of six target pitch angles: -15, -10, -5, $+5$, $+10$, and $+15$ deg. The axis of rotation went through the center of the observer's head, so the pitch movements did not translate the head. On each trial, the platform was rotated from the upright position to the target pitch angle over 10 sec at a constant rate (0.5, 1, or 1.5 deg/sec depending on the target angle). The platform was kept at the target pitch angle for 3 sec, and then returned to the upright position over 15 sec, again at a constant rate (0.33, 0.66, or 1 deg/sec). We wanted to be sure that we did not stimulate the semi-circular canals because such stimulation would signal to the nervous system that the observer had been pitched rather than accelerated. The rotation rates were slow enough to remain below threshold for the semi-circular canals (Gillingham & Previc, 1993).

For half of the experimental conditions, we translated the platform in the forward or backward direction with the onset of the pitch movement. The translation was 50 cm with rapid acceleration and much slower

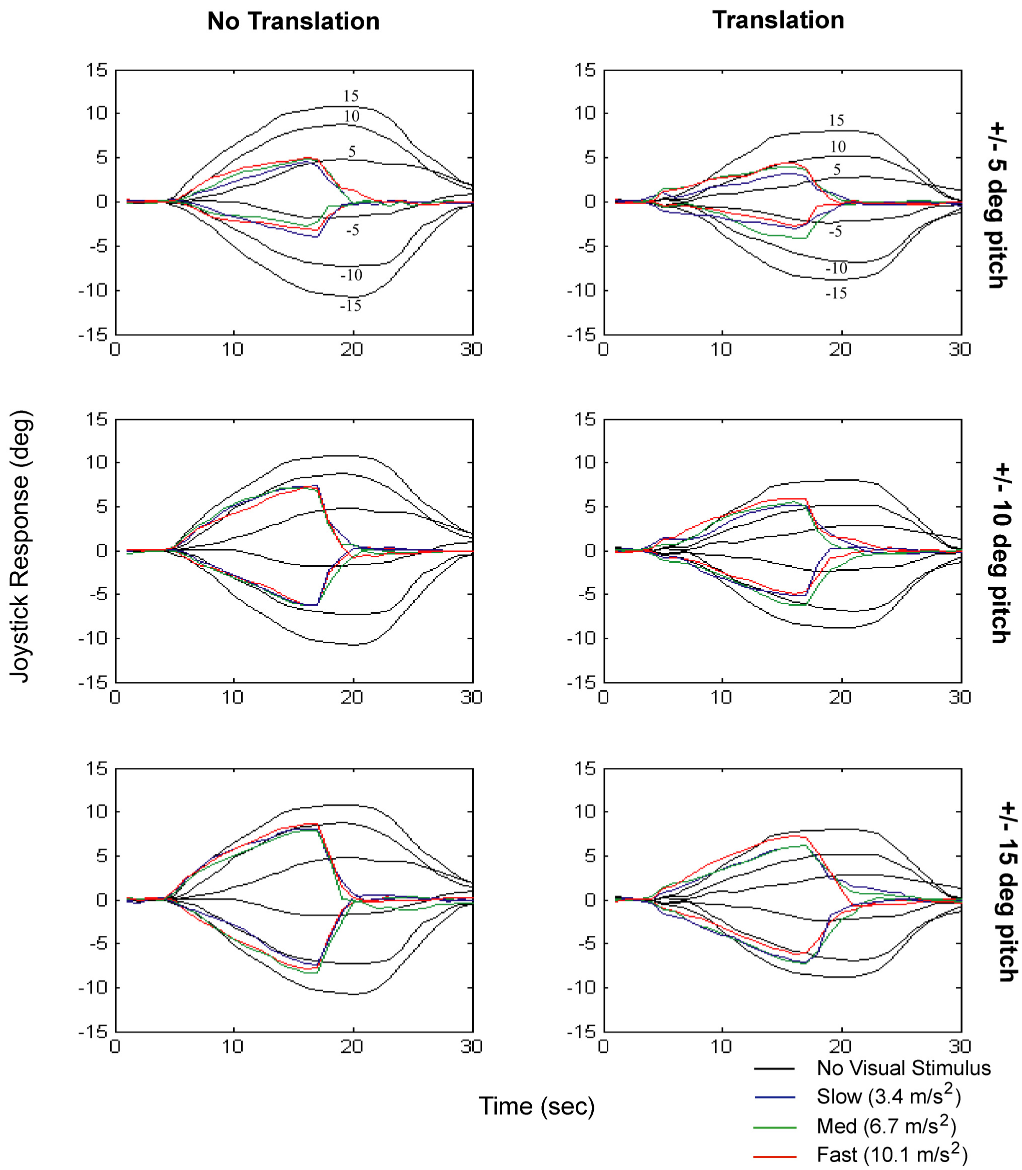

Figure 6: Joystick movement profiles for all conditions averaged across subjects. The black lines indicate the No Visual Stimulus conditions; all 6 No Visual Stimulus conditions ($\pm$ 5, 10, and 15 deg) are plotted in every graph as a reference. Translation conditions are plotted in the right column and No Translation conditions in the left. The colored lines show the movement profiles for the different visual accelerations. Profiles for $\pm$ 5, 10, and 15 deg of platform pitch are plotted in the first, second and third rows.

deceleration. The entire movement took 5 sec, but the translation was only perceptible during the rapid acceleration, which lasted 1.5 sec. The translation was forward in the case of backward pitch and backward in the case of forward pitch. This movement simulates the jerk one feels when accelerating from a standstill, which we hoped would enhance the illusion of forward (or backward) acceleration as opposed to backward (or forward) pitch without acceleration. If platform translation in fact enhanced the illusion, we would expect responses to differ with and without translation. We return to this point in the results and discussion sections.

In conditions in which a visual stimulus was presented, the stimulus simulated acceleration over a uniformly textured ground plane (figure 4). The simulated height above the ground plane was constant at 2 m. The simulated visual accelerations were consis-

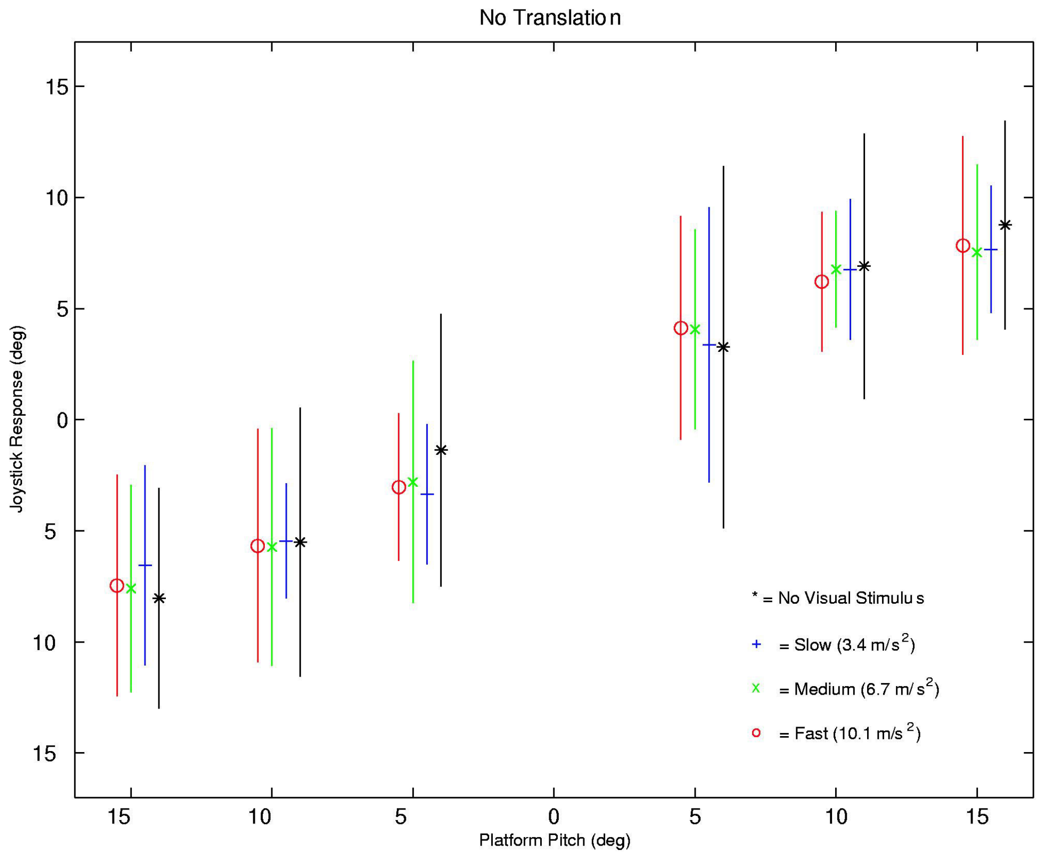

Figure 7: Mean responses across subjects for the no-translation conditions. Negative platform pitch means that subjects were pitched backwards and were visually accelerating forwards. Error bars represent one standard deviation.

tent with the six target pitch angles. For an upright observer, there is one inertial acceleration (in the earth horizontal direction) that is commensurate with a given non-upright GI force (see figure 2). This relationship was used to derive visual acceleration profiles for each of the six target pitches. The result was three forward and three backward acceleration profiles. To increase the likelihood of seeing some effect of the visual stimulus, we doubled these derived acceleration profiles. (Doubling the velocity is equivalent to reducing the eye-height from 2 m to 1 m; because there are no visual cues in the display that would allow the observer to accurately scale the scene, we do not believe the doubling of the velocity introduces a cue conflict). Figure 5 shows the platform pitch profile for a target pitch angle of -10 degrees, and the visual acceleration and velocity profiles derived from this pitch angle.

The starting simulated velocity was always zero and the visual acceleration always began with the onset of platform movement. The visual acceleration lasted 13 sec: 10 sec to reach the target pitch angle, and 3 sec of steady state. The visual stimulus faded to black at the end of the 13-sec trial.

2.3 Procedure

Seven naive observers (3 male, 4 female) were each run in four conditions:

1. No visual stimulus - Observers wore a blindfold. They were pitched to each of the six pitch values (± 5, 10, 15 deg) five times, for a total of 30 trials.

2. Visual acceleration - Observers wore an eye patch over the left eye and viewed the fixation cross with the right. The three backward pitches were combined with the three forward visual accelerations (3×3), and the three forward pitches were combined with the three backward accelerations (3×3), for a total of 18 combinations. Observers experienced each combination three times, for a total of 54 trials.

3. No visual stimulus / platform translation - This was the same as the no-visual-stimulus condi-

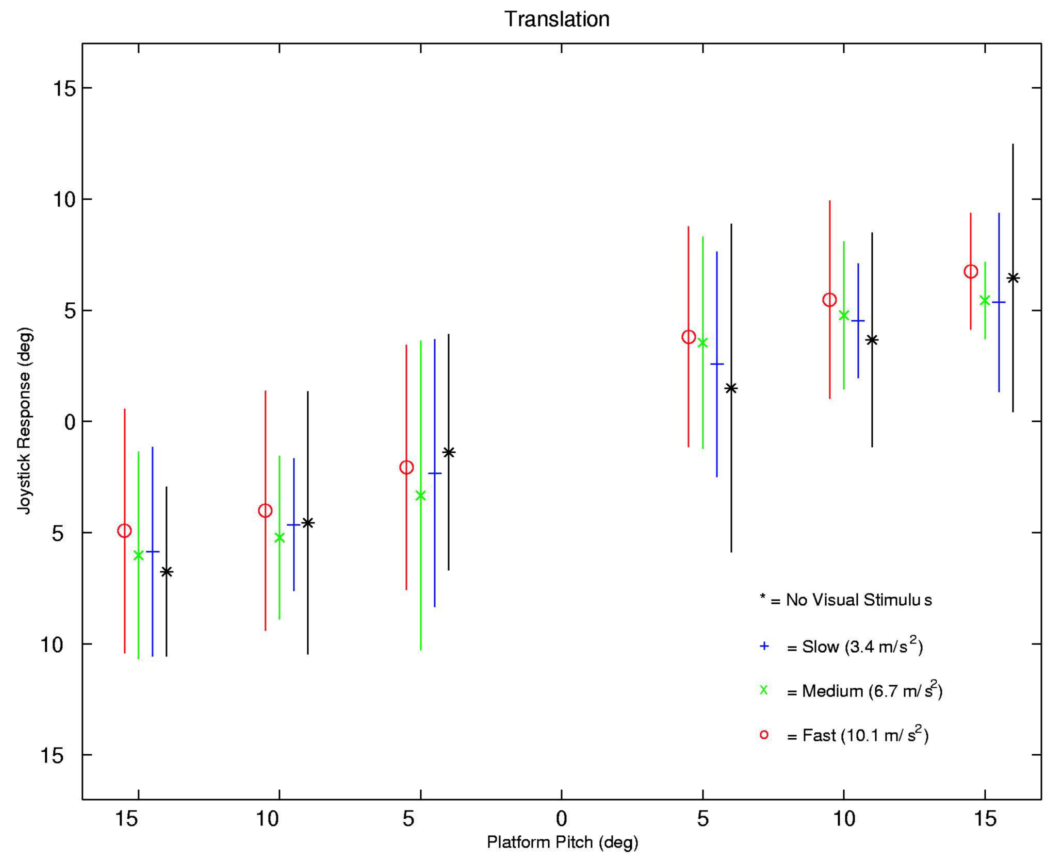

Figure 8: Mean responses across subjects for the translation conditions. Negative platform pitch means that subjects were pitched backwards and were visually accelerating forwards. Error bars represent one standard deviation.

tion described above, except that the platform was translated with the onset of the pitch movement.

4. Visual acceleration / platform translation - This was the same as the visual-acceleration condition described above, except that observers were translated with the onset of the pitch movement.

Observers were placed into one of four groups, which determined the order in which they ran the four condition sets. Observers ran two conditions per session (indicated by square brackets [] below). The order of conditions for the four groups was:

Group 1:	[1 2]	[3 4]	(2 observers)
Group 2:	[2 1]	[4 3]	(2 observers)
Group 3:	[3 4]	[1 2]	(2 observers)
Group 4:	[4 3]	[2 1]	(1 observer)

This order was used so that half of the observers ran translation sessions before no-translation sessions, and half ran visual stimulus conditions before no-visual-stimulus conditions.

Each trial lasted 33 sec. The sequence of events described below is for conditions in which visual acceleration was presented. The trial structure for the no-visual-stimulus conditions was identical except that observers wore a blindfold and the projector was turned off. At the beginning of each trial, the observers were in an upright position and were told that. They released the joystick, allowing it to return to the default, upright position. They remained in a stationary and upright position for 5 sec. During this time, an upright scene was displayed on the screen for 3 sec. Then the stationary ground plane was displayed for 2 sec. The onset of platform movement was synchronized with the onset of visual acceleration. For 10 sec, the platform rotated (pitched) at a constant rate until it reached the target pitch. Acceleration over the ground plane increased during this time. A steady state (constant pitch and constant visual acceleration) followed for 3 sec (see figure 5 for an example of platform pitch and visual acceleration profiles). Observers were told to adjust the orientation of the joystick to point toward perceived earth vertical throughout the trial. One re-

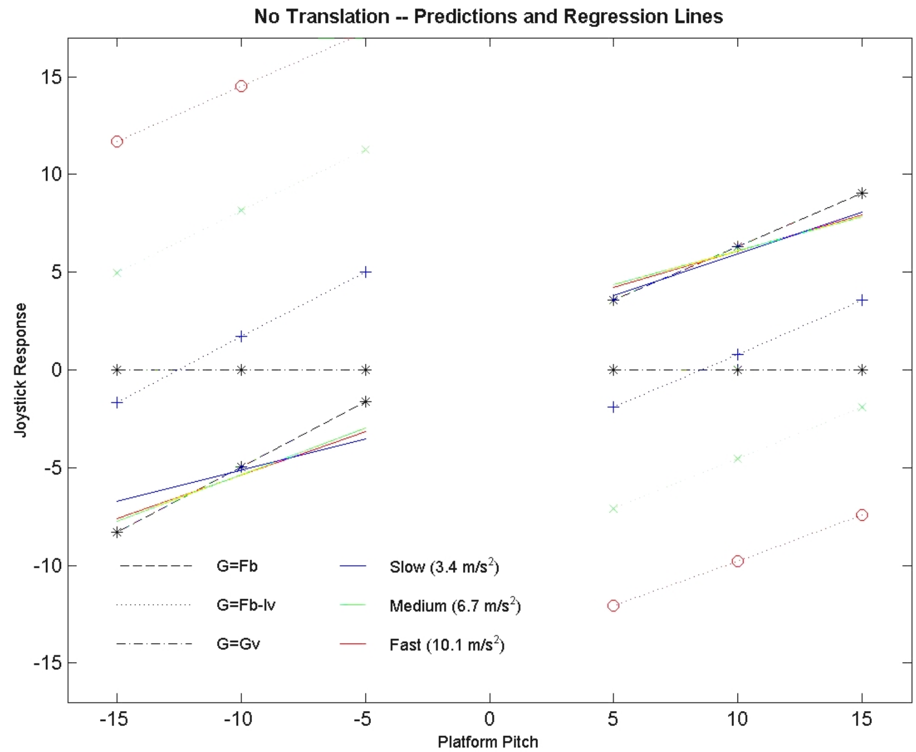

Figure 9: Predictions and regression lines for *no translation* conditions. Predictions of each method of estimating G are plotted separately. The black dashed line indicates predictions for method 1) $G = F_b$ (this is also the regression line for the No Visual Stimulus condition). The dotted colored lines indicate predicted responses for method 2) $G = F_b - I_v$. The horizontal black dotted and dashed line indicates predicted responses for method 3) $G = G_v$. The solid colored lines are regression lines through the mean response data points from figure 7.

sponse value was calculated for each trial. This was the average joystick position during the middle 2 sec of the 3-sec steady-state interval. At the end of the steady-state period, the screen faded to black and the platform began to move slowly back to the initial, upright position (which took 15 sec). Then the next trial began.

3 Results

The complete joystick movement profiles for all conditions are shown in figure 6. These are averaged across the seven subjects.

The mean joystick positions for the two-second response interval for all conditions are presented in figure 7 and 8; these are also averaged across the seven subjects. Figures 7 and 8 show the results for No Translation and Translation conditions respectively. Error bars represent one standard deviation and reflect the substantial variation in responses both within and between subjects. Variability in responses within subjects suggests that they found it difficult to perform the task consistently. Variability in responses between subjects is indicative of the fact that the mapping function between sensed direction of earth vertical and joystick response angle varied.

Our model proposes that there are three methods by which the nervous system might estimate the direction of earth vertical: 1) $G = F_b$, 2) $G = F_b - I_v$, and 3) $G = G_v$. In figures 9 and 10 we have plotted the responses for the visual stimulus conditions predicted by each of these methods. If observers were using only method 1), responses would depend only on the platform pitch. All responses would lie on the black dashed line, which is the regression line for the no-visual-stimulus responses. If observers were using only method 2), responses would vary depending on the visual acceleration presented. Responses for each visual acceleration would lie on the corresponding colored dotted lines. If observers were using only method 3), responses would depend only on the horizon, which specifies zero pitch for all trials. All responses would

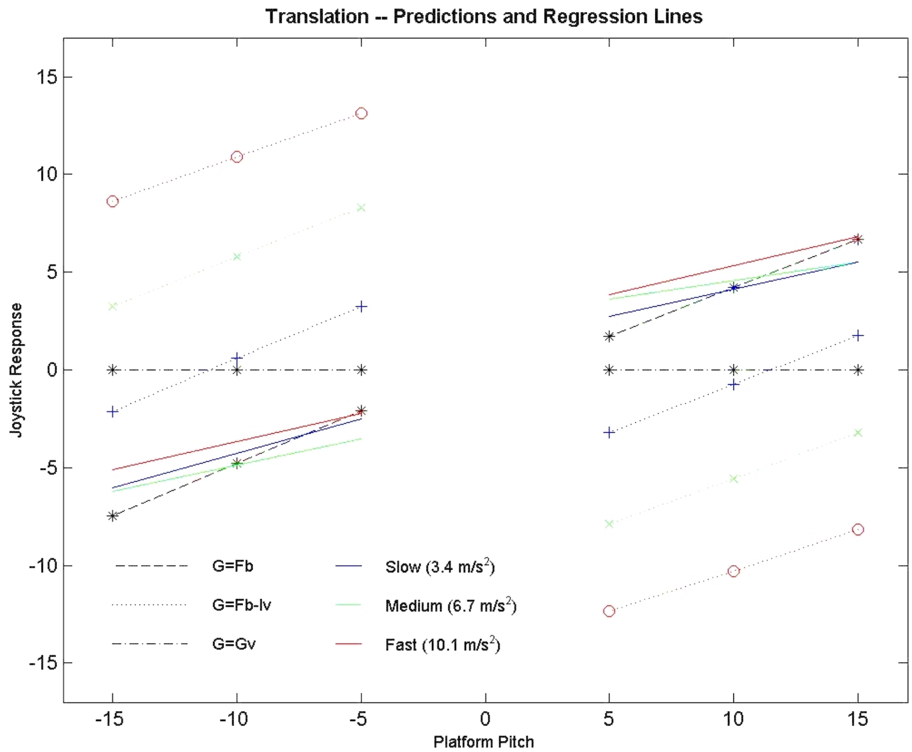

Figure 10: Predictions and regression lines for *translation* conditions.The meaning of the lines in the plot is equal to figure 9, with the only difference that the solid colored lines are regression lines through the mean response data points from figure 8.

lie on the black horizontal dashed and dotted line. The solid colored lines are regression lines that were fit to the mean response data points from figures 7 and 8; backwards and forwards pitch were fit with separate regression lines.

Visual inspection of the predictions and regression lines in figures 9 and 10 suggests that method 1) accounts best for the observed responses. Calculation of the r-squared statistic (proportion of variance accounted for) for each method confirms that method 1) provides the best fit to the data ($R^2 = 0.77$).

The above analysis supports the conclusion that $G = F_b$ was the dominant means by which observers estimated earth vertical. However, there is a trend in the data to suggest that something in the visual scene was influencing observer responses. This is evidenced in figure 11 by the shallower slopes of the regression lines for visual stimulus conditions (red lines) than no-visual-stimulus conditions (black lines). In terms of our model, this suggests that contradictory visually-influenced estimates of earth vertical exist, but that they are not heavily weighted under the conditions of this experiment. This point is expanded upon below.

There was also a noticeable effect of the platform translation that was presented with the onset of the translation conditions. The mean responses with translation are less pitched than the corresponding mean response with no translation. The regression lines in figure 11 reflect this difference. Our model does not provide a clear interpretation of this result, though some possible explanations are discussed below.

4 Discussion

Under the conditions of the present experiment, subjects relied primarily on vestibular and somatosensory cues to estimate the direction of earth vertical. This result is consistent with the findings of other studies. Previc et al., 1992 did not see any effect of visual cues, while Lessard et al., 2000 did not see an effect of visual cues for non-pilots.

However, we cannot conclude that visual cues play no role at all in estimating the direction of earth vertical. Airplane pilots do not experience the SG illu-

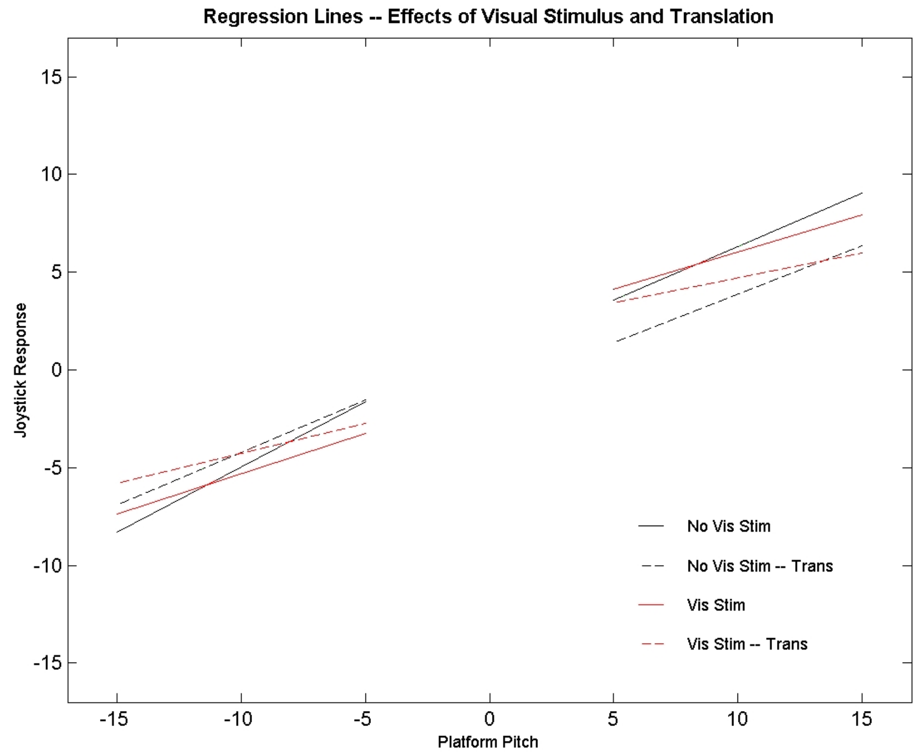

Figure 11: Regression lines with and without visual stimulus and translation. The solid lines indicate Translation conditions and the dashed lines indicate No Translation Conditions. The black regression lines are through the No Visual Stimulus conditions. The red regression lines are through the mean data points for all visual stimulus conditions.

sion when they can see the ground clearly, and Lessard et al., 2000 found that pilots' perception of earth vertical in a flight simulator were strongly influenced by visual scenes.

So, visual cues can definitely influence the perception of earth vertical, but under what conditions and to what extent?

Interpreting our results in the context of our model, we conclude that the weight given to the pure vestibular/somatosensory estimate of G ($G = F_b$) was close to one, while the weights given to the other estimates of G were closer to zero. In the case of cue combination, weights are typically determined by the reliability of the estimate (Ernst & Banks, 2002). In the absence of inertial acceleration, which is the usual state of affairs, $G = F_b$. It makes sense for the nervous system to assume that $G = F_b$ is a reliable way to estimate G, unless similarly reliable cues to self-acceleration are present. It may be that the cues to self-acceleration in our experiment were not deemed reliable enough to influence the prior assumption that $G = F_b$.

Our optic flow cues to self-acceleration may have been deemed unreliable because the rate of acceleration, which determines the inertial forces, was ambiguous. The distance to a scene element and the observer speed through the scene can only be determined to within a scale factor (Longuet-Higgins & Prazdny, 1980). There were no objects of familiar size that would allow the observers to visually scale the scene and determine the absolute value of their acceleration, which is the only way they could solve for inertial forces. In future experiments, we plan to increase the salience and hopefully the reliability of our optic flow stimulus by including objects of familiar size and making other improvements to the display.

While our results suggest that $G = F_b$ was the dominant means by which observers estimated earth vertical, the difference in the slope of the regression lines through the visual-stimulus (red lines) and no-visual-stimulus (black lines) data in figure 11 suggest that some aspect of the visual scene influenced observer responses. The shallower slope for the visual-stimulus data indicates that the different platform pitches some-how seemed more similar in the presence of the visual scene. Unfortunately, since the variability in responses is so great and the differences in responses with and without visual scene are so small, these differences cannot be clearly interpreted to be a result of the acceleration cue (I_v) or the horizon cue (G_v).

It is interesting to note that for small pitch angles of $\pm$ 5 degrees, responses with the visual stimulus are more pitched than responses without. Under the conditions of our experiment, none of the methods of estimating G would generate a more pitched response in the presence of the visual stimulus. For this reason, we believe that this trend may reflect a bias in the visual stimulus responses. As discussed in the methods section, backwards pitch was always paired with forward visual acceleration and forward pitch with backward visual acceleration. After a few trials subjects would have become aware of this association, and the direction of self-motion may have become a cue to direction of platform pitch. Five degrees of pitch can be difficult to detect vestibularly (in the absence of visual cues), so the direction-of-self-motion cue would have been useful and may have affected response magnitude at these small pitch angles.

The data show that the platform translation caused observers to feel less pitched. The translation movement was introduced to simulate forces experienced with the onset of acceleration in the real world. The decrease in response magnitude with the translation movement could be due to a modification of the prior assumption $G = F_b$. In the introduction we explain that an estimate of gravity based only on the body senses would have to solve the equation $G_b = F_b - I_b$. However, the body senses cannot provide independent estimates of gravity (G_b) and inertial forces (I_b). When inertial forces are not present, which is most often the case, I_b equals zero and the prior assumption, $G = F_b$, is valid. It may be that the translation movement leads to a non-zero estimate of I_b, and causes the nervous system to conclude that part of the sensed change in the direction of F_b is caused by an actual acceleration, which is consistent with a less pitched estimate of G. This modification of the prior assumption can explain the decrease in response magnitude we observed in the translation conditions. Note that this change of the prior depends on a temporal propagation of otolithic evidence for translation, as the subjects' feeling of a translation movement persists even after the real translation has stopped. This aspect is not yet covered by our simple model.

It was also thought that the translation might increase the salience of the visual simulation of acceleration. In terms of the model, this would be an increase in the weight given to the $G = F_b - I_v$ estimate. While translation conditions do show slightly more separation between the mean data points (figure 8) and regression lines (figure 10) for the different visual accelerations at each pitch, there is no consistent trend to support the idea that the $G = F_b - I_v$ estimate is given more weight.

We conclude that perception of earth vertical in the present experiment was predominantly determined by the experienced direction of GI force (platform pitch). We argue the optic flow cue may have been judged to be unreliable due to the absence of scaling cues. Differences in slopes of visual and non-visual regression lines (figure 11) suggest that the visual scene influenced observer responses. However, the effect was very small and there was great variability in responses. We cannot determine what cues were responsible for this small effect. Additionally, the translation movement caused observers to perceive less pitch, which could be due to a non-zero estimate of I_b, causing the nervous system to conclude thatpart of the sensed change in the direction of F_b is caused by an actual acceleration.

In future experiments we plan to use a two-alternative-forced-choice paradigm, which should yield more clearly interpretable results than the highly variable joystick responses. In addition, we plan to use more salient optic flow stimuli. It is hoped that taking these steps will allow us to determine exactly which cues are used by the nervous system to estimate the direction of earth vertical, and under what conditions these cues are used. Furthermore, we hope to determine the relative weights given to these cues in the calculation of a combined estimate of the direction of earth vertical.

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