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On the relation between roll and pitch

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Studies have found that rolling the visual environment affects observers' perception of gravitational vertical and horizontal and that pitching the environment affects observers' perception of pitch. However, the relationship between these two perceptions is not fully understood. In the present work, observers performed three tasks while in a visual surround whose pitch and roll was manipulated. In the first task, observers adjusted a rod in the frontal-parallel plane to the horizontal (roll). In a second task, they adjusted a rod along a plane parallel to straight-ahead to the vertical (pitch). In the final task (''in-between''), they adjusted a rod midway between the first two conditions. The typical pitch and roll effects were found, as well as a contribution of both pitch and roll to the in-between task. No interaction between pitch and roll effects was found, indicating independent cognitive representations.

The orientation of the visual environment can have a strong influence on the perception of horizontal and vertical. In particular, there have been a number of studies that measure the effects of the roll and pitch of the visual surround on orientation judgements. Roll is the clockwise or counterclockwise rotation of the image plane (see Figure 1a), while pitch is the slant up or down in front of the observer (see Figure 1b). In a classic series of studies, Witkin and Asch placed observers in a visual environment that was rolled about the line of sight (Asch & Witkin, 1948; Witkin & Asch, 1948). They demonstrated that observers' attempts to set a rod to the vertical or horizontal with respect to gravity erred in the direction of the visual environment, with no proprioceptive or other feedback. For example, in one experiment (Asch & Witkin, 1948, Exp. 1), they had observers view a frame that was rolled 22° in a counterclockwise direction. The task was to set a rod to be horizontal or vertical with respect to gravity. The average setting was 15° in the direction of the tilt of the frame. When the stimulus consists of only a tilted luminous frame, this effect of the visual

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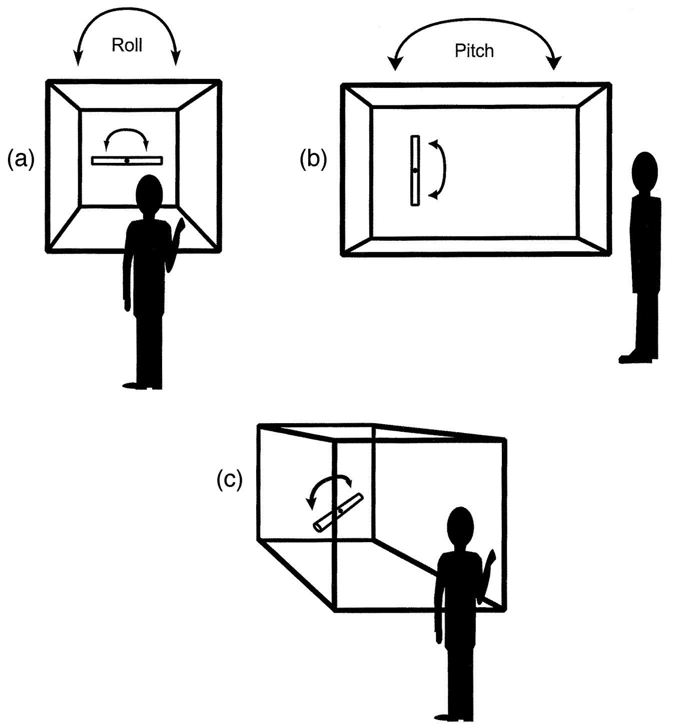

Figure 1. A schematic of the three tasks in Experiment 1. In (a), roll, observers adjusted a luminous rod to be horizontal along a plane orthogonal to straight ahead; in (b), pitch, they adjusted the pitch to be vertical along a plane parallel to straight ahead; and in (c), in between, they adjusted it to be horizontal along a plane midway between the pitch and roll dimensions. In all three tasks, both the pitch and the roll of the room were manipulated.

environment on orientation perception is called the rod-and-frame effect (Witkin & Asch, 1948).

The perception of pitch is also affected by the visual environment (Kleinhans, 1971; see Matin & Li, 1995 for a comprehensive review). For example, Stoper and Cohen (1989, Exp. 1) had observers peer into a large box. The rear of the box was pitched up or down 15° relative to the front of the box. The task was to indicate with a laser pointer the location on the rear wall of the box that was at eye level (visually perceived eye level, or VPEL). Observers' perceived eye level was raised or lowered in the direction of the pitch environment by an average of nearly 10°. This effect is called the pitch or the pitch-box effect.

Several studies have found a positive correlation of about .74 between susceptibility to the pitch illusion and the rod-and-frame effect (e.g., Guzy, Cohen, & Ebenholtz, in press; Poquin, Ohlmann, & Barraud, 1998). The problem with these studies is that they fail to address the cause of this correlation. Does it reflect a common mechanism for the spatial representation of pitch and roll or, alternatively, the observer's overall susceptibility to the illusion-inducing component of the stimulus?

It is possible that when making one judgement (e.g., pitch), transforming the other dimension (e.g., roll) might increase the illusion. It is known that having an observer sit in a tilted (rolled) chair increases the roll effect (e.g., Asch & Witkin, 1948; Prinzmetal & Beck, 2001; Witkin & Asch, 1948). The source of this effect is not clear, but it may be that unusual posture increases disorientation, causing observers to rely more on the visual stimulus. A rolled visual environment might set up a conflict with gravitational vertical, similarly increasing disorientation, and increasing the pitch effect. It might be that an environment that is pitched and rolled causes disequilibrium, which makes observers attempt to ignore gravity. Thus, there are reasons that when making one judgement (e.g., pitch), transforming the other dimension (e.g., roll) might increase the illusion.

Alternately, the hypothesis that rolling the environment would decrease the pitch effect (and pitching the environment would decrease the roll effect) comes from a series of papers by Redding (1973, 1975). Redding was interested in a similar problem, the relation between adaptation to a rolled visual environment and adaptation to an environment that has undergone lateral displacement. He reasoned that if tilt and displacement adaptation were based on a shared mechanism, an environment that was both tilted and displaced would create a greater problem for the visual system than one that was just tilted. Hence, he predicted less tilt adaptation to an environment that was tilted and laterally displaced that one that was just tilted.

His experiments (Redding, 1973, 1975) compared performance on a rod-and-frame task after adapting to either a visual environment that was just tilted or tilted and laterally displaced. He found, counter to his hypothesis, that the lateral displacement did not affect tilt adaptation. Similarly, adaptation of a laterally displaced environment was not influenced by whether the environment was also tilted. He concludes that this is evidence for independent mechanisms mediating lateral displacement and orientation perception. Li and Matin (1996) also examined a related question. They varied the roll of two lines and found that each line had an additive effect on pitch judgements. However, they did not examine the effect of the roll of the visual environment on pitch judgements, nor the effect of pitch on roll judgements.

The present experiments are most similar to the work of Poquin et al. (1998, Exp. 1), who presented observers with a visual environment that was both pitched and rolled. Observers adjusted a rod that was free to rotate on both pitch and roll axes and thus reflected their perception of both of these dimensions. However, because the rod could be rotated along two dimensions, it was not possible to isolate one dimension at a time and ask whether the perception of one dimension is affected by the orientation of the other.

In the present research, three questions about the relation between the perceptions of pitch and roll are addressed:

1. When making judgements of pitch, does the roll of the environment also affect performance? In other words, if the environment is rolled, is the magnitude of the pitch–room effect increased or decreased?
2. When making judgements of roll, does the pitch of the environment affect performance?
3. How do observers integrate information about environmental pitch and roll when making a judgement about an orientation that falls in between these two cardinal orientations?

The first experiment used a within-subjects design to address these questions. In the presence of a simultaneously rolled and pitched visual surround, observers, on separate blocks of trials, adjusted a rod so that it appeared (1) gravitationally horizontal in the roll dimension (Figure 1a), (2) gravitationally vertical in the pitch dimension[1] (Figure 1b), and (3) gravitationally horizontal in the in-between (combined roll and pitch) dimension (Figure 1c).

The in-between condition was set up such that the orientation of the rod was at a 45° angle to straight-ahead viewing. Since both pitch and roll influence the actual 45° orientation of the room, both should also influence the perceived orientation of the rod, which lies along this angle. The issue in this task was how observers would combine information from the pitch and roll dimensions in making their judgement. The simplest model is that in-between judgements are a linear combination of pitch and roll. Such a result would be consistent with independent effects of visual pitch and roll. Alternatively, there could be a nonadditive interaction on the pitch and roll of the environment on the in-between judgement. This result would be inconsistent with independent effects of pitch and roll.

Our motivation for undertaking this research derived, in part, from visits to a roadside attraction sometimes referred to as an ''antigravity'' house (see, for example, Banta, 1995; Shimamura & Prinzmetal, 1999; www.mysteryspot.com), a few dozen of which are scattered across North America. When one enters one of these houses, facing forward, the visual environment is both pitched and rolled. The consequence is that balls appear to roll uphill, water appears to flow uphill, people appear to be standing at a gravity defying angle, it seems almost impossible to stand up from an apparently level chair, people appear to change

[1] Performance on this task has been shown to correlate highly with VPEL (Poquin et al., 1998; Welch, Post, Lum, Kang, Napoli, & Cohen, 1998). Hudson, Li, and Matin (2000) have questioned whether the perception of pitch is caused by the same mechanism as VPEL. However, we do not take a position on this issue. We were more interested in the perception of environmental coordinates, and thus the measure we employed was more appropriate for our goals than VPEL.

height depending on where they stand, etc. (Shimamura & Prinzmetal, 1999). One question we had was whether the transformation of visual pitch and roll has a synergistic effect, increasing the various illusions in the antigravity house. That is, are the illusions somehow magnified because both pitch and roll are perturbed?

EXPERIMENT 1

Method

Observers. Twelve undergraduate students (six males and six females) from the University of California, Berkeley, participated in the study as a means of fulfilling a course requirement. Subjects signed a standard consent form, which described the general nature of the experiment and indicated that they could withdraw from it at any time.

Materials. The visual surround consisted of a rectangular frame constructed out of PVC tubing (see Figure 2). The frame was 88-inches long, with a width and a height of 42.5-inches. Half-inch-wide strips of phosphorescent (glow-in-the-dark) tape affixed to the edges of the PVC tubing made it visible in the dark.

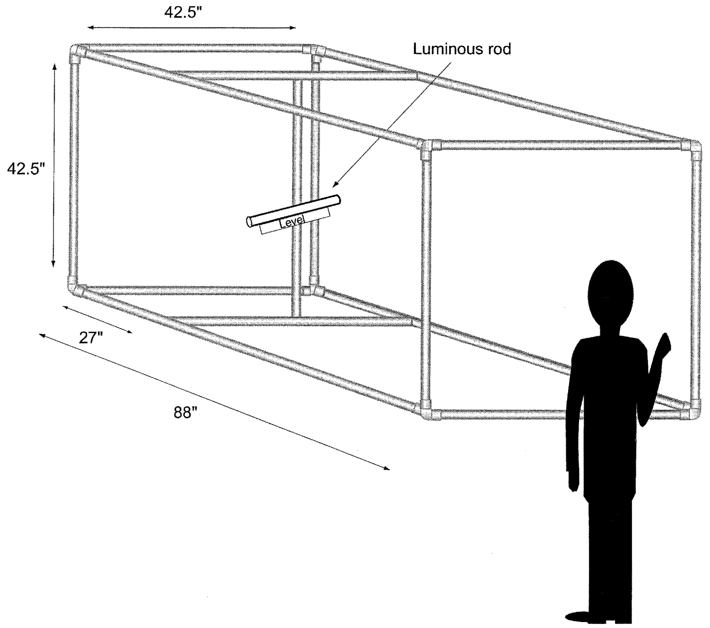

Figure 2. The apparatus used in the present experiments.

Each of the corners of the frame was attached to a pulley on the ceiling, such that the experimenters could adjust the height of each corner.

Attached to the centre of the frame, 27-inch from the back of the frame, was a luminous rod. The rod could be controlled with one degree of freedom by the observer by moving a string up or down. Attached to the rod was an electronic level, from which the experimenters could read its orientation. For the roll task the rod pivoted about its centre in the subject's frontal-parallel plane (Figure 1a). For the pitch task, it pivoted around its centre in the pitch dimension (Figure 1b). Finally, for the ''in-between task,'' the rod pivoted around its centre at a 45° angle from the observer's line of sight (Figure 1c).

Procedure. Observers were brought into the room with their eyes closed. They were given a string to adjust the luminous rod and then the overhead lights were extinguished. Next, they were instructed to open their eyes, and told how to adjust the luminous rod. After each adjustment, they turned their back to the apparatus, the lights were turned on, and the experimenters repositioned the frame. The overhead lights were turned off again before the next trial began.

Each observer participated in three blocks of trials, one for each task. In the roll judgement task (Figure 1a), observers adjusted the rod along a plane orthogonal to straight-ahead viewing, so that it appeared horizontal with respect to gravity. In the pitch task condition (Figure 1b), they adjusted the rod along a plane perpendicular to straight-ahead viewing, so that it appeared vertical with respect to gravity. Finally, in the in-between task (Figure 1c), they adjusted the rod along a plane midway between the pitch and roll conditions, at a 45° angle from straight-ahead viewing, so that it appeared horizontal with respect to gravity. On each trial, the initial setting of the rod was randomly offset from horizontal between about 20° clockwise and 20° counterclockwise. These three blocks were presented between observers in a Latin squares design.

Within each block, the frame itself was in one of eight positions. Pitch could be up 11°, down 11°, or 0°. Roll could be clockwise 11°, counterclockwise 11°, or 0°. The only combination of these conditions not included was both a pitch and roll of 0°, as this was not expected to affect judgements. There were two repetitions of all these positions (randomly presented) for a total of 16 judgements per block, and a total of 48 judgements per observer. The experiment took about an hour.

Results and discussion

Figure 3 shows the average error in degrees for observers' pitch, roll, and in-between judgements. Table 1 shows standard deviations across observers for all conditions.

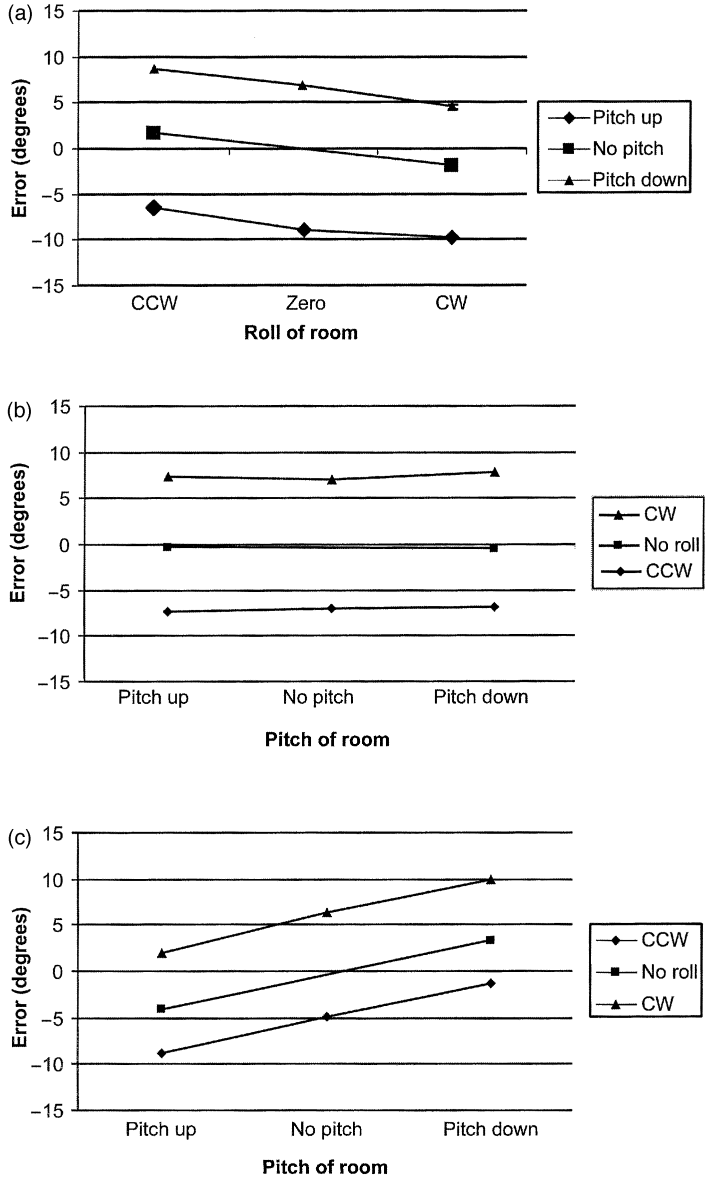

Figure 3. Average errors for the three conditions of Experiment 1. (a) shows the average error (always in the direction of the frame) for pitch judgements across the three roll conditions—counterclockwise (CCW) 11°, clockwise (CW) 11°, and no roll. (b) shows the average error (always in the direction of the frame) for roll judgements across the three pitch conditions—pitch down 11°, pitch up 11°, and no pitch. (c) shows the average error for the in-between condition. Positive error is in the CW and pitch down direction; negative error is in the CCW and pitch up direction.

TABLE 1
Standard deviations (in degrees) across observers for Experiment 1

	Judgement		
	Pitch	*Roll*	*In-between*
Pitch down			
CCW	2.73	2.22	2.66
CW	5.12	2.44	3.78
No roll	2.40	1.14	3.23
Pitch up			
CCW	5.09	1.81	2.15
CW	7.27	1.75	2.88
No roll	5.09	1.40	1.40
No pitch			
CCW	5.54	2.12	2.10
CW	6.16	2.67	2.74

Consistent with previous experiments (Guzy et al., in press; Poquin et al., 1998), the magnitude of the pitch error and the roll error was positively correlated across observers, $r = .54$.

Analyses of variance (ANOVAs) on the factors of both pitch and roll for each task revealed several effects. In the roll task, there was a main effect of frame roll, $F(2, 22) = 224.6$, $p < .001$, but no effect of frame pitch, $F(2, 22) = 0.40$. In the pitch task, there was a main effect of frame pitch, $F(2, 22) = 94.27$, $p < .001$, and a smaller effect of frame roll, $F(2, 22) = 6.25$, $p < .01$. The latter effect is that when the room was rolled clockwise, observers had a tendency to adjust the rod consistent with pitch up. Importantly, there was *no* interaction between the pitch and roll tasks and frame orientation for the roll task, $F(4, 44) = 1.42$, $p >$ .05, and for the pitch task, $F(4, 44) = 0.32$. That is, there was no difference in the *magnitude* of error for different frame pitch in the roll task and for different roll in the pitch task. We do not have an explanation of why the pitch judgements were affected in the presence of roll. However, the factor of interest was whether the amount of error in pitch or roll judgements would be affected by frame orientation in the orthogonal dimension, and the findings indicate that they are not.

Both pitch and roll affected the in-between condition (Figure 3c). There was both a main effect of pitch, $F(2, 22)=131.28$, $p < .001$, as well as a main effect of roll, $F(2, 22) = 93.95$, $p < .001$.

Despite the fact that both pitch and roll of the frame had an effect on in-between judgements, there was *no* interaction of the two, $F(4, 44) = 0.21$.

Consistent with the lack of interaction in the ANOVA, the settings in the in-between error, *e*, can be expressed as a linear model with two parameters, the pitch of the frame (*p*) and the roll of the frame (*r*). The result of fitting the data by means of linear multiple regression was:

$$e = 0.35^* p + 0.51^* r \tag{1}$$

This equation provides an excellent fit of the data, $R^2 = .99$, and it was unnecessary to include an interaction term.

An alternative way of expressing the relation of in-between error and environmental pitch and roll emerges from the fact that in the three-dimensional physical world, roll and pitch can be varied independently. Because of this independence, the following relation holds for an in-between condition that is midway between the pitch and roll dimensions:

$$B = \arccos\left(\sqrt{\frac{(\cos\ \theta)^2 + (\cos\ \phi)^2}{\sqrt{2}}}\right) \tag{2}$$

where θ = frame roll, and ϕ = frame pitch , and *B* is the in-between angle measured relative to gravity (0° is level, see Figure 1c). Thus, environmental pitch and roll can be collapsed into one variable, *B*. If perceived environmental pitch and roll are *psychologically* independent such that equation 2 holds for observers, the in-between error, *e*, should be:

$$e = \mathrm{a} + (\mathrm{b}\ {}^* B) \tag{3}$$

a and *b* are parameters, and *B* is the physical in-between angle, as calculated above. Fitting this equation, we obtained:

$$e = 0.30 + (0.73^* B) \tag{4}$$

This regression also provides a good fit of the data, $R^2 = .93$. Note that this relation does not require a reference frame anchored to the observers' ''straight ahead''. In other words, horizontal, vertical, and the observer's straight ahead do not have to be special. However, equation 2 does require that the dimensions are psychologically independent.

In summary, the results of the first experiment demonstrated that (1) a rolled visual surround influences the apparent roll of an object located within the surround but not the magnitude of its apparent pitch, (2) a pitched visual surround affects the apparent pitch of the object, but not the magnitude of its apparent roll, and (3) judgements for an orientation midway between pitch and roll appear to be based on a linear combination of environmental pitch and roll.

EXPERIMENT 2

The results of Experiment 1 demonstrated that judgements of a dimension between pitch and roll (i.e., the in-between task, see Figure 1c), could be modelled as a linear combination of the pitch and roll of the visual environment. This result may be misleading, however, owing to the fact that our manipulation of visual surround orientation entailed 0° conditions, which presumably had no effect on the subjects' perceptual judgements. Therefore, it could be argued that, functionally, subjects were exposed to only two levels of each of rotation, making our finding that the in-between judgements could be modelled by a linear combination of pitch and roll inescapable regardless of the true relationship that exists. The goal of Experiment 2 was to clarify this situation by increasing the number of levels of pitch and roll and thereby determine whether a linear combination of pitch and roll continued to account for the in-between task judgements.

Methods

Observers. Twelve undergraduates (seven males, five females) from the same pool of observers used in Experiment 1 participated in this study

Procedure. The same apparatus was used as in Experiment 1 and, with a few exceptions, the same experimental procedure. Subjects were measured only on in-between judgements. There were five conditions for pitch (11° down, 5° down, no pitch, 5° up, and 11° up) and five conditions for roll (11° counterclockwise, 5° counterclockwise, no roll, 5° clockwise, and 11° clockwise) that were combined in all possible ways, for a total of 25 judgements per observer (i.e., one observation per condition).

Results and discussion

The average in-between error for each level of pitch and roll and their standard deviations are presented in Figure 4 and Table 2, respectively. The results were similar to those of Experiment 1: A main effect of pitch, $F(4, 44) = 59.44$, $p < .001$, and roll, $F(4, 44) = 42.09$, $p < .001$, but no Pitch × Roll interaction, $F(16, 176) = 1.41$, $p > .05$.

Analysing the data with linear regression (see equation 1) produced the following result:

$$e = 0.37^{*}p + 0.37^{*}r \tag{5}$$

where e is the in-between error, p is the frame pitch, and r is the frame roll. This relation provided a good fit of the data, $R^2 = .97$. Consistent with the ANOVA, an interaction term was unnecessary.

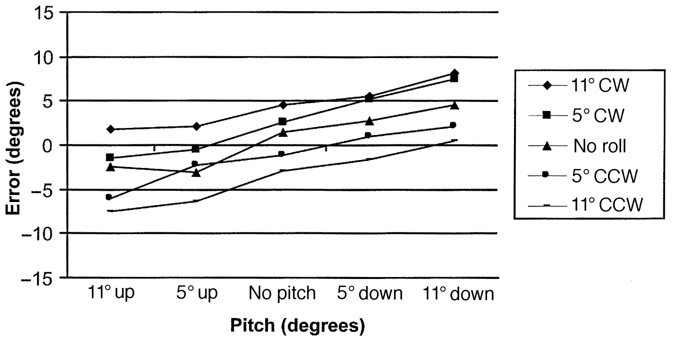

Figure 4. Average errors for Experiment 2. All judgements were made on the in-between angle. Positive error is in the CW and pitch down direction; negative error is in the CCW and pitch up direction.

TABLE 2
Standard deviations (in degrees) across observers for Experiment 2

Roll	*11° up*	*5° up*	*No pitch*	*5° down*	*11° down*
11° CW	4.59	2.65	3.40	2.77	3.67
5° CW	5.50	3.58	2.69	3.27	2.59
No roll	6.42	3.12	2.20	2.38	2.59
5° CCW	4.87	3.93	2.89	2.83	2.13
11° CCW	3.99	3.87	3.96	3.39	2.31

As in Experiment 1, this formula can be reduced to a single parameter equation, as long as the assumption of psychological independence of pitch and roll (as assumed in equation 2) holds. Fit with this single parameter:

$$e = 0.59 + 0.64^{*}B \tag{6}$$

This relation provides a good fit of the data, $R^2 = .94$.

In sum, this experiment replicated the results of Experiment 1 in its demonstration that the in-between error can be accounted for by a linear combination of environmental pitch and roll.

GENERAL DISCUSSION

The results provide a clearer understanding of the perceptions of pitch and roll and their interrelationship. The fact that changing the roll or pitch of the environment has no effect on the magnitude of judgements in the other dimension narrows the possibilities for their interaction. Using the same logic

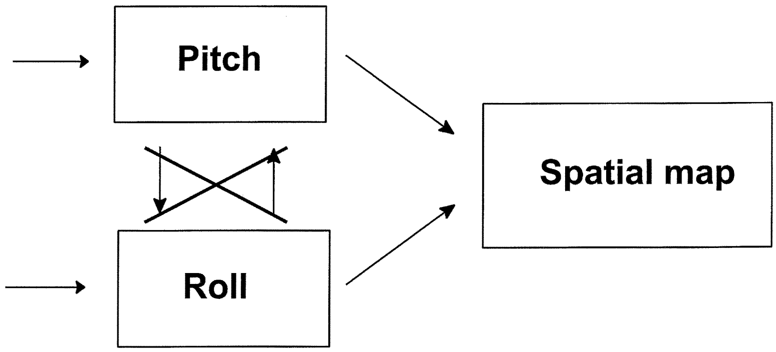

Figure 5. A schematic for the relation between pitch and roll perception. See text for details.

regarding the dissociability of cognitive mechanisms as Redding (1973, 1975) in his studies on orientation and displacement adaptation, we conclude that the two systems are, at least in some respects, independent of one another.

A simplified schematic of the implications of our results is shown in Figure 5. Both pitch and roll perception are assumed to provide inputs to a complete 3D spatial map. Our findings indicate that the output of pitch perception does not have any impact on the perception of roll, and the output of the roll perception does not have any impact on the perception of pitch. This is indicated in the schematic by the removal of connections between pitch and roll.

Note that the schematic says nothing about whether this process is done in parallel or whether one precedes the other in a serial fashion. Although it is tempting to place roll perception before pitch perception because roll perception requires an ''earlier'' (i.e., 2D) representation, we have no direct evidence about this. That is, there is no logical or empirical reason to state that roll perception need operate on a 2D representation rather than a full 3D representation.

Another consideration regarding the relation of pitch and roll perception involves the relative weighting of environmental pitch and roll when making in-between judgements, when they both contribute to the percept. For this weighting purpose, a potentially important difference is that pitch perception involves the integration of depth information whereas roll perception does not.[2] Reconstructing depth is an ''extra step'' of processing, and is inherently less constrained than the 2D representation needed for roll perception. Because of the greater inherent uncertainty in pitch perception, we might expect that the variability of responding should be greater for making pitch judgements than for roll judgements.

[2] Li and Matin (1996; Matin & Li, 1992, 1994) have argued that pitch can be determined without a 3D representation from the 2D retinal projection. It may indeed be possible to obtain a pitch effect measured with VPEL from a two-dimensional representation. Our method of measuring pitch (setting a rod to vertical), however, probably requires depth perception.

Support for this expectation is found in the group standard deviations, which are presented in Tables 1 and 2. The average variance for pitch judgements was 4.83°, whereas for roll judgements it was only 1.45°. This is a significant difference, $t(1, 12) = 5.01$, $p < .001$, Scheffe adjusted.

In this case where the variance differs, an ideal observer would presumably assign a greater perceptual weight to the dimension with the lesser variance (e.g., see Ernst & Banks, 2002; Ernst, Banks, & Buelthoff, 2000; Landy, Maloney, Johnston, & Young, 1995). Thus, one would expect that when integrating pitch and roll for in-between judgements, a greater weight would be given to roll than pitch. That is what we found in the regression equation of Experiment 1. In Experiment 2, the weights assigned to pitch and roll were nearly equal. Unfortunately, we do not have independent estimates of the variance of pitch and roll judgements in that experiment. We do not know why the weights differed in the two experiments. However, this does not invalidate the ideal observer model; it might simply reflect individual differences (Ernst et al., 2000).

Our research has addressed the nature of the functional relation between pitch and roll perception. Although it does not address what neural substrates may underlie them, it does pose an interesting question for future research. Is it the case they are mediated by separate modular neural mechanisms so that, for example, some specific brain damage might affect the perception of roll, but not pitch? We have not heard of such a patient; however, it is unlikely that anyone has even looked for such a disorder.

On a final note, our question about the workings of orientation illusions at antigravity houses can now be answered. We now know that there is no increase in the size of the illusion when the environment is simultaneously pitched and rolled. Rather, in whichever direction an observer (visitor) is facing, he or she will be affected, in an additive manner, by the combination of pitch and roll of the environment.

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