Pitching up in VR

H. L. Jenkin, R. T. Dyde, M. R. Jenkin[1], L. R. Harris[2]

Centre for Vision Research and
Departments of Computer Science and Engineering[1] and Psychology[2]
York University,
4700 Keele St., Toronto, Ontario, Canada, M3J 1P3

hjenkin@yorku.ca, dyde@hpl.cvr.yorku.ca, jenkin@cs.yorku.ca, harris@yorku.ca

Abstract

Virtual reality is often used to simulate environments in which the direction of up is not aligned with the normal direction of gravity or the body. What is the effect of such an environment on the perceived direction of up? In earlier work (e.g. [8]) we examined the effect of a wide-field virtual environment on the perceived up direction under different simulations of tilt (rotation around the naso-occipital axis). Here we extend this earlier work by examining the influence of a wide-field virtual environment on the perceived direction of up under different simulations of pitch (rotation around the inter-aural axis). Subjects sat in a virtual room simulated using an immersive projective display system. The room could be pitched about an axis passing through the subjects' head. Subjects indicted their perceived direction of up by adjusting the orientation of an indicator until it aligned with the perceived direction of gravity. Subjects' judgments indicated that for physically upright subjects the visual display is an important factor in determining the perceived up direction. However as was found to be the case for roll simulations, this technique for influencing a subject's perceived direction of up is most effective for pitch rotations within approximately ±35° of true gravitational vertical.

Key words: human performance, virtual reality, human perception, subjective visual vertical

1. Introduction

In virtual reality (VR) it is often desirable to simulate an up direction that differs from the 'up' defined by gravity. This is necessary in situations as varied as the development of effective amusement park rides and the development of teleoperational interfaces for remotely piloted devices. Failure to correctly capture the intended up direction may have a significant effect on tasks performed in VR (see [1] for a discussion of the effect of a tilted visual display on eye-hand coordination) When an up direction that is not aligned with gravity is simulated, the operator is presented with conflicting cues to the up direction. How does the operator combine these cues into a single coherent sensation of the direction of up?

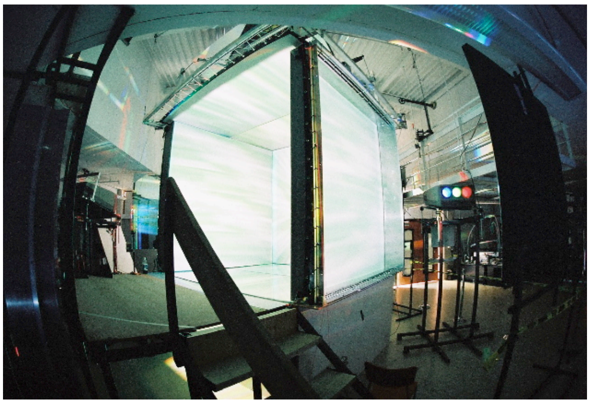


Figure 1. External view of IVY. IVY is a fully immersive projective environment. All of the six external surfaces (including the floor and ceiling) present rear projected stereo imagery. Note that the back wall (shown open here) can be closed on the user.

Extensive psychophysical research (see [6,7,13] for reviews) has identified the following three factors as crucial contributors to the perceived up direction:

The Body Axis. Axes related to the orientation of the body can be defined relative to the eye (oculocentric), head (craniocentric) or body (somatocentric). In the experiments reported here we kept the eye, head and body approximately aligned in their normal arrangement and consider the whole as a single, body-centred reference frame. The brain's representation of this direction is referred to as the idiotropic vector (see [10]). Head mounted display-based virtual reality systems occlude the view of one's body, thus potentially weakening the idiotropic vector. Immersive Projective Displays permit the view of the body thus possibly providing stronger bodycentric cues. The experiments

Figure 2. Exploded view of the display. Facing forward the subject viewed a hallway that pitched up and down about an axis that passed through their ears. A bar was displayed in front of the subject that could be adjust through the use of a gamepad. See also Figure 3.

reported here did not manipulate the orientation of the body axis.

The Physical Direction of Gravity. Internally the direction of gravity is sensed by the utricles of the vestibular system and by proprioception and touch sensors. The changes in force needed by muscles when they are working with or against gravity can also provide a cue to the direction of gravity[7]. Touch receptors detect the force that the weight that the body applies to support surfaces through the feet when standing and back and buttocks when seated. There are techniques that can be used to disrupt the normal function of the utricles (such as electrical stimulation through the skull behind the ears [2,3]), and touch sensors (eg. by use of cushions or water tanks that apply pressure equally over the body surface or by providing additional applied pressure). The force of gravity can also be manipulated experimentally. For example, it can be cancelled by parabolic or space flight, or redirected by the addition of other accelerations using a sled or centrifuge. As with the body axis, the experiments reported here did not manipulate the direction of gravity.

Visual Cues. Vision provides orientation cues that are intrinsic to individual objects or contained in the structure of the environment. Intrinsic cues include the fact that objects and people usually stand up in a particular way, that people's hair is usually on the top of their heads, and that fluids are to be found at the bottom of containers. Environmental cues include the general structure of the frame including the walls, ground plane, and ceiling, or sky. Usually, virtual reality visual displays provide orientation cues from both the properties of the individual objects and from the overall structure of the entire visual scene. In the study reported here the individual components of the visual scene were not manipulated, rather the entire visual environment moved as a coherent whole.

2. Which way is up?

Given the various and potentially conflictingcues to the direction of up, how does a subject determine which way is up?

In an earlier study [8] we examined how subjects combine the competing visual, body axis and gravity cues to the up direction within a wide-field virtual environment at different roll angles. This earlier work validated a weighted vector sum direction model for small (±35°) roll rotations[8]. That is, the perceived direction of up under roll can be expressed as the direction of

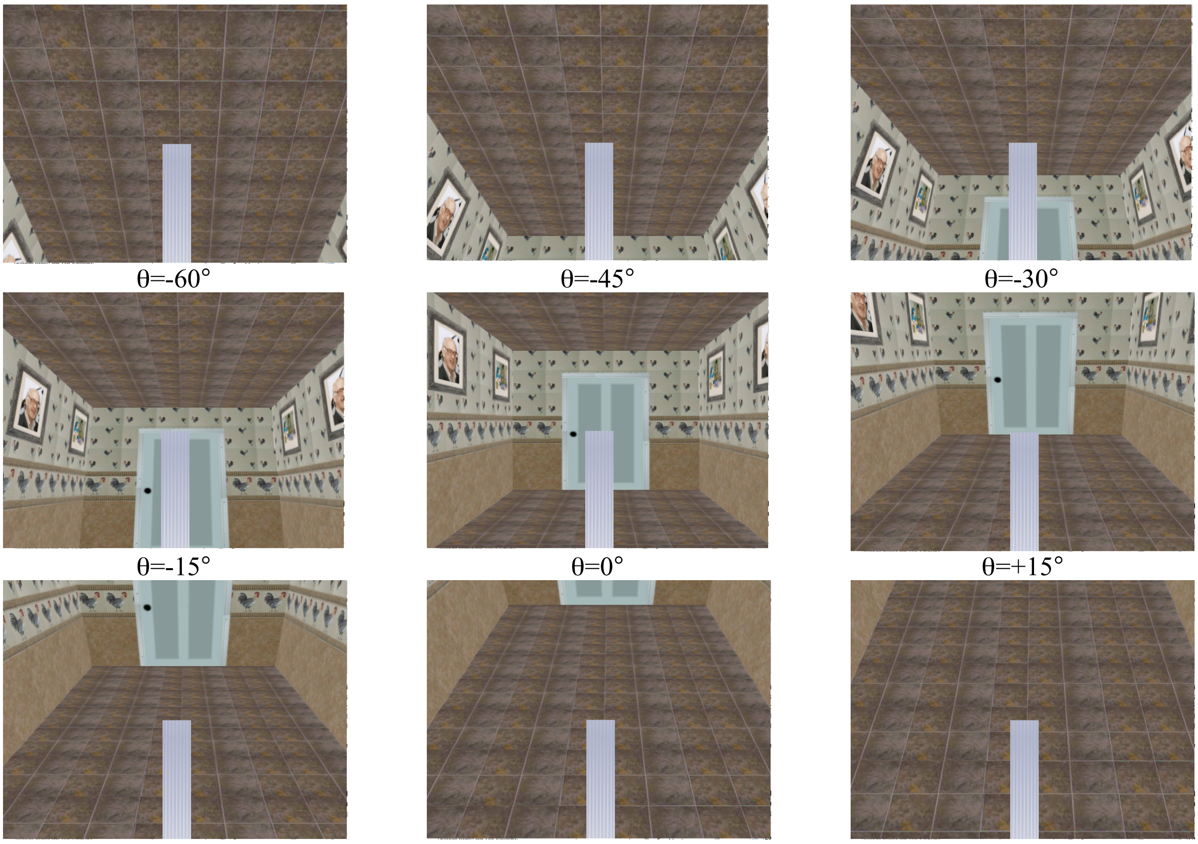
$$\overrightarrow{up} = k_1\overrightarrow{gravity} + k_2\overrightarrow{body} + k_3\overrightarrow{vision}.$$

This model has been found to be quite effective in modeling the perceived up direction under various combinations of visual, body and gravity cues for roll rotations of the visual cue relative to body. Here we extend this earlier work and examine how the conflicting cues to the perception of up are combined under different static *pitch* presentations of the visual environment.

3. Method

3.1 The Immersive Visual environment at York (IVY).

In order to separate the directions of visually defined up and those of the gravity and the body, experiments were conducted inside the Immersive Visual Environment at York (IVY), an immersive projective display illustrated in Figure 1. IVY is a 243 cm x 243 cm x 243 cm, six-sided immersive projective display housed within the Computer Science and Engineering Building at York University, Canada. Stereo imagery is presented on IVY's six walls and decoded using CrystalEyes glasses. Long-range IR emitters have been found to be sufficiently powerful to be transmitted through the walls, floor and ceiling of IVY and to drive CrystalEyes glasses worn by an observer within IVY. Imagery projected on the walls are displayed at 1024x768 at 96hz. Imagery on the ceiling and floor are displayed at 1024x1536 at 96hz. Head tracking within IVY is normally accomplished via a novel hybrid tracking system [5] although for the experiments reported here, no head tracking was required as the subject's head was restrained. Video is generated via a cluster of tightly synchronized Linux workstations equipped with Nvidia FX3000G graphics cards. The FX3000G provides external synchronization to the video signals ensuring that the video frames being displayed are properly synchronized to the CrystalEyes glasses. Full details of IVY and its construction can be found in [11] and [12].



θ=-60° θ=-45° θ=-30°

θ=-15° θ=0° θ=+15°

θ=+30° θ=+45° θ=+60°

Figure 3. The nine room pitches as seen by the subject. The visual display fully surrounded the subject so that the views shown here are just the central portion of the display. The adjustable rod is visible. The room pitched about the subject. The rod was simulated 120cm in front of the subject.

3.2 Visual display.

Subjects sat in a simulated 243 x 243 x 486 cm^3 (wxhxd) room with their back just in front of the simulated back wall of the room. The room contained no three dimensional structure within it, but consisted only of walls decorated with pictures and a textured floor and ceiling (see Figures 2 and 3). The front wall of the simulated room was 446cm in front of the subject. The simulated room was pitched at one of nine orientations (-60°, -45°, -30°, -15°, 0°, 15°, 30°, 45°, 60°) around the interaural axis. The physical structure of IVY was thus not necessarily aligned with those of the simulated room. The room image was neutral in terms of the point of illumination. That is no lighting cues as to the apparent direction of illumination were provided by the textured walls, floor or ceiling of the room.

3.3 The probe of the subjective visual vertical.

A critical issue in evaluating the perceived up direction is the nature of the probe to be used. In [8] we used a probe based upon the perceived concavity/convexity of a shaded disk. The convexity probe exploits the fact that the perceived three-dimensional shape of an object is deduced using the assumption that the illumination comes from above. The probe is a shaded disc that looks like a convex hemisphere when its shading is oriented to be compatible with light coming from above. Thus the perceived up direction could be deduced from the orientation of the disc that appeared maximally convex. This technique however was not possible here because the disc needs to be viewed face on or else disparity and monocular perspective cues prevent the illusion of convexity. We therefore used a modified luminous line task for the present study.

A virtual plank (10cm wide x 100cm tall see Figure 3) was hung from a virtual hinge at a fixed point 120cm directly in front of the subject with its flat surface facing the subject. The hinge point was not affected by the pitch of the room. The pitch of the plank was adjustable by the subject by means of two Gamepad buttons that altered its pitch in steps of 1 degree in opposite directions. The edges of the plank provided clear binocular disparity cues as to the orientation of the plank, in addition to the monocular perspective cues. The plank probe is a VR extension of the classical luminous line probe that has been used extensively in the psychological literature since the mid 1940's (see [14] and [9] for example). More recently, the luminous line test has been used in the VR community as a

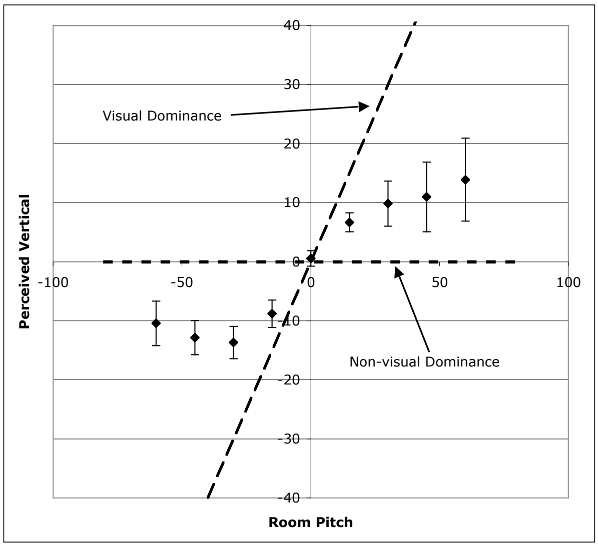


Figure 4. Subject responses. If the subject chose the pitch of the plank based on the visual display alone, their responses would have fallen on the diagonal dashed line labeled "visual dominance". If they chose based on the true gravity or body axis, their responses would have fallen on the horizontal dashed line labeled "non-visual dominance". Subjects followed a strategy where they responded between these two extremes. Error bars indicate standard errors

measure of the efficacy of VR (see [4]). In classical psychological experiments, subjects align a luminous line (often in the dark) to indicate their subjective vertical. Given aliasing and other rendering issues associated with VR displays, the traditional rod is replaced here with a plank probe. As can be seen in Figures 2 and 3, the plank itself is textured with a vertical texture. A vertical texture was chosen to enhance disparity cues that are associated with the structure.

3.4 Procedure.

Twelve subjects participated in the experiments. Subjects were drawn from the York University graduate student population and from researchers in the laboratory. Subjects sat on a chair in the physical centre of IVY directly in front one of the walls with their viewpoint 121cm above the physical floor. A room was simulated around the subject in one of the nine pitch orientations (see Figure 3). Subjects were instructed to adjust the plank probe until it appeared vertical and that something dropped from the top would land at the base of the plank. Subjects pressed a third button on the Gamepad to indicate their choice and to move on to the next trial.

This adjustment process was repeated nine times from different starting orientations of the rod (-60°, -45°, -30°, -15°, 0°, 15°, 30°, 45°, 60°) for each room orientation, in a random sequence resulting in 81 trials per subject.

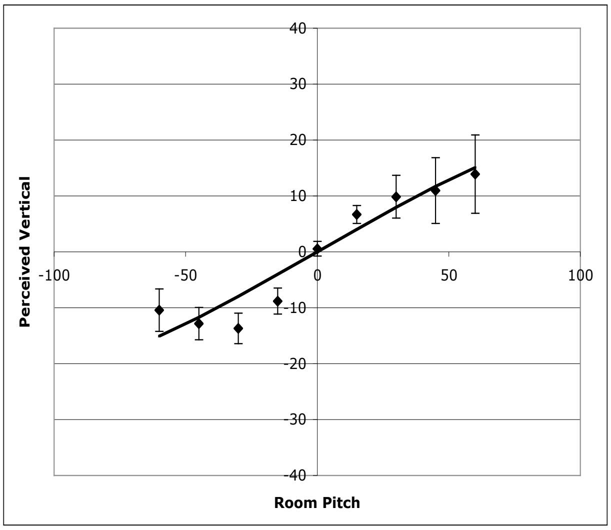


Figure 5. The weighted vector sum direction model with the visual cue weighted 0.37 relative to the gravity/body vector. fitted to the data.

4. Results

Although there was significant variability among subjects, the setting of the plank probe was quite accurate for the zero pitch condition across all subjects (mean=+0.5 degrees, standard deviation +/- 4.7 degrees, standard error +/- 1.3 degrees). Figure 4 shows the orientation (plotted on the vertical axis relative to the body and gravity) to which subjects' adjusted the plank to indicate vertical as a function of the simulated pitch of the room. The horizontal scale indicates the pitch of the room relative to the body and gravity (0 indicates aligned with gravity, positive orientations corresponds to the room pitching 'up' as viewed by the subject, negative orientations correspond to the room pitching down – see Figure 3). If subjects had set the plank to indicate their perception of up based on visual information only, their responses would have fallen along the diagonal dashed line. If subjects had set the plank based on gravity and body orientation only, their response would have fallen along the horizontal dashed line (that is, they would have been unaffected by the visual pitch of the room).

The results clearly indicate that the perceived up direction was influenced by the orientation of the visual display; that is, the data do not follow a horizontal line. The visual display did not, however, completely dominate (or capture) the perceived 'up' direction as indicated by the fact that the data do not follow the oblique dashed line either.

The linear vector sum direction model [ref] can be simplified for the experimental condition considered here (in which gravity and body are aligned). In this case, the predicted up direction is the direction of the weighted sum of the coupled gravity+body vector and

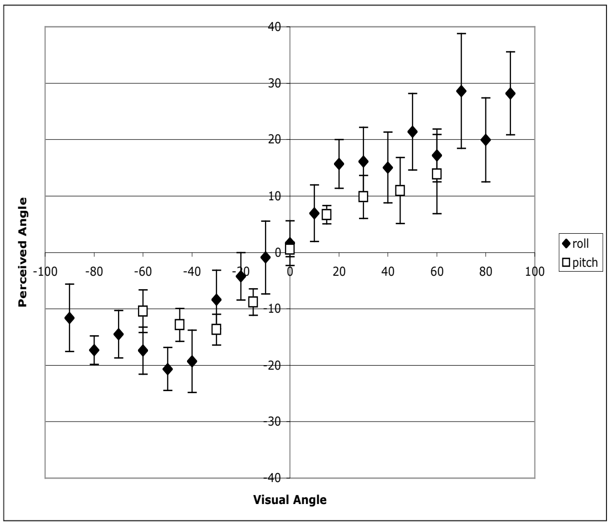


Figure 6. Comparison between roll[6] and pitch data. Although the roll and pitch data were collected using different probes, very similar patterns of responses are obtained.

the vision vector. Assigning the gravity+body vector a weight of 1, results in

$$\overrightarrow{up} = \overrightarrow{gravity + body} + \overrightarrow{kvision}$$

where k is the weight of the vision frame relative to the body-gravity frame. Expressing the up direction (θ_{up}) in terms of the visually defined up direction (θ_{vision}) and the unknown relative strength k of the vision vector relative to the body-gravity frame, then

$$\theta_{up} = \tan^{-1}(\frac{k\sin(\theta_{vision})}{1+k\cos(\theta_{vision})}).$$

Fitting this expression to the data plotted in Figure 4, indicates that the visual cues is weighted 0.37 as much as the as the body/gravity vector (k=0.37). Using this weighting the predicted direction of the subject visual vertical can be calculated for all visual angles. The prediction is plotted as a solid line through the data in Figure 5.

5. Discussion

When presented with a visual environment relative to themselves and gravity, subjects have competing cues as to which way is up. The visual display defines up according to the polarized visual cues, and especially according to the structure of the surfaces, which in this case are provided only by the walls and ceiling of the room. The body and gravity axes are aligned with each other in this study although they could be easily separated through maneuvers such as repositioning the subject's body with respect to the gravity vector (i.e. by having the subject lying down). How do subjects combine these cues to provide a single up direction? Results presented here for pitch suggest that for a pitch mismatch between gravity-body and visually defined up, the resulting perceptual up is neither the up defined by gravity-body nor that defined by the visual display. Rather for pitch angles in the range -60° to +60° an up direction is computed that can be approximated as a weighted vector sum of the two, where the visually defined frame is weighted 0.37 relative to the body-gravity frame.

In [8] we demonstrated that a simple vector sum direction model could explain how subjects combined visual and gravity-body cues to estimate the up direction when the visual environment was manipulated in roll. The data from [8] are superimposed on the present data in Figure 6. Pitch data (open symbols) here shows a similar pattern to roll (closed symbols) although the effect of visual tilt appears slightly larger for roll than pitch. For roll the relative weighting of vision was 0.45, slightly higher than the 0.37 value obtained here. The difference may be due in part to differences in the experimental protocols of the two experiments. The roll data was collected in the same virtual room but the estimate of up was made with a convexity test that is more biased towards the visual cue.

5.1 Implications for VR.

Many aspects of the perception of a scene include and depend upon a reference direction of verticality and 'up'. For example, reading an instrument, interpreting the status of an on/off switch, as well more fundamental acts of perception such as perceiving the relative orientation of the horizon, and predicting which way things are going to fall or curve when thrown. Consider a virtual reality interface for teleoperation of an aircraft. Perceiving the scene correctly as the aircraft – and hence the resulting visual display – pitches, rolls and yaws includes matching the perceived direction of up in the real world and simulated situations. The present study indicates that the perceived direction of vertical can be manipulated by simply reorienting the visual environment. These manipulations, however, will not completely shift the perception of up in the expected direction in the presence of competing gravity and body orientation cues.

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