ICAT 2003
December 3-5, Tokyo, JAPAN

In Virtual Reality, which way is up?

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

Centre for Vision Research and
Departments of Computer Science[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. How effective are these environments in terms of generating a compelling illusion of different up directions? Here we examine this question by asking: "In virtual reality, which way is up?". Using an immersive projective display, subjects sat in a virtual room that could be rolled about the line of sight. Subjects indicted their perceived direction of up by adjusting the orientation of a shaded disk until it appeared maximally convex. This orientation depends upon the perceived direction of the illumination which thus indirectly indicates the perceived direction of up. Their judgements indicate that for physically upright subjects the visual display is an important factor in the perceived up direction. However this technique is limited to roll rotations away from the gravity direction in the range ±35°.

Key words: human performance, virtual reality, perception.

1. Introduction

In many VR applications the direction of 'up' defined by gravity differs from the direction of up defined by the visual display. Consider the case of flying an unmanned aircraft such as the US Air Force Predator or US Navy Pioneer via a teleoperational link. As the aircraft undergoes maneuvers such as banking or turning, the operator – who typically remains seated while viewing instruments and a live video feed from the remote aircraft – is presented with a visual display obtained from a camera fixed to the remote vehicle. The operator is thus presented with conflicting cues as to the direction of up. The visual display is aligned with the aircraft and objects within this display, such as the ground and sky, define a particular direction of up. The operator's ground-based station also defines its own direction of up, as does gravity. The relationship between gravity and visual cues, such as the orientation of the ground plane for this remote operator, are different from that experienced by a person actually sitting in the flying cockpit. How might an operator combine these different cues to obtain a perceived up direction while remotely piloting the vehicle? How might this perception differ from the experience of someone actually flying the aircraft? And what might be the consequences of any differences between two?

Figure 1. The left and right views of the face appear normal (and similar) when viewed in the 'normal' orientation. Large structural changes are easily overlooked in the upside-down face, but these changes become readily apparent when the face is seen in its normal upright orientation. This figure is based on the Thatcher Illusion[15].

The direction of up is fundamental for many aspects of perception and determines not only our ability to move around and remain oriented within an environment but also helps us to identify objects. Figure 1 demonstrates the significance of the perception of up, even on the printed page. First, view the figure in its normal orientation. Then view the figure "upside down". Distortion of the features of the face are not evident but become readily apparent when the page is rotated "upside down" and the faces become "upright" (after [15]).

The perception of the direction of up has received considerable study in the psychological literature (see [4], [6] and [14] for reviews). The perceived up direction has been shown to be influenced by a number of factors including the orientation of each of the following frames of reference (see [4]):

The Body Axis. Bodycentric axes can be defined by the eye (oculocentric), head (headcentric) or body (bodycentric) orientations. In the experiments reported here we kept the eye, head and body approximately aligned in their normal arrangement and consider the

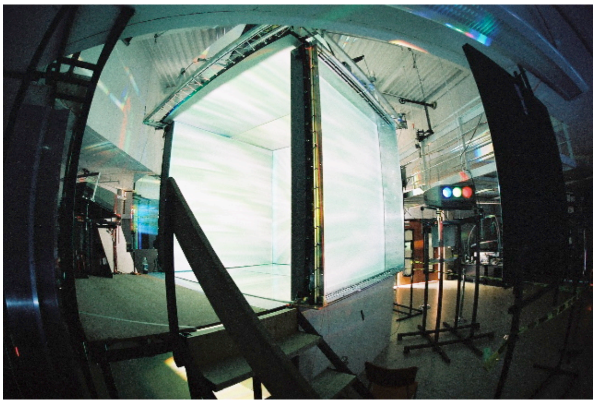

Figure 2. IVY. the 6-sided immersive projective environment used in this experiment. IVY is shown here with the rear wall open

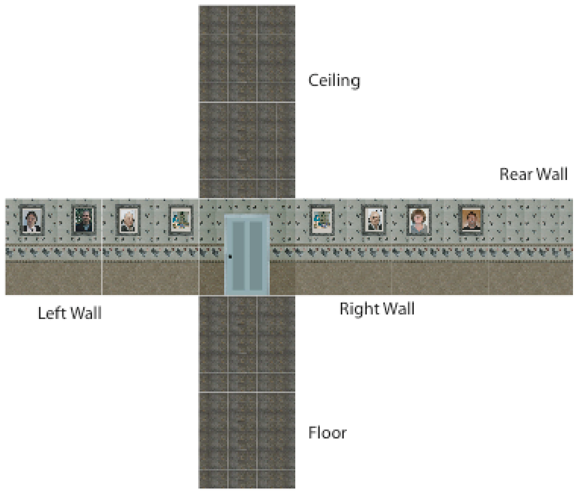

Figure 3. Simulated environment shown in an 'exploded' view. Subjects were presented with a fully enclosed (six sided) visual environment 243x243x486cm^3. Subjects sat opposite the front wall textured with a large door. The entire environment was presented in different static roll orientations.

whole as a single, body-centred reference frame. This is referred to as the idiotropic vector [9]. 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 providing stronger bodycentric cues.

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. 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 [1, 2]), 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.

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.

2. Determining which way is up

Earlier work (see [7,8,9,10]) investigated the various factors that influence the perceived up direction. One critical issue in investigating these factors is finding an object measure of a subject's perceived direction of up. Various methods have been used including simply pointing, or aligning a rod with the subjective vertical or horizontal. These methods involve drawing a subject's attention to the idea of up – a concept of which they are not normally aware – and therefore involve cognitive factors.

To reduce the influence of cognitive factors we used a task that requires knowledge of up but which does not require a subject to consider the question directly. In the absence of information about the origin of illumination, people interpret surface structure revealed by shading and shadows by assuming that the direction of illumination is from above [4,5,10,11]. This tendency can be used to explore the direction that an observer perceives as up. The "light from above" assumption allows observers to resolve the visual ambiguity presented by a flat representation of a surface with only a shading gradient.

3. Experimental Design

Experiments were conducted inside IVY, an immersive projective display (see Figure 2). IVY (the Immersive Visual environment at York) 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. Given the limited physical space available for IVY, video for three of the four vertical walls, and the floor and ceiling are projected using mirrors to bend the light path within the available physical footprint. The floor and ceiling displays are generated using two projectors, in order to reduce the total physical height of the device.

A sliding back wall provides entry to and exit from this enclosed space. With this wall slid back in place, an

Figure 4. Subject's view within IVY. Note the floating disc with its associated annulus.

observer within IVY cannot distinguish between the opening/closing wall and the other three fixed walls. Figure 2 shows IVY in operation with the door open.

Due to the high bandwidth of the video display (96hz video at 1024x768) and the physical separation between the display and the video generation computer --- an SGI Onyx2 --- it is necessary to convert the eight video signals from the SGI to digital signals that run over optical fiber cable and are then reconstituted into analog video signals at the projection site. The physical separation of the computer from the display also has implications for input devices. An input device server has been built to allow standard input devices to be used with IVY.

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 detectable through the walls, floor and ceiling and to drive the CrystalEyes glasses. 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 (see [3]) although for the experiments reported here, no head tracking was required as the subject's head was restrained. Full details of IVY can be found in [12,13].

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. Visually subjects were placed within a simulated room 243x243x486 cm^3 (wxhxd) with their back just in front of the simulated back wall of the room (see Figures 4 and 5). The front wall of the room was 446cm in front of the subject. The simulated room appeared in various roll conditions and thus the physical floor of IVY did not necessarily

Figure 5. Subject in IVY viewing the target

correspond to the visual floor of the simulated room. The room image was neutral in terms of point of illumination, i.e. there were no cues as to the apparent direction of illumination provided by the textured walls of the room.

Ten subjects with normal or corrected-to-normal vision and normal stereo acuity viewed a simulated 25cm diameter shaded disc (including its annulus). The disc was suspended in the air 170cm in front of the subject at eye height inside of the simulated room. For each of the 19 orientations of the room, the orientation of the shaded disc was adjusted until it appeared most convex. This corresponded with the perceived direction of illumination. Since this is assumed to come from above, the orientation of the disc chosen by the subject indicates the subject's perceptual 'up' direction. These orientations were either counter-clockwise (indicated by a negative angle) or clockwise (positive angles) around a gravity defined upright. Room orientation was in the range -90° to 90° in 10° increments. The order of room orientation presentation was randomized as was the orientation of the disc's starting position. Each room orientation was viewed 10 times with different disc starting orientations. The subject's responses for each orientation were averaged.

3. Results

Figure 6 shows the average and standard error of the orientation of the disc that was seen as most convex, plotted as a function of the room orientation by the 10 subjects. The horizontal scale indicates the orientation of the room relative to gravity (0 – aligned with gravity, positive orientations corresponds to rotation clockwise around the line of sight). The vertical axis is the group mean orientation of the disc, also plotted relative to gravity. The solid line plotted through the data shows the orientation of the disc that would be chosen if light was always seen as coming from the visual ceiling of the room (slope of 1). The horizontal line through the origin is the orientation of the disc that would be chosen if light was always seen as coming from either the gravitationally-defined or body-defined up direction. The results indicate that the perceived up direction was clearly influenced by the orientation of the

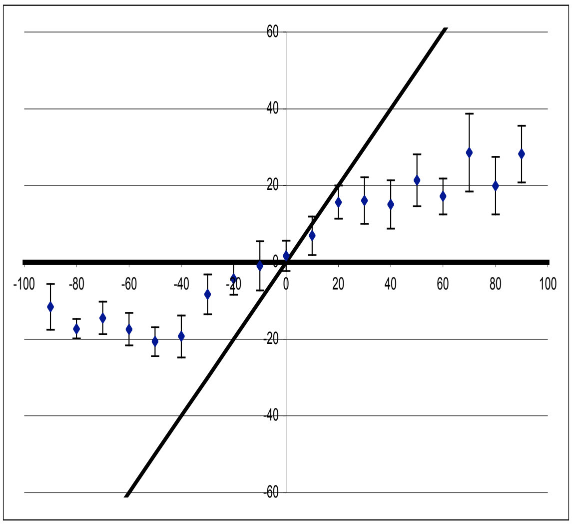

Figure 6. Subject's perceived up direction as a function of room roll. The solid line with a slope of 1 indicates expected responses if the up direction were fully captured by the room roll. If instead the subject up direction were fully captured by gravity, a horizontal response (slope of 0) would be expected. Error bars indicate standard errors.

visual display although the visual display did not completely dominate (or capture) the perceived 'up' direction.

4. Discussion

When presented with a rolled visual environment relative to themselves and gravity, subjects have competing cues as to which way is up. Subjects perceive a single 'up' direction – it is inconceivable to have more than one, but that up direction is influenced by more than one cue. The visual display defines up according to the polarized visual cues, and especially according to the structure of the floors, walls and ceiling. The body and gravity axes are aligned with each other in this study but these can 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 various cues to provide a single up direction?

A simple possible combination strategy is to take the direction of the weighted vector sum of all vectors defining the up direction. That is to define the up direction as being given by 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 perceived up direction under various combinations of visual, body and gravity cues (see [7,8], for example). In the experiment reported here, the gravity and body vectors are aligned, and the model can be simplified to

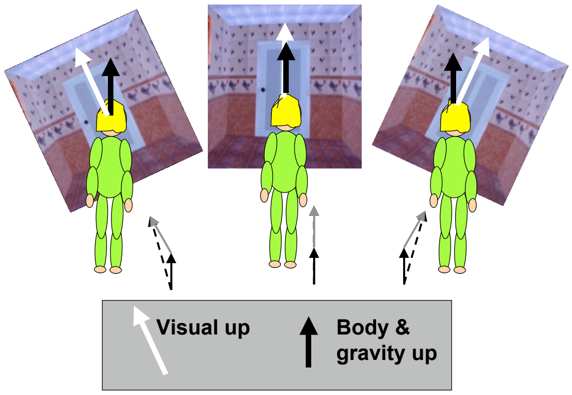

Figure 7. Vector directional model. The perceived up direction is modeled as being the direction of the weighted sum of two vectors, one aligned with the body and gravity, the other aligned with the visual display.

$$\overrightarrow{up} = \overrightarrow{gravity + body} + k\overrightarrow{vision}.$$

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

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

The basic concept of the model is shown in Figure 7.

Figure 8 shows the best fit prediction of the model. The best fit value of k was found to be 0.45 meaning that the relative weight of the visual display relative to body and gravity together was 0.45. The maximum induced deviation in the 'up' direction was 35°.

Implications for VR.

Many aspects of the perception of a scene include and depend on a reference direction of verticality and 'up'. For example, reading an instrument, interpreting the status of an on/off toggle switch, as well as 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 tilts, yaws and rolls relative to gravity includes matching the perceived direction of up in the real and simulated situations. Is it possible to manipulate a virtual reality simulation to increase or otherwise manipulate the role of the visual cue in determining the perceived direction of up? The present experiments suggest that for small deviations (less than about 35°) it is possible to influence the perceived up direction using visual cues alone.

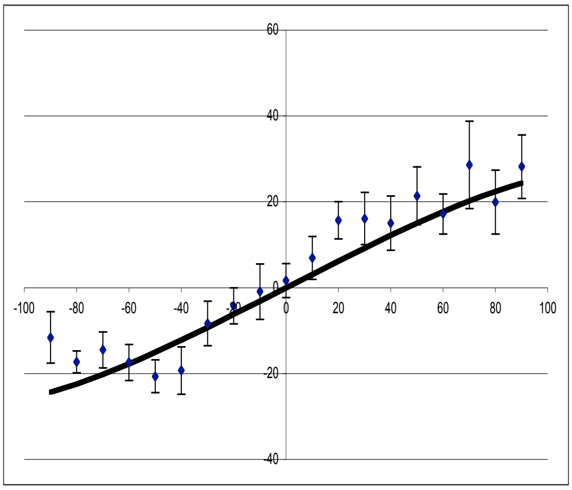

Figure 8.Best fit of the vector sum direction model (solid line) k=0.45.

References

[1] Coats, A. C. Limit of normal of the galvanic body-sway test, *Ann. Otol. Rhinol. Laryngol.*, 81: 410-416, 1972.

[2] Coats, A. C. The sinusoidal galvanic body-sway response, *Acta. Otoaryngol. (Stockh.)*, 74: 155-162, 1972.

[3] Hogue, A., Robinson, M., Jenkin, M. R., and Allison, R. S. A vision-based tracking system for fully immersive displays. Proc. IPC/EGVE 2003, Zurich, 2003

[4] Howard, I. P., Human Visual Orientation, John Wiley, New York, 1982.

[5] Howard, I. P., Bergström, S. B., and Ohmi, M. Shape from shading in different frames of reference. *Perception,* 19: 523-530, 1990.

[6] Howard, I. P. and Templeton, W. B. *Human Spatial Orientation*, London: Wiley, 1966.

[7] Jenkin, H. L., Dyde, R. T., Jenkin, M. R., Harris, L. R. Judging the direction of up in a tilted room. *Perception* , 2002.

[8] Jenkin, H. L., Dyde, R. T., Jenkin, M. R., Harris, L. R. and Howard, I. P., Relative role of visual and non-visual cues in determining the direction of 'up': experiments in the York Tilted Room Facility., J. Vestib. Res. (in press)

[9] Mittelstaedt, H. A new solution to the problem of subjective vertical. *Naturwissenschaften* 70: 272-281, 1983.

[10] Ramachandran, V. S. Perception of shape from shading, *Nature*, 331: 163-166, 1988.

[11] Ramachandran, V. S. Perceiving shape from shading. *Sci. Am.* 259: 76-83, 1988.

[12] Robinson, M., Laurence, J., Hogue, A., Zacher, J., German, A., Jenkin, M. IVY: Basic design and construction details. Proc. IC-AT 2002. 2002.

[13] Robinson, M., Laurence, J., Zacher, J., Hogue, A., Allision, R., Harris, L. R., Jenkin, M., and Stuerzlinger, W., IVY: The Immersive Visual environment at York. IPT Symposium (held in conjunction with VR2002). 2002.

[14] Rock, I. *Orientation and Form*, New York: Academic Press, 1973.

[15] Thompson, P. Margaret Thatcher: a new illusion. *Perception*, 9: 483-484, 1980.

Acknowledgments

Supported by NASA Co-operative Agreement NCC9-58 with the National Space Biomedical Research Institute, Natural Sciences and Engineering Research Council of Canada (NSERC), the Canadian Foundation for Innovation (CFI), the Canadian Space Agency (CSA), and the Centre for Research in Earth and Space Technology (CRESTech).