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Gravity and perceptual stability during translational head movement on earth and in microgravity

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Abstract

We measured the amount of visual movement judged consistent with translational head movement under normal and microgravity conditions. Subjects wore a virtual reality helmet in which the ratio of the movement of the world to the movement of the head (visual gain) was variable. Using the method of adjustment under normal gravity 10 subjects adjusted the visual gain until the visual world appeared stable during head movements that were either parallel or orthogonal to gravity. Using the method of constant stimuli under normal gravity, seven subjects moved their heads and judged whether the virtual world appeared to move "with" or "against" their movement for several visual gains. One subject repeated the constant stimuli judgements in microgravity during parabolic flight. The accuracy of judgements appeared unaffected by the direction or absence of gravity. Only the variability appeared affected by the absence of gravity. These results are discussed in relation to discomfort during head movements in microgravity.

1. Introduction

The perceptual 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. A breakdown in perceived stability occurs if a difference is detected between the expected and actual visual movement. The brain is informed about normal active head movements by visual and non-visual sensory systems and by knowledge of the intention to move. An estimate of the movement's magnitude is obtained from the combination of all this information, from which an estimate of the expected corresponding movement of the world relative to the observer can be derived. Information about the actual motion of the world relative to the observer, which can confirm or reveal errors in this internally generated estimate, is provided by visual, haptic and auditory information.

Measuring the visual movement judged by observers as consistent with their own self-movement provides a performance rating for the entire system that generates an internal estimate of self-motion and tests it against sensory information. Here we use

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performance on such a judgement task to assess the possible role of gravity in judging perceptual stability during active head movements. In microgravity, head movements are highly provocative [1,2] and, although reports of oscillopsia in a microgravity environment are rare, perceptual instability related to head movement is often reported when returning to a normal gravity environment after spaceflight [3]. A role of the vestibular system, the predominant detector of gravity in the body, is further suggested by the fact that oscillopsia is often associated with vestibular damage [4,5]. Furthermore, the eye movements evoked by head rotation in the dark are strongly affected by changes in the head's orientation relative to gravity [6–9] and changes in 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 [10]. All these factors lead us to expect that gravity might contribute to the maintenance of perceptual stability during active head movement.

In order to investigate this potential linkage we measured perceptual stability under conditions of normal and microgravity. Our logic was that astronauts might experience an abnormal amount of perceived motion during head movements, even if this motion was not enough to evoke a full-fledged sensation of oscillopsia. We therefore used a sensitive psychophysical method of constant stimuli with a two-alternative forced-choice paradigm to reveal subtle alterations in the way in which the visual motion associated with head movements might be affected in microgravity. We compared these results with control measures performed on earth.

2. Methods

2.1. Overview

A virtual reality (VR) system (Fig. 1) 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 in a head mounted display (HMD). The device was constructed to unusually rigorous criteria so that it could be flown in a research aircraft capable of performing parabolic flights. Subjects made controlled head trans-

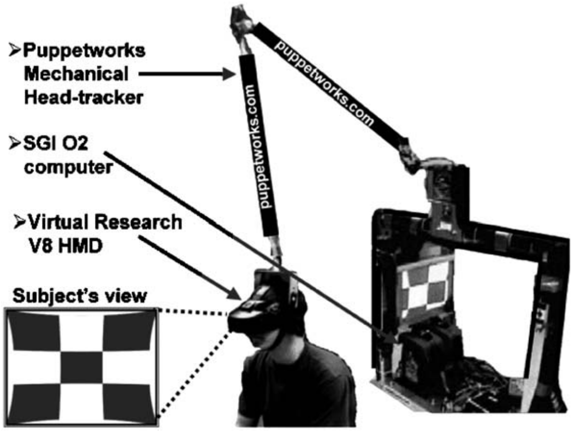

Fig. 1. Presenting the visual world. Subjects were positioned within a virtual world presented on a V8 helmet mounted display. The subject's head was centred inside a 2m diameter virtual sphere. The sphere was textured with a red and white checkerboard pattern. A Puppetworks mechanical head tracker measured the position of the head and provided the information to the computer that updated the subjects position in the world as they moved.

lations either parallel with or orthogonal to gravity or during the brief periods of microgravity obtainable under parabolic flight and adjusted the gain until the world appeared stable.

2.2. Subjects

Ten subjects participated in the method of adjustment normal gravity experiments, seven subjects participated in the constant stimuli normal gravity experiments, and one subject participated in the microgravity 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 who were not members of the research team were paid for their participation at standard rates.

2.3. Visual simulation and head tracking

All the experiments used the same visual display and head tracking system. The immersive visual display was presented using a Virtual Research V8 stereoscopic HMD operating in monoscopic mode. The displays, one for each eye, presented full-colour, 640 × 480 pixel images at 60 Hz. Each display subtended a diagonal field of view of 60° (48° × 36°).

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 in normal gravity (Fig. 1) or without a counterweight in microgravity conditions. One end of the mechanical tracker was fixed to the frame of the device and the other end was fixed rigidly to a custom mount on the head mounted display. 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.

The virtual environment was created using custom code and Open-GL graphics. The visual environment consisted of a simulated sphere 2 m in diameter (see Fig. 1) with the subject's viewpoint reset to 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). The modelled virtual world was 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 in an earlier study of display lag [11]. Each trial began with the same portion of the sphere in front of the subject. Alternate squares making up the visual texture of the sphere were coloured red and white to form the pattern. The sphere was illuminated graphically by a single virtual light source located at its centre. The visual display was generated using a projection whose nodal point was located between the eyes.

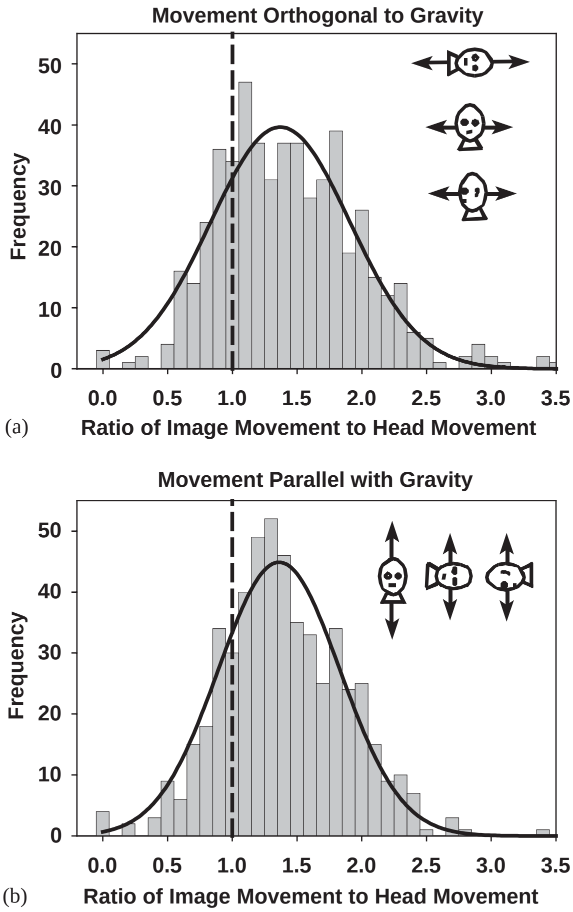

Fig. 2. Frequency at which a particular ratio of visual to head movement was regarded as 'world stable' during translations that were either parallel with (a) or orthogonal to gravity (b). The vertical dashed line at a ratio of 1 corresponds to visual motion that agrees, within the limits of calibration of the hardware, to the subject's physical motion. The inserts shows the motions the data from which are combined in the histograms. There were no differences between the fits to the two histograms (see text).

2.4. Experimental conditions: normal gravity, method of adjustment

Oscillatory translational movements of about ±17 cm were made by the subject in either the naso-occipital, interaural, or up/down directions. Initially movements were measured by the experimenter who used a ruler and gave feedback to the subjects. Subjects were arranged so that the movements were either along earth-vertical or earth-horizontal axes (see inserts to Fig. 2 and [12]). Subjects controlled the pace of their movements using audio cues provided by a metronome. To allow movements orthogonal to gravity, subjects lay on their back on a garage creeper (a low platform on smooth wheels) that rolled on a track. Visual gain was measured on a scale where a value of one indicated world stable and zero indicated head stable. Subjects adjusted the ratio between visual and head motion in steps of 0.04 units until the display appeared earth stable. The initial ratios were varied randomly between 0.5 (where the simulated visual world was moved half as far as was geometrically correct) and 2.0 (where the simulated visual world was moved twice as far as the geometry demanded).

2.5. Experimental conditions: normal gravity, method of constant stimuli

Subjects were presented with one of the following visual gains: 0.6, 0.8, 1.0, 1.2 and 1.4. Each gain was presented 14 times. Subjects had to make a two-alternative forced choice between whether the visual movement was in the same direction as their physical motion (“with”) or in the opposite direction (“against”). If the visual gain was greater than 1, it meant that during an upward movement, for example, the virtual world moved further than it should in the direction opposite to the movement (down in this example) and should be judged “against”. A gain of less than 1 corresponded to the virtual world moving with the observer and should be judged as “with”. At its extreme, a gain of 0 corresponded to the visual display not moving on the screen at all, but remaining fixed relative to the subject’s head. This condition should be judged as “with”. A gain of precisely 1 corresponded to the virtual world being simulated as though it were truly earth stable. The point that was perceptually equivalent to this earth stable condition is where the percentage of “with” and “against” judgements were equal.

2.6. Parabolic flight: microgravity method of constant stimuli

The equipment described above was mounted in the Canadian National Research Council (NRC)’s Microgravity Facility Falcon 20 aircraft that is capable of parabolic flight. We ran the experiment on one subject during two flights. During each flight the aircraft performed four parabolas, each of which generated approximately 22 s of microgravity. The subject lay still during the associated hypergravity phases of the flight. Thus a total of $2 \times 4 \times 22 = 176$ s of data collection time was available. During this time, the subject (DZ) made as many judgements as possible as to whether the visual display was moving with him or against him. Because it was not possible to know in advance how many trials the subject would be able to complete in a given flight, there are an uneven number of decisions for each of the five visual gains tested. In total, 73 measurements were collected (average of 2.4 s/decision) distributed as follows: for the gain of 0.6 $n = 15$, gain 0.8 $n = 15$, gain 1.0 $n = 13$, gain 1.2 $n = 15$, and gain 1.4 $n = 15$.

2.7. Data analysis

Method of adjustment stability judgements were plotted as frequency histograms (Fig. 2) and fitted using a Gaussian-like distribution.

$$\text{Frequency} = a\ \exp(-0.5((x - x_0)/b)^2), \qquad (1)$$

where x_0 is the peak of the Gaussian, b is an estimate of the width, and a is the height of the peak.

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

Method of constant stimuli data were converted to percentages of the number of time the “with” judgement was made and plotted as psychometric functions (Fig. 3) and fitted with sigmoid distributions with the same variables, given above:

$$\text{probability} = a/(1 + \exp(-((x - x_0)/b))). \qquad (2)$$

3. Results

3.1. Perceptual stability during head translation: method of adjustment data

Fig. 2 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 almost 1.4 as shown by the peaks of the Gaussian fits to the frequency histograms. That is, subjects required almost 40% more visual motion than was required by the geometry to judge that the environment was visually stable.

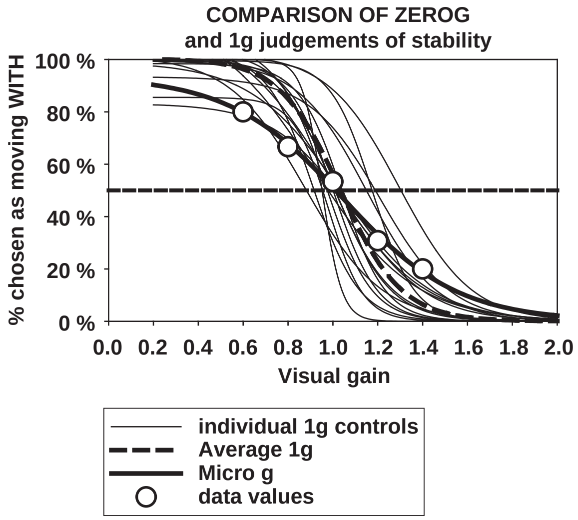

Fig. 3. Psychometric functions obtained under normal gravity and for one subject under microgravity. The curves show the percentage of responses where the visual motion was chosen as moving ‘with’ the subject. The value of visual gain (the ratio of visual to body motion) at the 50% point of these curves indicates the visual gain where the motion was equally likely to be judged as moving with or against. The microgravity curve (thick solid line) crosses the 50% level close to those obtained under normal gravity (individual curves shown as thin lines, average as thick dashed line), but the slope of the microgravity function, indicating the certainty of the subject’s decisions, is significantly shallower than for data obtained under normal gravity.

The data have been divided into the responses obtained when translation was orthogonal to (Fig. 2a) or parallel with (Fig. 2b) the direction of gravity. The movement conditions are shown in cartoon form as inserts next to each histogram. Separate repeated measures t-tests found 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, $t(9) = 0.871$, $p > 0.05$). There was no effect of whether translation was parallel with or orthogonal to gravity.

3.2. *Perceptual judgements: method of constant stimuli comparison of normal gravity and microgravity*

Fig. 3 shows psychometric functions drawn through the data collected under normal gravity (thin lines with average shown dashed) and microgravity (thick line). The data values are shown for the microgravity data. Note that there are no estimates of variability on these data points: they are just the total number of times that each visual gain value was chosen by our single subject as moving with him, expressed as a percentage of the number of times that value was presented.

The points of stimulus equivalence (PSE, where the graph crosses 50%) and the standard deviations (which correspond to the maximum slope of the lines) for the normal gravity data are plotted as frequency distribution histograms in Fig. 4. Also shown on these plots are the corresponding values for the microgravity data function. The PSE from the microgravity data (1.04) is not significantly different from the normal gravity controls (mean 1.04, see Fig. 4b) or from unity gain. However the standard deviation (b in the equation given in the methods) is significantly larger in DZ’s microgravity data (0.26) than the normal gravity distribution (0.12) ($Z = -4.249$, $p = 0.0002$) (see Fig. 4a). DZ’s normal gravity data had an average standard deviation of 0.16 (shown by an asterisk in Fig. 4a), which was not significantly different from the mean. The b value that corresponds to $p = 0.05$ is 0.22.

4. Discussion

4.1. *Perceptual judgements of stability under normal gravity*

This study has quantified subjects’ tolerance to visual motion during translational movement and found no variation in judgements that depended on the orientation of the movement relative to gravity. The data show a number of interesting features that are discussed further elsewhere [13]. These include the observation that the ratio of visual to physical motion most likely to be regarded as perceptually stable involved 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 significant effects of gravity on the accuracy of performance during head movements in normal gravity.

Head movements in a direction aligned with gravity stimulate the otoliths in a different pattern from those that are orthogonal. In the former case the acceleration of gravity is modulated by the imposed acceleration,

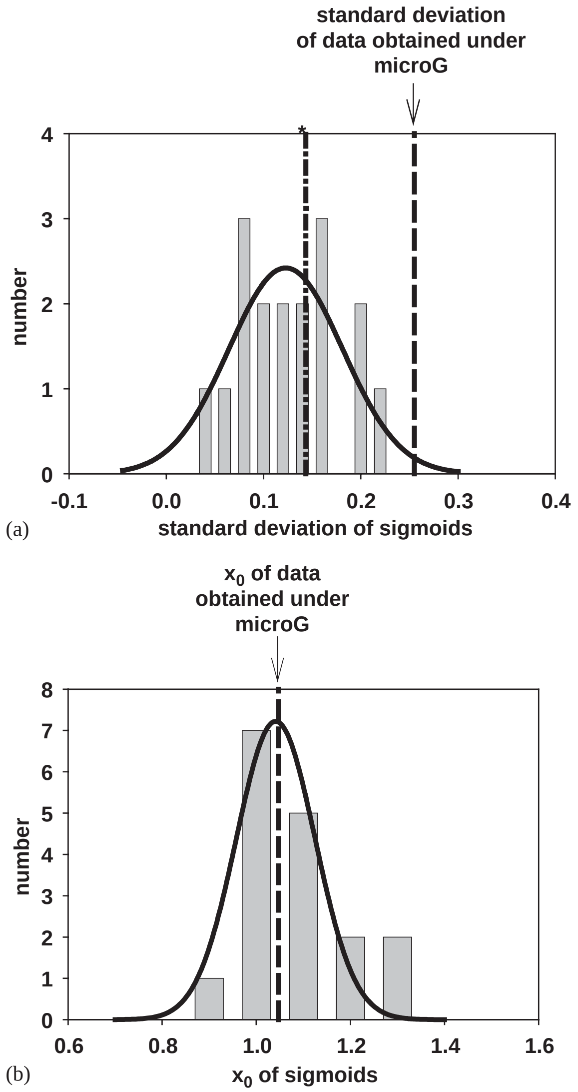

Fig. 4. The distribution of the standard deviations (a) and means (b) of the psychometric curves shown in Fig. 3 obtained under normal gravity. The standard deviation data (a) are distributed as a Gaussian (plotted as a thick line through the histogram) with a peak around 0.13. The chances are less than 0.05 that the standard deviation of DZ's estimate obtained under microgravity (shown as a vertical dashed line) is from the distribution of standard deviations obtained under normal gravity. The mean of subject DZ's normal-gravity data is indicated by the asterisk. The distribution of the means (b) peaks at a visual gain a little above 1. The value for the microgravity data (shown as a vertical dashed line) is not significantly different from the normal gravity data.

and in the latter different receptors from those affected by gravity are involved. 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 [14]. Although the function was indeed narrower when the movements were associated with gravity modulation (0.47 as opposed to 0.54) this difference was not significant, suggesting that either knowledge of head position was already optimal or that otolith signals were not used during these active head movements [15] to determine perceptual stability [16]. Perhaps our frequencies were too slow for the otoliths to be useful and therefore subjects were forced to rely on non-vestibular cues.

During subjects' movements the otoliths were stimulated directly by the accelerations imposed. The otolith signal is always ambiguous as to whether the stimulation was caused by tilt or acceleration. To interpret the otolith signal, the brain needs to choose between assigning it to gravity alone (in which case, if the acceleration is in an unusual direction, it indicates tilt) or resolving it into two vectors, one for gravity and one corresponding to the imposed acceleration. There are various strategies available to assist in this decision but a major one is thought to be frequency [17] (but see [18,19]). Low frequencies (below around 0.5 Hz) tend to be assigned to tilt (e.g. [9]) whereas higher frequencies are interpreted as linear motion (e.g. [20]). Our frequency of 0.5 Hz is right at the cusp of this relationship and so perhaps if higher frequencies were used one might see more effect. These speculations await further testing.

4.2. Perceptual judgements of stability under microgravity

Although on average our subject (DZ) chose the same visual gain to match his head movement as he chose under normal gravity, he was significantly less certain about the direction of motion seen during head movements in microgravity than the pool of subjects tested in normal gravity (which included him). Fig. 3 shows that at a visual gain of 0.6 our microgravity subject decided the stimulus was moving with him only 80% of the time, as opposed to almost 100% for the normal gravity subjects. Thus, 20% of the time even with this extremely small amount of movement, our microgravity subject still thought the amount of movement was actually too much to correspond to the current head movement. This could be interpreted as a greater uncertainty either about the extent of the head movement or about the accompanying visual movement. Since the visual sensory stimulus was the same for all the experiments, it would seem likely that it was the physical acceleration system that was affected by the microgravity experience and rendered less reliable. However, other studies [21] have demonstrated a reduced reliance on vision for other tasks in microgravity. Our observations are consistent with a model that places more reliance on the vestibular system that should still be a reliable transducer of imposed accelerations, and reduces the reliance on visual cues.

There is another possible explanation, however, that must be entertained. That is that the alteration in the uncertainty of the judgements that we have observed was due to the highly distracting nature of the environment in which the experiments were carried out rather than anything to do with the gravity levels per se. In order to investigate this possible role of attention and arousal, we plan to conduct experiments under comparably distracting circumstances on earth.

4.3. Conclusions and significance to moving in a microgravity environment

Since judgements of perceptual stability during translations under normal gravity were not affected by the relationship between the direction of the movement and the direction of 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 self-motion is subordinate to proprioceptive and efferent copy information [15,22]. Perceptual stability judgements show greater uncertainty in the absence of gravity. This uncertainty may contribute to discomfort during head movements in microgravity. Finding ways to increase the certainty by, for example, manipulating the visual information available may provide the basis of an effective countermeasure strategy for reducing the discomfort associated with making head movements in microgravity.

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