Perceptual stability during active head movements orthogonal and parallel to gravity

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Received 4 November 2002
Accepted 26 May 2003

Abstract. We measured how much the visual world could be moved during various head rotations and translations and still be perceived as visually stable. Using this as a monitor of how well subjects know about their own movement, we compared performance in different directions relative to gravity. For head rotations, we compared the range of visual motion judged compatible with a stable environment while rotating around an axis orthogonal to gravity (where rotation created a rotating gravity vector across the otolith macula), with judgements made when rotation was around an earth-vertical axis. For translations, we compared the corresponding range of visual motion when translation was parallel to gravity (when imposed accelerations added to or subtracted from gravity), with translations orthogonal to gravity. Ten subjects wore a head-mounted display and made active head movements at 0.5 Hz that were monitored by a low-latency mechanical tracker. Subjects adjusted the ratio between head and image motion until the display appeared perceptually stable. For neither rotation nor translation were there any differences in judgements of perceptual stability that depended on the direction of the movement with respect to the direction of gravity.

1. Introduction

The perceived world normally remains stable during voluntary head movement. Loss of this perceptual stability is highly debilitating and may contribute to the discomfort experienced when making head movements in unusual environments such as microgravity. Achieving perceptual stability requires knowing about your movement relative to the visual scene, predicting the expected visual movement, detecting the actual image movement and then comparing the expected and actual movements. A breakdown in perceived stability occurs if a difference between the expected and actual visual movement is detected. To make this comparison both motion of the self relative to the world and motion of the scene relative to the observer needs to be monitored. During normal, active movement, the main cues that can inform the brain about movement relative to the world include the resulting visual movement, direct sensory information about the head movement itself including vestibular, neck muscle, joint activity, and efference copy of the intention to make the movement in the first place. Motion of the world relative to the observer can also be provided by many cues including touching surfaces, listening to sounds and vision.

Measuring the range of visual movements judged as corresponding to self movement thus represents a performance rating for the entire system. Here we used this measure to assess the possible role of gravity in processing active head movements. Under microgravity, head movements are highly provocative \cite{13,14} and although reports of oscillopsia in a microgravity environment are rare, perceptual instability related to head movement is often reported when returning to a 1G environment after spaceflight \cite{5}. A role of the vestibular system, the predominant detector of gravity in the body, is further suggested by the oscillopsia that

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is often found associated with vestibular damage [4, 19]. Furthermore, the eye movements evoked by head rotation in the dark are strongly affected by changes in the head’s orientation relative to gravity [3,7,10,18] and changes to the oculomotor response to pitch head movements (which would normally be accompanied by a change in orientation relative to gravity here on earth) have been reported in microgravity [6]. All these factors lead us to expect gravity to affect the maintenance of perceptual stability during active head movement.

Whether gravity plays a role in the maintenance of a perceptual visual world depends on the head movement (Fig. 1). During head rotations around an off-vertical axis, the gravity vector swings across the otolith maculae [2] (Fig. 1a). The changing direction of gravity relative to the head is a potential source of information about the movement. When rotation is about an earth vertical axis (Fig. 1b) this additional source is not present. During translation, accelerations due to self-movement need to be extracted from the single gravitoinertial vector created by the sum of the imposed acceleration and gravity vectors. When movement is orthogonal to gravity (Fig. 1c), the magnitude of the resulting vector is hardly different from gravity alone but the direction of the gravitoinertial vector is altered. When translation is parallel to gravity (Fig. 1d), the resulting vector differs from gravity only in magnitude. We therefore compared judgements of perceptual stability during active head movements for rotational and translational movements orthogonal to and parallel with the direction of gravity.

2. Methods

2.1. Overview

A virtual reality (VR) system (Fig. 2) was constructed in which a variable gain could be introduced between the measured head motion and the resulting visual motion that was viewed by observers wearing a head mounted display (HMD). Subjects made controlled head rotations and translations either parallel with or orthogonal to gravity and adjusted the gain until the world appeared stable.

2.2. Subjects

Ten subjects participated in each experiment (age range 21–50, 8 males). Eight subjects participated in both rotation and translation experiments. Subjects had normal or corrected-to-normal visual acuity and had no history of vestibular or balance problems. Experiments were approved by the York Ethics Approval Committee. Subjects were paid for their participation at standard rates.

2.3. Visual simulation and head tracking

An immersive visual display was presented using a Virtual Research V8 stereoscopic head mounted display operating in monoscopic mode. The displays, one for each eye, presented full-colour, 640 by 480 pixel images at 60 Hz. The displays subtended a diagonal field of view of 60 degrees. Stereo headphones presented stereophonic sound to the subject.

The position and orientation of the head was sensed by a Puppetworks six-degree-of-freedom mechanical head tracker balanced by a counterweight to reduce the physical load on the user (Fig. 2). One end of the mechanical tracker was earth-fixed and the other end was fixed rigidly to a custom mount on the helmet. The head tracker sensed the orientation of seven joints between the rigid links that made up the head tracker and transmitted these data via a serial link to the SGI O2 display computer. Head position and orientation were calculated from the known kinematics of the tracker and this information was used to drive the simulation with an update time of less than one frame rate (i.e. < 16 msecs). This fast update produced a very smooth movement with no appreciable delay.

The virtual environment was created using custom code and Open-GL graphics. The modelled virtual world (see Fig. 2) was deliberately kept simple for both computational and scientific reasons. A simple environment allowed a scene update rate of 30 Hz. The world used was a textured sphere similar to that used earlier in a study of display lag [1]. The visual environment consisted of a sphere two meters in diameter and the subject’s head was placed in the centre of the sphere at the start of each trial. One advantage of using a sphere is that all imagery is equidistant and complications of parallax are minimized. The sphere was patterned with a grid lattice similar to lines of latitude and longitude (the lines of longitude converged to a point above and below the subject). Before each trial the sphere was rotated so that the same portion of the sphere – that section away from the poles where the texture patterns converged – was used for each condition. Alternate squares making up the visual texture of the sphere were coloured red and white to form the pattern. The simulated sphere was illuminated by a
Fig. 1. Gravity has different effects during different head movements. During rotation orthogonal to gravity (A) the gravity vector (g) rotates around the head whereas during rotation parallel with gravity (B) the gravity vector does not move relative to the head. During translation orthogonal to gravity (C), the resultant gravito-inertial vector swings from side to side (from g+acc to g-acc) whereas during translation parallel to gravity (D), the gravito-inertial vector changes only its magnitude.

Fig. 2. Presenting the visual world. Subjects were positioned within a virtual world presented on a V8 helmet mounted display. The world consisted of a 2m sphere. The subject’s head was positioned at the centre of this virtual sphere: that is the subject viewed what they would see if they were in the centre of such a sphere. Subjects could only see a small part of this sphere at any one time but could view the entire inside surface of the sphere by moving their heads. The sphere was textured with a red and white checkerboard pattern. A Puppetworks mechanical head tracker measured the position and orientation of the head.

2.4. Experimental conditions: Rotation

In the rotation experiment, subjects rotated their heads under voluntary control approximately ±45° around either the roll, pitch or yaw axes either orthogonal to or parallel with the direction of gravity (see inserts to Fig. 3). Rotations about different axes were run in separate, counterbalanced blocks. Pitch and roll rotations around axes parallel with the direction of gravity were accomplished by having subjects move their heads while lying prone (roll) or left-side-down (pitch) and rotating around an earth-vertical axis (yaw). Yaw rotation with the axis parallel with gravity was done while sitting upright. Pitch and roll rotations around axes orthogonal to the direction of gravity were made while subjects sat upright. Yaw rotations were made while the subject leaned forwards supported by their hands on a bar. Only the rotation of the head was
used in generating the image motion. Subjects were instructed to synchronize 0.5 Hz movements with an electronic metronome played through the HMD’s headphones. Subjects pressed the left and right buttons of a standard three-button computer mouse to increase or decrease the ratio between the amount of visual motion in the display and their head motion in increments of 0.05 or 0.1. When subjects judged the display to be earth stable they pressed the centre button. Each condition was repeated eight times.

2.5. Experimental conditions: translation

In the translation experiment, oscillatory movements of about ±17 cm were made in either the naso-occipital (x), interaural (y) or dorsal/ventral (z) directions. Subjects were arranged so that the movements were either along earth-vertical or earth-horizontal axes (see inserts to Fig. 4). Head translations in the x and y directions parallel with the direction of gravity were accomplished by having subjects standing, leaning over, and supporting themselves by holding onto a crossbar while pushing up and down with their arms and legs with their heads pointing downwards (x) or sideways (y). Parallel-to-gravity translation in the z direction was carried out while subjects sat in a chair and moved their heads up and down. Orthogonal-to-gravity translations along the y and z paths were made while subjects held onto a pole and pushed and pulled themselves while lying in a prone body posture on a garage creeper that rolled along a track. They were either lying along the cart (z) or across the cart (y). Movements orthogonal to the direction of gravity in the x direction were carried out while subjects sat in a chair and moved their head back and forth. The length of the subjects’ head movement was monitored to ensure they were approximately 17 cm in either direction. Subjects controlled the pace of their movements using the metronome in the same manner as for the rotation experiments. All movements were actively carried out by the subjects. To allow movements orthogonal to gravity, a garage creeper that rolled on a track was used. Subjects adjusted the ratio between visual and head motion in steps of 0.04 until the display appeared earth stable.

2.6. Initial conditions

For the rotation experiment, the trials began with a ratio of visual motion to head motion of either 0.5 or 2.0. For the translation experiment the initial ratios varied randomly in the range between 0.5 and 2.0. The tolerance of visual movement during rotational and translational head movements was assessed on separate occasions.
Fig. 4. Frequency at which a particular ratio of visual to head movement was regarded as ‘world stable’ during translations that were either parallel with (A) or orthogonal to gravity (B). The vertical dashed line at a ratio of 1 corresponds to visual motion that agrees, within the limits of calibration of the hardware, to the subject’s physical motion. Format as for Fig. 3. There were no differences between the Gaussian fits to the two histograms (see text). The curves have been superimposed in the insert at the top right.

2.7. Data analysis

The values reported as stable were plotted as frequency histograms (Figs 3 and 4) and fitted with a Gaussian distribution.

$$\text{Frequency} = a \cdot \exp\left(-0.5 \cdot \left(\frac{(x - x_0)}{b}\right)^2\right)$$

Where:
- $x_0$ is the peak of the Gaussian
- $b$ is an estimate of the width
- $a$ is an arbitrary scaling factor

Separate repeated measures t-tests were used to determine if there were any significant differences between the means and the standard deviations of the rotation and translation conditions orthogonal to and parallel with gravity. The dependent measure for each subject was obtained by averaging across trials in each condition.

3. Results

3.1. Perceptual stability during head rotation

Figure 3 shows the frequency at which each ratio of image-to-head-movement was chosen as appearing stable during self-generated approximately sinusoidal head rotations at 0.5 Hz. All data from all subjects have been pooled. A ratio of 1 corresponds to the normal situation. The most likely ratio to be selected by subjects as appearing stable was around 1.2 as shown by the peaks of the Gaussian fits to the frequency histograms. That is, subjects preferred about 20% more visual motion than was required by the rotation geometry.

The data have been divided into the responses obtained when the rotation axes were orthogonal to (Fig. 3a) or parallel with (Fig. 3b) the direction of gravity. These conditions are shown in cartoon form as inserts next to each histogram. Separate repeated measures t-tests (based on intra-subject variability) showed that there was no significant difference between the means (orthogonal 1.21, parallel 1.17, $t(9) = 1.712$, $p > 0.05$) or between the standard deviations (orthogonal 0.40, parallel 0.35, $t(9) = 0.439$, $p > 0.05$), showing that there was no effect of whether the rotation axis was parallel with, or orthogonal to gravity.

3.2. Perceptual stability during head translation

Figure 4 shows the frequency at which each ratio of image-to-head-movement was chosen as appearing stable during self-generated approximately sinusoidal head translations at 0.5 Hz. The most likely ratio to be selected by subjects as appearing stable was a little higher than for rotations at almost 1.4 as shown by the peaks of the Gaussian fits to the frequency histograms.
That is, subjects preferred almost 40% more visual motion than was required by the geometry in order for the display to appear perceptually stable.

The data have been divided into the responses obtained when translation was orthogonal to (Fig. 4a) or parallel with (Fig. 4b) the direction of gravity. These conditions are shown in cartoon form as inserts next to each histogram. Separate repeated measures t-tests showed that there was no significant difference between the means (orthogonal 1.37, parallel 1.36, $t(9) = -0.505, p > 0.05$) or between the standard deviations (orthogonal 0.54, parallel 0.47, $t(9) = 0.871, p > 0.05$), showing that there was no effect of whether translation was parallel with, or orthogonal to gravity.

4. Discussion

This study has quantified the tolerance to visual motion during rotation around yaw, pitch and roll axes and during translation along the naso-occipital, interaural and dorso-ventral directions but has found no variation in performance that depended on the orientation of the movement relative to gravity. The data show a number of interesting features that are discussed elsewhere [11]. These include the observation that the ratio of visual to physical motion most likely to be regarded as perceptually stable resulted in considerably more visual movement than was geometrically necessary. Furthermore there was a wide range of ratios that were accepted as appearing earth stationary. However, we were surprised to find no apparent effect of gravity on performance.

Head movements that change the head’s position relative to gravity (such as a pitching motion while in an upright body posture) activate the otoliths as well as the semicircular canals whereas rotations around an earth vertical axis activate only the canals. That there was no difference in tolerance to visual movement, either in the amount of visual movement required or the range of movements tolerated as corresponding to an earth stable scene during these two movements was surprising. We expected the additional contribution from the otolith organs to narrow the width of the function by improving knowledge about the head movement as had been predicted by Wallach [20]. No difference was found, however, suggesting that either knowledge of head position was already optimal or that otolith signals were not used to determine perceptual stability during these active head movements [8,9]. Perhaps our frequencies were too slow for the otoliths to be useful and therefore subjects were forced to rely on non-vestibular cues.

Despite the similar feel of our rotation and translation experiments, the otoliths were potentially involved in the response to these stimuli in very different ways. During rotation around an off-vertical axis (Fig. 1a), the otoliths essentially report a series of tilts as rotation proceeds. For the translations, the otoliths were stimulated directly by the accelerations imposed. The otolith signal is always ambiguous and these two roles, detecting tilt or acceleration, represent the poles of their ambiguity. To interpret the otolith signal (corresponding to a single acceleration at any one time), the brain needs to choose between assigning the signal to either gravity alone (in which case, if the acceleration is in an usual direction, it indicates tilt) or resolving it into two vectors, one for gravity and one for the imposed acceleration. There are various strategies available to help this decision but a major one is thought to be frequency [12, 15]. Low frequencies (below around 0.5 Hz) tend to be assigned to tilt e.g. [18] whereas higher frequencies are interpreted as linear motion e.g. [16]. Our frequency of 0.5 Hz is right at the cusp of this relationship and so perhaps if we used higher frequencies we might see some effect during translations and lower might have revealed effects during rotations. These speculations await further testing.

4.1. Conclusions and significance to moving in a microgravity environment

Since judgements of perceptual stability during rotations and translations were not affected by the relationship between the movement and gravity, it appears that the detection of gravity plays a relatively small role in determining perceptual stability during active head motion, at least at around 0.5 Hz. These results support emerging studies that also suggest that the vestibular contribution to estimating of self-motion is subordinate to proprioceptive and efferent copy information [9,17].

Acknowledgements

Supported by NASA Co-operative Agreement NCC9-58 with the National Space Biomedical Research Institute, the Canadian Space Agency, NSERC and the Centre for Research in Earth and Space Technology (CRESTech). We would also like to thank Jeff Laurence for building the equipment.
References


