COMBINED INFLUENCES OF GRAVITINOERTIAL FORCE LEVEL AND VISUAL FIELD PITCH ON VISUALLY PERCEIVED EYE LEVEL

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Abstract—Psychophysical measurements of the level at which observers set a small visual target so as to appear at eye level (VPEL) were made on 13 subjects in 1.0 g and 1.5 g environments in the Graybiel Laboratory rotating room while they viewed a pitched visual field or while in total darkness. The gravitoinertial force was parallel to the z-axis of the head and body during the measurements. The visual field consisted of two 58° high, luminous, pitched-from-vertical, bilaterally symmetric, parallel lines, viewed in otherwise total darkness. The lines were horizontally separated by 53° and presented at each of 7 angles of pitch ranging from 30° with the top of the visual field turned away from the subject (top backward) to 30° with the top turned toward the subject (top forward). At 1.5 g, VPEL changed linearly with the pitch of the 2-line stimulus and was depressed with top backward pitch and elevated with top forward pitch as had been reported previously at 1.0 g (1,2); however, the slopes of the VPEL-vs-pitch functions at 1.0 g and 1.5 g were indistinguishable. As reported previously also (3,4), the VPEL in darkness was considerably lower at 1.5 g than at 1.0 g; however, although the y-intercept of the VPEL-vs-pitch function in the presence of the 2-line visual field (visual field erect) was also lower at 1.5 g than at 1.0 g as it was in darkness, the G-related difference was significantly attenuated by the presence of the visual field. The quantitative characteristics of the results are consistent with a model in which VPEL is treated as a consequence of an algebraic weighted average or a vector sum of visual and tactual influences although the two combining rules lead to fits that are equally good. © 1997 Elsevier Science Inc.

Keywords—eye level; visual localization; visual field; gravitoinertial force; sensorimotor integration; spatial orientation; human.

Introduction

The joint involvement of gravitotaxial and visual information in egocentric spatial localization has long been recognized (5–21). Several recent studies (1,2,24–30) have focused upon visually perceived eye level (VPEL), defined and measured as the angular deviation between the elevation of a visual target set to appear at eye level and the horizontal plane containing true eye level.

"True eye level" can be defined as the plane normal to the background gravitoinertial force (G) field at the height of the center of rotation of the eyes. Under normal stationary conditions, G corresponds to the 1.0 g gravitotaxial force field of Earth. Observers, at 1.0 g, attempting to set a small visible target to appear at eye level in an otherwise dark field, position it within 6° of true eye level with a precision typically under 1° (1,2,19,22–24,31–34). The ability to make such settings has been related to a "body-referenced mechanism" using extraretinal neural signals
regarding the orientations of the head relative to gravity and the eyes within the orbits in combination with retinal signals regarding the oculocentric direction of the visual target.

In complete darkness, centrifugal rotation generates forces (Figure 1) that produce systematic effects on VPEL (3,4). When the magnitude of the resultant G vector is increased relative to g and the G vector is pitched so that the subject is tilted backward relative to the G field, a visual target that is fixed relative to the observer appears to rise, indicating a lowering of VPEL. Coreia and colleagues (3) found 2 good fits to their average VPEL measurements in darkness with equation (1):

\[
\text{VPEL}_{\text{DARK}} = \frac{-\left(\text{atan}\left[\left|G\tan(\theta_G + 30^\circ)\right]\right] - 30^\circ - \phi_G\right)}{1} 
\]

where \(|G|\) and \(\phi_G\) are the magnitude and orientation of \(G\) in the sagittal plane of the head.\(^1\) Coten (4) obtained a somewhat better fit by including an additional term for neck proprioception. The presence of a structured visual field greatly attenuates changes in VPEL induced by centrifugal stimulation of the body-referenced system in darkness (12,13).

Experiments on humans partially paralyzed by cerebrovascular accidents (19) have shown influences of extra-retinal signals and of the visual field on VPEL in 1.0 g. In an darkened room, a visual target at true eye level appears too high or too low to each subject by an amount that depends on the vertical deviation of the eyes in the head from some central position. The same visual target, physically located at true eye level, appears at or very close to eye level when the room's visual contours are illuminated. Thus, a normal visual field influences VPEL when extra-retinal information regarding eye position (an element of the body-referenced system) is impaired.

\(^1\)The equation actually published by Coreia and colleagues (3) was \(\tau = \text{atan}\left[\left|G\tan(\theta_G + 30^\circ)\right]\right] - 30^\circ\). They defined \(\tau\) as the angle between the line of sight to a target set at subjective eye level and a plane fixed to the head's anatomical horizontal plane, with positive angles for settings below that plane. We define VPEL relative to the horizontal plane that is perpendicular to the gravito/vertical vertical and give positive values to settings above that plane. Thus, VPEL_{DARK} = (\tau - \phi_G), which leads to equation (1).

The results just described indicate that both the visual system and a body-referenced system are involved in determining VPEL. Matlin and Fox (22,23) studied their relative influence on VPEL by requiring subjects seated upright to set a visual target to VPEL, while the visible and richly structured walls of the test chamber were pitched. VPEL changed systematically with the
orientation of the room: it was above true eye level when the room was pitched toward the observer and below true eye level when pitched top away. The deviation of VPEL from true eye level was linearly proportional to the pitch of the room, with the slope of the function relating VPEL to static visual pitch equal to +0.61. The functions of individual subjects were also linear but the slopes varied among different individuals, ranging from +0.45 to +0.81. Using a smaller visual display and smaller range of pitches, Soper and Cohen (35) obtained similar results with individual VPEL-vs-pitch slopes ranging from 0.1 to 0.7.

Later experiments demonstrated that the major influence on VPEL is generated by the pitched-from-vertical lines on the surface facing the subject; horizontal lines on the frontal surface have only a very small influence. In fact, just one or two pitched-from-vertical lines can generate changes in VPEL that are only slightly smaller than those occurring in a fully structured, illuminated pitch room (1,2,24,25,26,36,37).

Matin and Fox (22,23) proposed a model for VPEL in which the influences of the visual field and the body-referenced mechanism were combined in either of two ways: as a weighted sum of the two influences combined by algebraic addition, or by vectorial combination of the two influences. The results were fit equally well by the model incorporating either combining rule. The model with the weighted algebraic sum can be represented as

\[
\text{VPEL} = k_v V_S + V_O + k_b (B_S + B_O).
\]

(2)

\( V_S \) represents a signal from the visual system that depends on the pitch of the visual field. \( B_S \) represents a signal from the body-referenced system that is a function of \( G \), external inputs from other sources including eye position information, neck proprioception, and information regarding stimulus focus on the retina (retinal local sign). \( V_O \) and \( B_O \) are constants characteristic of the individual observer and are related to the visual field and the body-referenced mechanisms, respectively. \( k_v \) and \( k_b \) are the relative weights of the two influences, with \( k_v + k_b = 1 \).

With a single set of parameters, this equation fits the results of VPEL measurements for both the pitched visual environment and for darkness. In the initial reports, the values for the weights, \( k_v \) and \( k_b \), were fairly equal in the illuminated visual field, approximating 0.5; the results in darkness were compatible with the assumption that \( k_v \) and \( k_b \) were equal to 0 and 1, respectively.

The vectorial combining rule can be represented by equation (3) below: It is assumed that the visual system produces a vector \( \mathbf{V} = (\mathbf{v}_b, \mathbf{V}) \), where \( \mathbf{v}_b \) is a representation of visual pitch and \( \mathbf{V} \) is the visual signal strength. Similarly, \( \mathbf{B} = (\mathbf{b}_b, \mathbf{B}) \) is a vector from the body-referenced system signaling the orientation, \( \mathbf{b}_b \), and magnitude, \( \mathbf{B} \), of \( G \) in the sagittal plane. If \( \mathbf{V} \) and \( \mathbf{B} \) are the lengths \( v_b \) and \( b_b \) the orientations of the vectors \( V \) and \( B \), then VPEL is the orientation of their sum,

\[
\text{VPEL} = \frac{V \sin \theta_v + B \sin \theta_b}{V \cos \theta_v + B \cos \theta_b},
\]

(3)

\( \theta_v \) is assumed to be the algebraic counterpart of \( V_S + V_O \) and \( \theta_b \) to \( B_S + B_O \) of equation (2). \( V \) is assumed to be 0 in the dark and 1 in the light, and \( B \) to be equal to \( G \) level. Visual suppression is not directly represented in this model in the sense that \( B \) is not constrained to change when \( V \) changes because of variations in illumination level or complexity of visual structure. In the model of equation (1), \( k_b \) and \( k_v \) must vary inversely because \( k_v + k_b = 1 \). Mittelstaedt (20) has previously proposed a related vectorial treatment for multicomponent influences on perceived vertical in the roll dimension.

Understanding how and when \( k_v \) and \( k_b \) might change would permit evaluation of equation (2) and could provide a more complete picture of the joint contribution of visual and mechanical stimuli to VPEL. Although previous models (34) have been used to predict the influence of changes in \( G \) on VPEL in darkness, and the visual field has been observed to have a suppressive effect on the G-induced influence (12,13,38,39,40), predictions of the quantitative influence of a pitched visual field on the G-induced shifts of VPEL have not previously been articulated.

Several stimulus parameters have been found to produce sizable influences on the slope of the VPEL-vs-pitch function: the state of dark
adaptation (27), the horizontal eccentricity of the two parallel pitched-from-vertical lines (41), and a change in the rot orientation of both the subject and 2-line stimulus relative to gravity (42). This raises the possibility that variation in the magnitude of G with no change in its orientation might also produce a change in slope. All of the previous experiments with VPEL were carried out in a normal 1.0 g environment. In the present experiment, the influence of joint variation in force background and visual pitch in a normal 1.0 g and a 1.5 g environment was measured on subjects with the head in an upright posture relative to the G field.

Methods

Subjects

Thirteen normal individuals served as observers. Six were paid Brandeis undergraduate students, the other 7 were either the experimenters, graduate students, or laboratory personnel. All were permitted to wear their normal corrective lenses, if any, during the experiment. All participants gave informed consent.

Apparatus

Experimental observations were carried out in the Graybiel Laboratory rotating room, which is a fully enclosed, circular structure, 6.7 m in diameter, that can be rotated about its central vertical axis. The subject’s chair was located at the periphery of the room, facing radially inward. During rotation, the net gravitoinertial force on the chair was greater than the 1.0 g force of terrestrial gravity and was tilted relative to it. The chair and the affixed bite bar could be pre-adjusted in pitch so that the subject’s head would be in the same orientation relative to the G field during testing in both a normal, stationary, 1.0 g environment and a rotating 1.5 g environment.

The apparatus for presenting a pitched visual display was attached to the chair. It consisted of a flat, rectangular surface that was painted flat black and was attached to a 1 mm long cantilevered arm that pivoted about the subject’s interaural axis. The surface could be aligned with the G vector and thus with the z-axis of the observer or be pitched top-toward the observer (positive display angles) or top-away (negative angles). The display consisted of two parallel, phosphorescent strips of 2-mm-wide tape mounted near the edges of the surface (Figure 1, top). The strips had a luminance of 0.1 cd/m² and were viewed in total darkness. This display was similar to that used in prior experiments (1,26-28,30). When positioned in the subject’s frontal plane, the lines subtended 58° of visual angle vertically and were 5° apart; the lines were centered about the median plane. Since the center of rotation of the display was coincident with the subject’s interaural axis and the viewing distance was constant (1 m), the visual angle of the 2-line stimulus that was subtended at the eye did not change with the pitch of the surface, and the normal plane through the subject’s viewing eye to the surface containing the lines intersected the midpoints of the lines at all pitch settings. Occluders hinged to the surface allowed the lines to be hidden or visible to the observer, as desired. Figure 1 illustrates the test situation.

A 20 minarc He-Ne laser target (red) was projected onto the visual display in the median plane. Both the subject and the experimenter held switches that could move it up or down (at 6°). Target position was electronically read out and calibrated in degrees of visual angle, with the position corresponding to true eye level assigned the value 0° and positions above true eye level having positive values.

Procedure

Each subject set the laser target to VPEL in complete darkness and with the 2-line visual display in each of 7 pitch positions. The pitch positions were +30°, 0°, -1°, -11°, -20.5°, and -30.5° relative to the gravitoinertial vertical. Settings were made first under 1.0 g (stationary) condition and later under 1.5 g (rotating) conditions. Twelve of the subjects wore a patch over the left eye; the 13th (TG) viewed the visual field binocularly.

In 1.0 g sessions, the subject chose a comfortable upright posture in the apparatus, and
His/her head was then stabilized with an individually molded bite plate. The rigid bite plate kept the head in the same orientation relative to G in the 1.0 and 1.5 g conditions. Before the room lights were turned off, the visual display was set to one of the 7 pitch angles. The room light was extinguished, and 1 min later the subjects began setting the laser target to VPEL. Prior to each setting, the experimenter positioned the laser target at a random height while the subject’s eyes were closed, then the subject opened his/her eyes and moved the target to VPEL. Eight VPEL measurements were made in complete darkness, followed by 8 with the 2-line stimulus in view. This procedure was repeated until VPEL had been measured at all 7 pitch angles of the display surface, both in darkness and with the 2-line stimulus in view. The order of presentation of the different pitch angles was randomized across subjects. No limit was placed on the time allowed to make settings, and it took subjects an average of 150 seconds to make 8 VPEL settings in darkness and 147 seconds with the 2-line display present.

The 1.5 g conditions were run at least one day later and at most 7 months later. Prior to room rotation, the test chair was tilted 48.1° toward the center of the room, and the visual display was set at one of the 7 pitch angles. Then the room was accelerated at 1.5°/s² to a constant speed of 140°/s, which produced a resultant force of 1.5 g at the subject’s head directed along the subject’s z-axis. The bite plate that had been prepared for the 1.0 g session was used again to ensure a repeatable upright orientation of the head relative to the G vector. One minute after the attainment of constant velocity, the subject began VPEL settings — 8 in the dark, followed by 8 in the presence of the 2-line display. The room was then decelerated to a stop so that the stimulus surface could be set to a new angle of pitch. This procedure was repeated until all 7 visual pitch positions had been presented. The duration of exposure to 1.5 g averaged about 9 min for each stimulus angle. On average, it took 161 seconds to make 8 VPEL settings in complete darkness and 157 seconds with the 2-line display in view. Measurements at two different visual pitches were separated by a minimum of 10 min.

Results

The complete VPEL data over time for a typical subject, ND, are presented in Figure 2 to provide a ready visualization of the experimen-

![Figure 2](image-url)
Figure 3. Plots of perceived eye level versus pitch of the visual stimulus in darkness (solid squares) and with the 2-line stimulus visible (open squares), averaged for all 13 subjects in 1.0 g (A) and 1.5 g (B), and for subject ND in 1.0 g (C) and 1.5 g (D). Dashed lines are least squares linear fits to the data.

tal results. The average VPEL values in each condition for all subjects are plotted in Figures 3A and 3B, with the slopes and y-intercepts of the best-fitting least squares lines through the VPEL-vs-visual pitch data. Figures 3C and 3D, show the results for subject ND. When the 2-line visual display was pitched top toward the observer or top away, VPEL was elevated or depressed, respectively, in both 1.0 g and 1.5 g. The average slopes of the VPEL-vs-visual pitch functions in the presence of the visual display were 0.40 and 0.43 in 1.0 g and 1.5 g, respectively; the average slopes in the dark were 0.03 and 0.08 in 1.0 g and 1.5 g (see Figure 4, top). An analysis of variance of the slopes showed an effect of presence or absence of the 2-line display ($F(1, 12) = 38.89, p < .0001$) but no influence of G level; nor was there an interaction between G level and presence or absence of the visual display. The average and standard deviation of each subject’s 8 repeated measures at each pitch are presented in Table 1 for 1.0 g and Table 2 for 1.5 g.

The y-intercept of the VPEL-vs-visual pitch function in darkness, averaged across subjects, was 7.8° lower in 1.5 g (−12.2°) than in 1.0 g
Table 1. VPELs and Standard Deviations (SDs) at 1.0 g

<table>
<thead>
<tr>
<th>Pitch (degrees)</th>
<th>−3.5</th>
<th>−2.0</th>
<th>−1.0</th>
<th>0.0</th>
<th>1.0</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cond</td>
<td>VPEL</td>
<td>SD</td>
<td>VPEL</td>
<td>SD</td>
<td>VPEL</td>
<td>SD</td>
</tr>
<tr>
<td>1° W</td>
<td>−2.0</td>
<td>4.4</td>
<td>−1.5</td>
<td>1.9</td>
<td>2.0</td>
<td>3.7</td>
</tr>
<tr>
<td>1° L</td>
<td>−2.0</td>
<td>4.4</td>
<td>−1.5</td>
<td>1.9</td>
<td>2.0</td>
<td>3.7</td>
</tr>
<tr>
<td>2° W</td>
<td>−2.0</td>
<td>4.4</td>
<td>−1.5</td>
<td>1.9</td>
<td>2.0</td>
<td>3.7</td>
</tr>
<tr>
<td>2° L</td>
<td>−2.0</td>
<td>4.4</td>
<td>−1.5</td>
<td>1.9</td>
<td>2.0</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Mean: −4.0 ± 0.8.  (−4.4°); with the 2-line stimulus present, the y-intercept was only 2.8° lower in 1.5 g than in 1.0 g (Figure 4, bottom). An analysis of variance showed significant main effects of G level (F[1, 12] = 22.5, p < .0001) and of presence or absence of the visual display (F[1, 12] = 26.61, p < .0001) and an interaction between the two (F[1, 12] = 41.20, p < .0001). Separate matched t tests showed that the y-intercept was significantly lower at 1.5 g than at 1.0 g in the presence of the visual field (p < .05) as well as in darkness (p < .001) and that the change in VPEL between 1.0 g and 1.5 g was significantly larger in darkness than with the 2-line visual display present (p < .001). Thus, the downward shift in VPEL that was induced by a G increase in darkness was significantly reduced by the presence of the vertical 2-line stimulus.

Figure 5 displays the relation across subjects between the VPEL in the presence of the vertical visual field and in darkness (each point plots the y-intercept in the presence of the visual field against the y-intercept in darkness). The correlations across subjects were 0.95 and 0.87 in 1.0 g and in 1.5 g, respectively. Both correlations are large and significant (p < .001), indicating great individual consistency across the judgments in the dark and against the visual field not only in 1.0 g, as had previously been reported (12.22.23), but in 1.5 g as well. Also, in agreement with those previous reports, although there are substantial individual differences among subjects, the y-intercept determined in the presence of the 2-line stimulus lay above the dark VPEL for each of the 13 subjects in 1.5 g and for 8 of the subjects at 1.0 g; the reversals for the other 5 subjects at 1.0 g were of very small magnitude.

Figure 6 plots the average within-subject variability of VPEL for each pitch of the visual display at each of the combinations of G level.
<table>
<thead>
<tr>
<th>Pitch (degrees)</th>
<th>31.5</th>
<th>20.5</th>
<th>11.0</th>
<th>0.0</th>
<th>18.0</th>
<th>27.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cond</td>
<td>Subj</td>
<td>VPEL SD</td>
<td>VPEL SD</td>
<td>VPEL SD</td>
<td>VPEL SD</td>
<td>VPEL SD</td>
</tr>
<tr>
<td>1.5 G</td>
<td>WL</td>
<td>-11.5 2.3</td>
<td>-15.9 3.9</td>
<td>-10.2 2.1</td>
<td>-17.5 0.8</td>
<td>-4.3 4.8</td>
</tr>
<tr>
<td>DARK</td>
<td>NB</td>
<td>-23.3 2.6</td>
<td>-29.2 3.2</td>
<td>-22.3 2.3</td>
<td>-19.1 3.6</td>
<td>-17.9 1.9</td>
</tr>
<tr>
<td></td>
<td>TG</td>
<td>-16.5 2.0</td>
<td>-26 3.3</td>
<td>-12.5 2.8</td>
<td>-12.1 1.4</td>
<td>-3.7 1.3</td>
</tr>
<tr>
<td>MEAN</td>
<td>PD</td>
<td>-17.5 3.2</td>
<td>-8.4 1.3</td>
<td>-7.9 2.1</td>
<td>-10.4 0.8</td>
<td>-4.1 0.8</td>
</tr>
<tr>
<td></td>
<td>SZ</td>
<td>-18.1 1.4</td>
<td>-6.1 1.7</td>
<td>-1.8 1.6</td>
<td>-5.3 1.5</td>
<td>-4.3 1.5</td>
</tr>
<tr>
<td></td>
<td>TP</td>
<td>-14.1 1.1</td>
<td>-7.0 2.1</td>
<td>-10.9 1.8</td>
<td>-0.3 2.1</td>
<td>5.5 1.4</td>
</tr>
<tr>
<td></td>
<td>ND</td>
<td>-12.7 2.5</td>
<td>-16.2 2.7</td>
<td>-5.9 3.4</td>
<td>-9.5 1.3</td>
<td>-7.9 1.7</td>
</tr>
<tr>
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<td>JV</td>
<td>-21.7 3.3</td>
<td>-26.1 2.9</td>
<td>-22.8 2.3</td>
<td>-19.9 1.3</td>
<td>-23.4 2.6</td>
</tr>
<tr>
<td></td>
<td>SC</td>
<td>-18.1 3.2</td>
<td>-16.6 2.9</td>
<td>-23.1 3.3</td>
<td>-12.8 2.4</td>
<td>-10.5 1.7</td>
</tr>
<tr>
<td></td>
<td>AL</td>
<td>-13.4 1.6</td>
<td>-17.8 2.2</td>
<td>-6.6 2.3</td>
<td>-21.6 2.6</td>
<td>-14.2 1.4</td>
</tr>
<tr>
<td></td>
<td>BL</td>
<td>-11.3 2.6</td>
<td>-9.2 2.8</td>
<td>-13.6 1.0</td>
<td>-2.7 1.7</td>
<td>-10.3 1.5</td>
</tr>
<tr>
<td></td>
<td>JB</td>
<td>-5.3 1.9</td>
<td>-6.9 2.5</td>
<td>-18.9 1.2</td>
<td>-4.1 2.7</td>
<td>1.7 1.4</td>
</tr>
<tr>
<td></td>
<td>PS</td>
<td>-23.8 3.1</td>
<td>-21.8 1.0</td>
<td>-28.1 2.9</td>
<td>-24.1 2.0</td>
<td>-17.3 1.4</td>
</tr>
<tr>
<td>Mean</td>
<td>-14.7 2.5</td>
<td>-14.3 2.6</td>
<td>-14.4 2.4</td>
<td>-12.2 1.8</td>
<td>-8.5 1.6</td>
<td>-10.3 2.6</td>
</tr>
</tbody>
</table>

All values except slopes are in degrees of visual angle.

and illumination. A three-factor (Visual pitch G level x illumination) analysis of variance showed significance for G level (F1, 12) = 27.41, p < 0.0001) and illumination of the 2-line display (F1, 12) = 19.54, p = 0.001). Trial to trial variability was significantly higher in 1.5 g than in 1.0 g, and was higher in the dark than with the 2-line display present; interactions were not significant.

**Discussion**

Although the VPEL setting is to a direction defined by gravity (that is, the VPEL setting is to the visual direction perceived to be perpendicular to the direction of gravity), change in the magnitude G in the presence of an illuminated visual field produces no significant influence on the VPEL discrimination, neither on the slope of the VPEL-vs-visual pitch function nor on the y-intercept of that function. This contrasts with the influence that the magnitude of G has on VPEL is darkness, where increases in G lead to a lowering of VPEL.

On the assumption that the change from an illuminated visual field to total darkness involves a change in the relative weighting of all gravity and adding influence from the visual field and the body-referenced mechanism, Figure 7 displays predictions generated by equation (2) for the slope and y-intercept of VPEL-vs-visual pitch functions for different gravitoinertial force backgrounds in complete darkness and with a visual display. Assuming that in darkness kG = 1 and kv = 0 (since kG + kv = 1), then VPEL = B0 + B1, predictions which are consistent with the measured values in Figure 7. When the visual display is present, equation (2) predicts that the slope of the VPEL-vs-visual pitch function should equal kG and exhibit no significant changes with the level of G within
the present range, and that the y-intercept should decrease with G level more slowly than in darkness. The small decrease of the y-intercept with G level in the light is consistent with prediction. Consistent with prediction also, the similarity of the best-fitting slopes measured at 1.0 g and at 1.5 g, 0.40 and 0.43, respectively, indicates no dependence on G. The results in darkness are also consistent with the formulations of Corela and colleagues (3) in equation (1) and of Cohen (4), although neither of those formulations considered the influence of visual field orientation.

Thus, G-induced changes of VPEL in darkness, attenuation of these changes by an erect, structured visual field, and the constancy of the VPEL-vs-visual pitch slope with variation in G are all expressible within a framework that assumes that visual attenuation of G-induced illusions involves both visual suppression of the body-referenced system and algebraic combination of the contributions from the visual and body-referenced systems. The suppression is expressed as the parametric adjustment of the weighting of contributions from visual and body-referenced mechanisms in which \( k_0 \)

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**Figure 4.** Summary of the VPEL-vs-pitch functions in 1.0 g and in 1.5 g in darkness and with the 2-line stimulus (open squares). The slopes quantify the rate of change in VPEL as visual pitch changes. The y-intercepts are measures of VPEL when the visual field is upright.

**Figure 5.** Correlations between the y-intercept of each subject’s VPEL-vs-visual pitch functions in darkness and with the 2-line stimulus, in 1.0 g and in 1.5 g. Horizontal and vertical shifted lines indicate the origin of the ordinate and abscissa, and the diagonal indicates equal angles on the ordinate and abscissa.

**Figure 6.** Standard deviations of VPEL versus visual pitch for all subjects in 1.0 g and in 1.5 g in darkness and with the 2-line stimulus visible. Each point is the average of all 13 subjects’ standard deviations of VPEL for their 8 repeated trials in that condition.
changes from 1.0 in darkness to about 0.58 in illumination.

Visual suppression is not directly represented in the model employing the vectorial combining rule of equation (3) in the sense that [B] is not constrained to change when [V] changes because of variations in illumination level or complexity of visual structure. However, this difference between the two combining rules is one of appearance only: variation in the magnitude of [V] in equation (3) functions as does the relative weight variation in equation (2). For example, an increase in the magnitude of [V] reduces the relative contribution of [B]. Predictions of the y-intercept by vectorial combination are indistinguishable from predictions described above for the algebraic combining rule, but require a monotonic decrease of the VPEL-vs-visual pitch slope with increase in G level (Figure 7). The fit of the predicted slopes to the measured values at 1.0 g and at 1.5 g, is slightly worse than to the algebraic prediction of equation (2), but the differences between the fits by the two treatments are not sufficiently robust to allow a strong conclusion. A similar failure to distinguish between the two combining rules was described by Matin and Fox (23). Whatever the mechanism by which the influence from the visual field and from the body-referenced mechanism are combined, the strong relation between an individual’s VPEL in darkness and against a visual field (Figure 5) makes it clear that some aspect of the mechanism that does operate in the dark is involved in generating the VPEL in the light; one would not expect the strong relation between the two measures otherwise.

The increase in within-subject variability of VPEL in darkness relative to values in an illuminated visual field (Figure 6) was reported previously for 1.0 g environments (12,19,23,25,27,28,34,35). The present results show that it holds at 1.5 g as well. This would be consistent with both of the above theoretical treatments if the neural mechanism processing visual input possesses a smaller intrinsic response variability than the mechanism controlling the body-referenced mechanism, since it both treatments the shift from darkness to illumination is accompanied by a shift from complete control by the body-referenced mechanism to shared control by the visual influence and the body-referenced mechanism.

Figure 6 also shows that within-subject variability is greater at the 1.5 g level than at the normal 1.0 g level in darkness and that this difference holds separately in the illuminated vi-
sual field as well. The increased G level results in increased otolith response (43), and because increases in mean neural response rate are normally associated with increases in neural responsiveness, the increase in VPEL response variability with the increase in G is a reasonable outcome. This increase in VPEL variability at the higher G level is not attributable to variations in head position, either between subjects or across measurements on individual subjects. The following two facts are pertinent here: 1) In an experiment conducted at 1.0 g, systematic variation of head orientation around a horizontal axis that was in the fronto-paralle platean produce no change in the influence of VPEL; essentially identical slopes and intercepts were obtained at five different head orientations over the ±20° range (23, Figure 8, p. 506). 2) The influence of head orientation was measured in a repeat of the present experiments, in 1.0 g and 1.5 g, with the head either pitched forward 30° or at the erect orientation (to be reported in detail elsewhere). Thus, whereas in the present experiments our setting of head orientation was to a comfortable upright position and otolith orientation was consequently probably more variable among different subjects than we set the head to some criterion such as Reid's baseline, there is no reason to believe that this in any way contributed to the increased within-subject variability at the high G, nor indeed to the between-subject variability in any of our measures.

The results point to the importance of a visual surround for accurate visual localization in non-1.0 g environments. This can be seen in Figure 7, where both models predict that the y-intercepts of VPEL-vs-visual pitch functions in darkness and with a visual background diverge from each other and also from tree eye level in force backgrounds that are greater or less than 1.0 g. This implies that the visual layout of architectural surfaces and external views will influence perceived orientation in the weightless conditions of orbital flight, and in aircraft during takeoff and landing where G is altered. Although previous work has emphasized the suppressive influence of an illuminated visual field on the G-related changes in visual elevation—and such suppression is also the case for the larger segment of our range of visual pitch—the introduction of a visual field that is sufficiently piched up backward does just the opposite. Thus, for example, at 1.5 g, VPEL deviates further from verticality with the 2-line visual field pitched top backward by 30° than it does in total darkness (Figure 3, panels B and D; Table 2). In Figure 7, right, which displays the predictions by the models of the y-intercept (zero visual pitch) only, the predicted value with the visual field deviates less from verticality than in darkness, uniformly throughout the G range shown. However, calculations similar to those in Figure 7 for 'large enough non-zero pitches show crossover points that change systematically with pitch and do predict the worsening of VPEL produced by the visual field in Figure 3, panels B and D. Such combinations of pitch and landing G are not unlikely in aircraft under conditions in which the inside of the cabin provides the main portion of the visual field, and could result in serious orientation problems for aircraft personnel. However, solving practical problems of orientation will require consideration of other subsystems. Touch and pressure cues, architectural features, the mode of postural support and the state of adaptation (15, 28, 44–46) all influence orientation in unusual space environments. This means that spatial orientation depends on multiple sensory, motor, and cognitive systems of which the sensory interaction we have modeled here is just one.

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