# THE PERCEPTION OF UPRIGHT UNDER LUNAR GRAVITY

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**Harris, L.R., M.R.M. Jenkin, and R.T. Dyde.** The perception of upright under lunar gravity. *J. Grav. Physiol. 19(2):9--16, 2012.* – The perceived direction of "up" is determined by a weighted sum of the direction of gravity, visual cues to the orientation of the environment, and an internal representation of the orientation of the body known as the idiotropic vector (18). How does the magnitude of gravity contribute to the assignment of the relative weights? In a previous study we showed that under microgravity less weighting is given to the visual cue than under normal gravity (6). Here we measured the weighting assigned to visual cues in determining the perceptual upright during periods of lunar gravity created by parabolic flight. The emphasis placed on the visual cue was not significantly affected by lunar gravity compared to under normal gravity (during level flight). This finding is discussed in terms of multisensory cue weighting and attempts to simulate reduced gravity levels by bedrest in which the influence of gravity along the long axis of the body is reduced by lying supine.

**Key words:** Perception on the moon, Perceived vertical, Magnitude of gravity vector, Multisensory cue combination

## INTRODUCTION

Maintaining an upright posture on the moon is not easy. NASA documents abound with examples of astronauts falling on the moon during the visits between 1969 and 1972 (19,20). Even on the most recent moon visit (Apollo 17, 1972), Astronaut Harrison Schmidt fell over as he worked on the lunar surface.[1] However, although regarded as highly desirable (7), few studies have investigated the perceptual consequences of lunar gravity. Clark et al. (3) modeled expected changes in orientation perception during landing on the moon. Paloski et al. (23) and Johnston et al. (14) provide overviews of the perceptual and physiological risks associated with lunar and other environments likely to be encountered during space exploration. But, although there are anecdotal reports of perceptual and balance disturbances in lunar gravity, few controlled experiments have been conducted to explore the consequences of lunar gravity on human self-orientation perception.

Postural stability and many aspects of perception require an accurate representation of upright which can be used as a reference with which to align the body for maximum stability (12). The perception of upright is determined by a combination of the internal representation of the body, visual orienting cues (such as the horizon) and the direction of gravity. The direction of gravity is carried within the otolithic division of the vestibular system and also by somatosensory cues (see 16 for a review). All these cues to upright appear to add linearly as a weighted vector sum to provide a "best estimate" of upright (5). Errors in the representation of upright can lead to postural instability (11). The perceived upright could be altered on the moon if lunar gravity was below the threshold needed for it to exert an influence on the perceived upright or if the visual cue, whether or not gravity still played a direct role, was assigned a changed weighting in response to the diminished gravity cue.

For whole-body linear acceleration, the vestibular threshold is around 0.1 $m.s^{-2}$ (although studies have reported values ranging from 0.014 to 0.25 $m.s^{-2}$ (8) and so the lunar value of 1.6 $m.s^{-2}$ is well above threshold. This is compatible with Homick and Miller's conclusion (10) that lunar gravity is an adequate stimulus for the otolith organs to define a gravitation-

[1]Astronaut Schmitt Falls.
http://www.youtube.com/watch?v=NwEJewuXC8A

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al vertical and to guide posture control. Their conclusion, however, was based on anecdotal reports from Apollo astronauts that they experienced no disorientation on the lunar surface.

However, it is still possible that the weighting assigned to the gravity cue could be less, connected to its smaller magnitude. A lower weighting assigned to gravity would correspond to a higher relative weighting applied to vision. Such an increase has been observed in medicated Parkinson's patients (1) and might partially account for the reported balance problems associated with arrival on the moon (see 23). When the cues that define the perceived upright are misaligned, for example when the body or visual reference plane is tilted relative to gravity, an unusual pattern of sensory weightings can potentially pull the perceived direction of upright more in the direction of the relatively higher weighted cues and thus threaten the reliability of processes that rely on the perceptual upright.

When subjects are exposed to brief periods of microgravity (created by using parabolic flight) the weighting assigned to vision is significantly reduced rather than increased (6). In fact, many visual effects seem to be reduced under microgravity: the rod-and-frame effect (24), the horizontal/vertical illusion and Ponzo Illusion (4) and the influence of a tilted background on interpreting shape from the pattern of shading over an object's surface (13). The question becomes, therefore, whether a change in the emphasis put on vision is also found under lunar gravity. If so, is the emphasis increased, reflecting a decrease in the weighting applied to the gravity cue, or decreased in line with what has been observed in microgravity? Alternatively 1/6g may be adequate to provide a usable gravity-defined reference direction leaving the weighting of cues that determine the perceptual upright unchanged.

In order to investigate the effect of lunar gravity on the perception of upright we simulated brief periods of 1/6 g using parabolic flight and assessed the relative influence of visual cues in determining the perception of upright. We probed the perception of upright using the oriented character recognition test (OCHART; 5), a technique that is now well-established for detecting the consequences of brief periods of microgravity on the perception of upright (6) and which has been used to investigate such effects on the International Space Station (9). The OCHART methods uses an ambiguous probe character presented against a tilted visual background to reveal the relative effectiveness of the visual orientation cue in determining the perceptual upright (the orientation in which objects are seen as being "the right way up").

## METHODS

*Participants*

Eight participants (5 males, 3 females, mean age 28 yrs) were largely recruited from the graduate student pool at York University and included two of the authors (MJ, RTD). The study was conducted in compliance with the ethical requirements of York Univer-

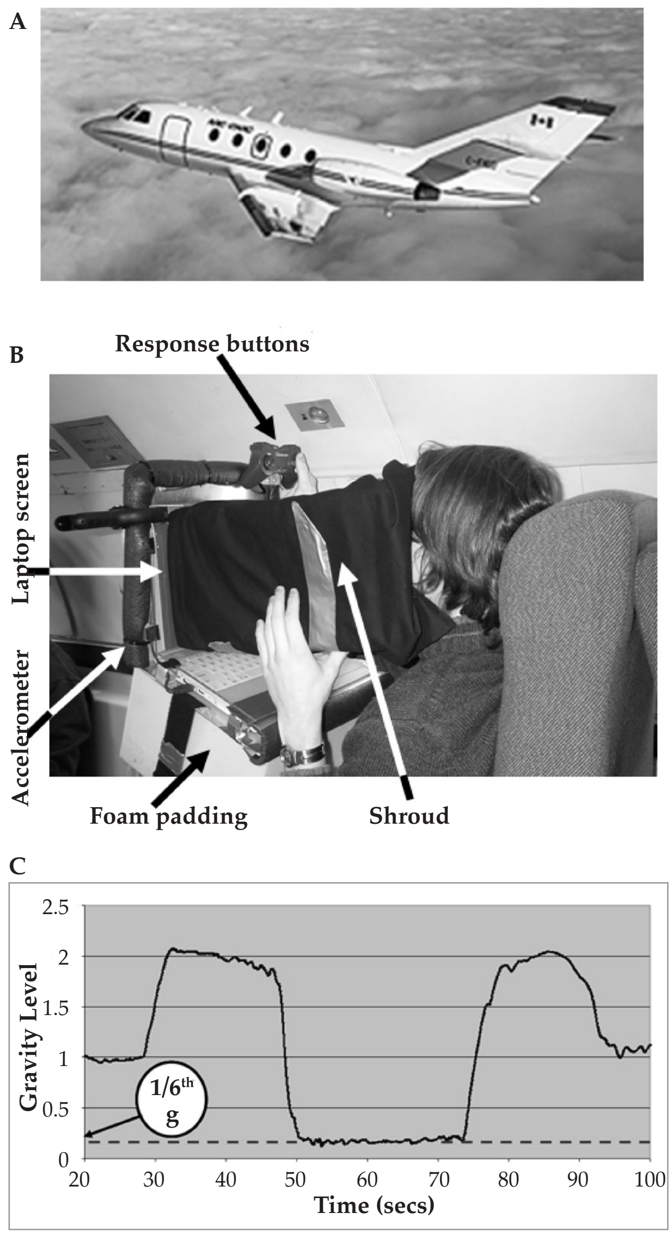


**Figure 1.** Experiments were performed using a Falcon 20 aircraft (A). Subjects sat in regular seats and viewed a laptop screen through a shroud that obscured all other vision (B). The aircraft flew a series of parabolas that partially cancelled the effects of gravity, creating periods of lunar gravity (1/6 g) of about 22s (C). Notice that the average gravity value in the hypergravity phase is below the 2g generated by 0g parabolic flights.

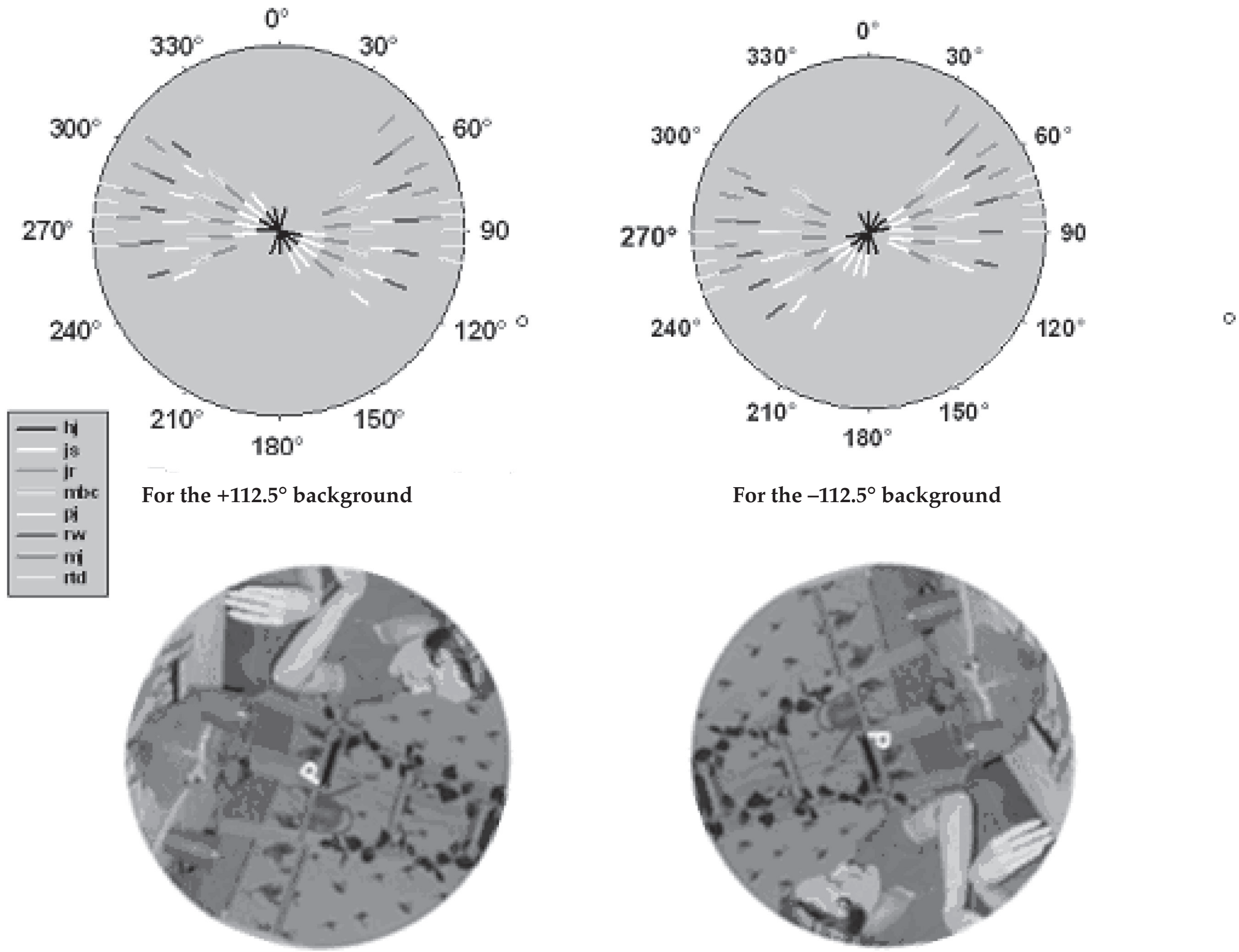


**Figure 2.** The orientations of the probe character (where 0 is with the "p" upright relative to the observer) that were used for testing each subject for the visual background tilted +112.5° (left panel) and -112.5° (right panel). Orientations were chosen based on each subject's performance during ground-based pilot data collection. For a given subject, the same values were used for all g-states.

sity, the National Research Council, and the 1964 Helsinki Agreement.

*Parabolic flights*

Brief periods of one sixth (lunar equivalent) gravity were generated using a Falcon 20 aircraft flying carefully prescribed parabolas (Fig. 1). Access to the plane was provided by the Canadian National Research Centre in Ottawa. Due to the rigid safety constraints applied at the Canadian Research Council research facility the number of near zero-g parabolas permitted per flight is usually specified at a maximum of six. However, over the course of the week in which our six flights took place it was found that the number of lunar gravity parabolas per flight could be increased to twelve per flight without compromising safety. As not all subjects flew on all six flights, the numbers of parabolas undertaken by each subject differed, ranging between 34 and 43 parabolas. The number of flights per subject was either four or five, the number differing as a result of subjects rotating in the role of onboard "safety spotter".

*The Oriented Character Recognition Test (OCHART)*

OCHART identifies the perceptual upright (PU), the "normal" orientation in which objects are most speedily and accurately recognized (15,17). The OCHART (5) method uses a character the identity of which depends on its orientation and identifies the orientations at which it is most ambiguous i.e., when its identity is most uncertain. From this, the orientation at which the character is least ambiguous can be obtained. Here we used the ambiguous symbol "p" which can be identified as a 'p' or a 'd' depending on its orientation. A range of orientations of the probe is tested and the subject is asked whether they see a 'p' or a 'd'. From their responses two psychometric functions are obtained corresponding to the transitions from a 'p' to a 'd' and from a 'd' to a 'p' (see "data analysis" below). The points of subjective equality (PSE) are obtained (see figure 3), i.e., the orientations at which the subject is equally likely to report either identify. The perceptual upright is then defined as the orientation midway between these two orientations. The challenge of applying this technique during parabolic flight is to collect reliable data within the constraints of the short duration exposure to lunar gravity associated with each parabola (around 22s). It is necessary to be selective about how many probe orientations are tested. As in our earlier experiments (6), we chose a range of orientations tailored to each subject based on their performance during ground-based pilot testing. For each subject ten probe orientations were chosen (five to span each expected point of maximum ambiguity). Five orientations is the minimum number from which a psychometric function can be reliably obtained. The orientations of the probe chosen for each subject are shown in Fig. 2.

*Display details*

The OCHART probe character was presented on an Apple iBook laptop computer with a resolution of 48 pixels/cm (21 pixels/deg: the character subtended approximately 3° x 2°). The computer screen was masked to a circle subtending 35° when viewed at 25 cm by means of a black circular shrouding tube that obscured all peripheral vision (see Fig. 1). The opening to the shroud was shaped to act as a semi-rigid, padded, head restraint to control both the viewing distance (25cm) and the orientation of the partici-

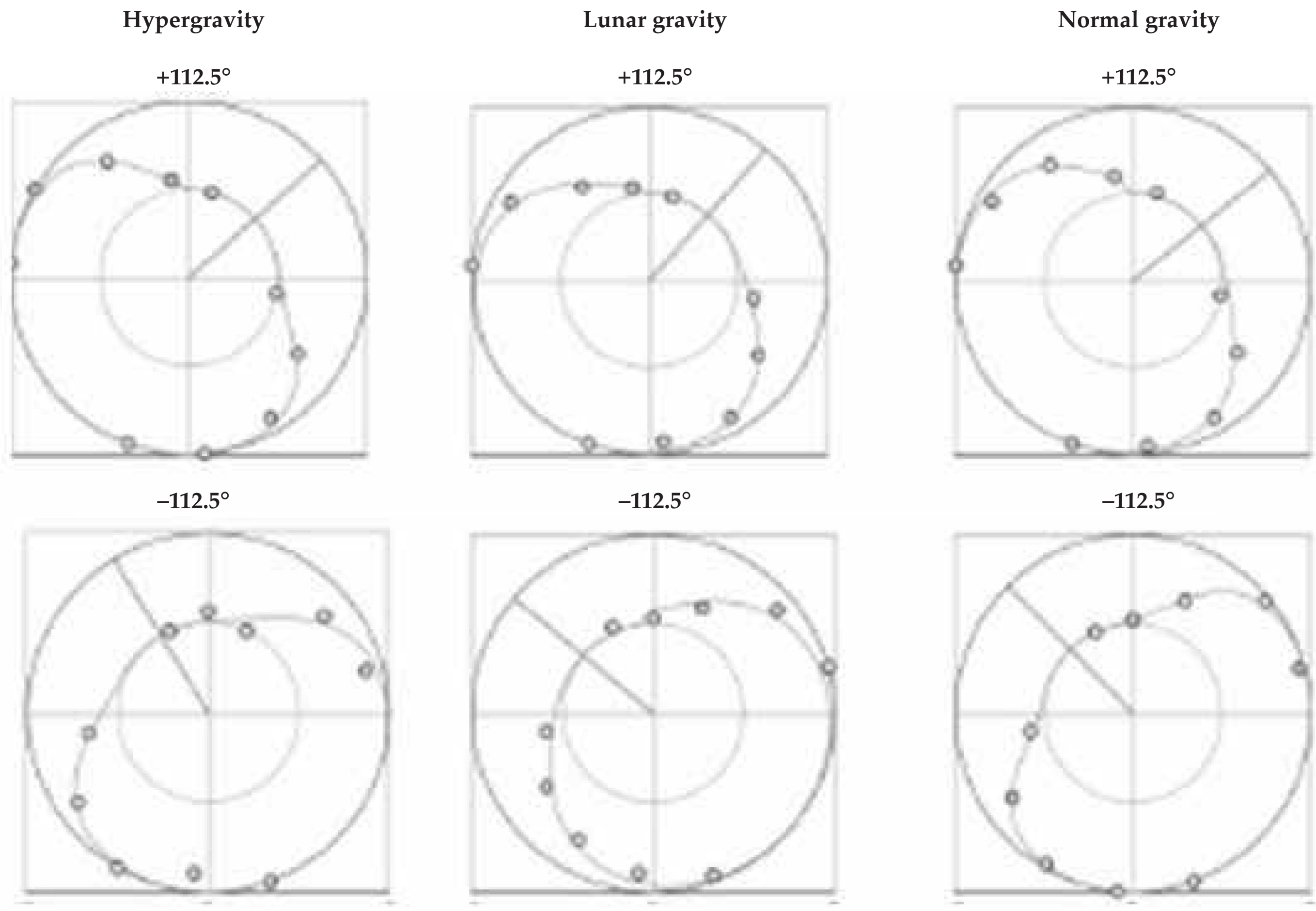


**Figure 3.** Typical responses for one subject. Each panel shows the data as a polar plot where the distance from the center represents the probability that the character represents a 'p'. The inner circle represents 0% (i.e. 100% p) and the outer circle represents 100% p (i.e. 0% d). The fit is the product of two hyperbolic tangents (see text) from which the 50% points were obtained. The perceptual upright (PU), defined as halfway between the two 50% points (PSEs), is indicated by a radial line. If the PU were upright this line would be vertical. The difference between the PUs obtained with the background tilted +112.5 degs (top row) and those obtained with the background tilted -112. degs (bottom row) is defined as the "visual effect".

pant's head relative to the screen. An ADXL311 dual axis digital accelerometer (Phidgits Inc) was mounted on each machine and X and Y accelerations in the plane of the testing screen were recorded at stimulus onset and at the point of the participant's response. The OCHART character was positioned centrally on a highly polarized background picture that was tilted left or right by 112.5° (see inserts to Fig. 2). These backgrounds were chosen as they had previously been shown to have the largest effect on PU (5).

*Procedure*

Each trial consisted of a stimulus formed by the p/d character of an orientation chosen randomly from the set of orientations selected for that particular subject (see Fig. 2) superimposed on a visual background at either ± 112.5° (where positive values correspond to a tilt to the right). Each stimulus was presented for 500 ms after which it was replaced by a blank screen of the same mean luminance. Participants chose between the "p" or "d" letter percepts by pressing one of two keys on a gamepad (Gravis Gamepad Pro). The participant's response was blocked by the controlling software until stimulus offset. Once the response was made, the next trial was initiated after an approximately 150 ms delay. Each trial took less than a second. Participants continued to make judgements throughout the flight which included periods of level flight, simulated lunar g and hypergravity. The instantaneous gravity level at the start and end of each trial was recorded along with the key presses so that the data could be analysed according to the prevailing g-level.

*Data analysis*

For each subject, data were divided into three groups according to the prevailing gravity level obtained from averaging the start and end gravity values. The three categories were 1g ±0.05g, 0.17g (lunar) ±0.05g and 2g (hypergravity) ±0.05g. Data associated with gravity levels outside these ranges were discarded. We calculated the perceptual upright in the presence of each background during each gravity state for each subject, pooling data across several flights, as follows. The percentage of trials in which the identity 'p' was chosen was plotted against the orientation of the character (see Fig. 3). The product of two hyperbolic tangent (eq. 1: equivalent to the product of two sigmoidal psychometric functions) was fit to each data set by minimizing the root mean square error between the data and the psychometric function.

$$p = 0.5 * (1 - \tanh((\theta-\theta_1)/\sigma) * \tanh((\theta-\theta_2)/\sigma)) \text{.........(eq 1)}$$

where p is the percentage of times the character was identified as a "p", theta is the orientation of the character ("d" at $\theta=0°$), $\theta_1$ and $\theta_2$ are the two orientations or point of subjective equality (PSE) i.e., the orientations at which either identity of the character was equally likely to be chosen (50%) and $\sigma$ is a parameter corresponding to the slope of the function. The bisector of the two PSEs was taken as the perceptual upright.

The difference in the perceptual upright between the two backgrounds defines the "visual effect" i.e., the amount the perceptual upright was shifted by the tilted visual backgrounds.

## RESULTS

Fig. 3 shows typical responses and psychometric functions fitted through the data obtained from one subject for all six experimental conditions (3x gravity states – lunar gravity, normal gravity, hyper gravity, 2x background orientations: ± 112.5°). Fig. 4 plots the magnitude of the visual effect for all subjects obtained from such plots under each of the three gravitational states (lunar, normal and hypergravity). The "normal" condition was obtained during level flight. The mean magnitudes of the visual effect were: under lunar g: 26.1 ±11.4°; under normal g: 28.0 ±13.2° and under hypergravity: 26.3 ±10.8°. The large standard errors are caused by the large inter-subject variations (see discussion). A repeated measures ANOVA was run using SPSS 19 on the visual effect. Mauchly's test indicated that the assumption of sphericity had not been violated $X^2(2)=0.193$, $p=0.91$ n.s., The repeated measures analysis showed no effect of gravity state on the size of the visual effect $F(2,14)=0.238$ n.s.

## DISCUSSION

There were no effects of change in gravity state found in this study. This contrasts with the results of a very similar experiment that we carried out in the same plane using the same equipment but flying parabolas that generated periods of zero G instead of the 1/6 g (lunar g) created here. Under zero G the visual effect was reduced by about 19% and under hypergravity it was reduced by about 15% (6). In the present study the reductions of 7% (lunar g) and 6% (hyper g) were not significant.

The perceptual upright on earth is influenced by visual and gravity cues to upright and by an internal representation of the long-axis of the body (5,18). Although there was substantial inter-subject variability (note the variability between our subjects), varying the relative directions of these cues shifted the direction of the perceptual upright suggesting a linear sum of these three influences with weighting of on average about 25% from vision, 25% from gravity and the

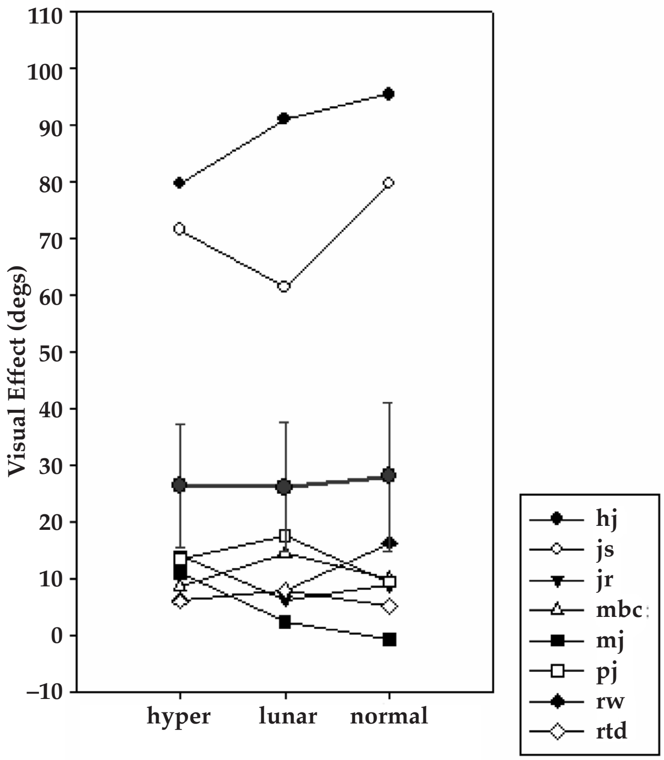


**Figure 4**. The size of the visual effect (VE) is shown here during level flight and lunar gravity conditions compared to during level flight for each individual subject (see key) and as means (large circles with standard error bars(. There was substantial inter-subject variation in the size of the visual effect, even under normal gravity but no systematic variation with g-state over this range.

remainder from the body. This is vector sum model which can be described as;

$$PU = g^* \text{ weight}_g + v * \text{weight}_v + b^*\text{weight}_b \text{.......(eq 2)}$$

where weight $_{g,v,b}$ are the relative weightings assigned to the gravity, visual and body cues respectively and g, v, b are unit vectors in the directions of each cue. This equation derives from the pioneering work of Mittelstaedt (18) and has been used to successfully model performance under normal gravity conditions (5). The prediction from a linear summation vector model is that if one of these cues is removed, the effect of the remaining cues should increase proportionally but that the relative weighting assigned to each of them should be maintained. The predicted increase in the contribution of visual cues was found in a previous experiment in which the influence of gravity was removed from the plane of testing by lying supine (5). This is consistent with the model used for bedrest microgravity simulation studies in which a supine position is used to simulate the effects of microgravity on the circulation and other physiological factors (see, for example, 2). However, when the effects of gravity were cancelled using parabolic flight the visual weighting decreased (Dyde et al. 2009) meaning that visual cues had less influence than expected in determining the perceptual upright and indicating a relative increase in the weighting assigned to the long-axis of the body rather than maintaining the normal relationship between visual and body cues. An increased significance of the body in determining orientation under microgravity has also been observed anecdotally (21,22).

The fact that visual weighting was unchanged under lunar g confirms assertions that lunar gravity is adequate (above threshold) for maintaining a normally balanced weighting between the three cues that determine the perceptual upright (10).

What would be the consequence to perceived orientation if the weighting assigned to gravity were directly proportional to the magnitude of gravity while the relative weighting of the visual and body cues were maintained? The vector sum model makes a clear prediction: vision would play a larger role in the vector sum (see eq. 2) as the magnitude of gravity decreased and conversely vision would play a smaller role as the magnitude of gravity increased. Fig. 5 plots the predicted effect of vision as a function of the magnitude of gravity. The data point obtained when gravity is simply shifted out of the testing plane by lying supine (data from 5, plotted on Fig. 5) is well predicted by this curve. Interestingly, when the magnitude of gravity is increased during the hypergravity phase of parabolic flight), the relative contribution of vision also appears to be decreased in line with the model's prediction. Although this reduction did not reach significance in the hypergravity phase of the present study, there was a significant reduction during the hypergravity phase reported in Dyde et al. (6). These data are also plotted in Fig. 5. However, the increased effect of vision that this simple model predicts should result from removing or reducing gravity is not found under either zero gravity (6) or lunar gravity (present study) levels. Instead there is a significant reduction in visual effect under microgravity and none at all under lunar conditions. Somewhere between these two gravity states (i.e., between 0 and 0.17g) the weighting applied to the visual cue is reduced. This is indicated diagrammatically in Fig. 5 by the thick grey line.

Our finding of no change in visual effect under lunar gravity compared to when measured under normal gravity suggests that lunar gravity should provide the same perceptual environment as on Earth. We need to look elsewhere to explain why astronauts fall when working on the lunar surface. Perhaps astronauts detect the reduced magnitude of

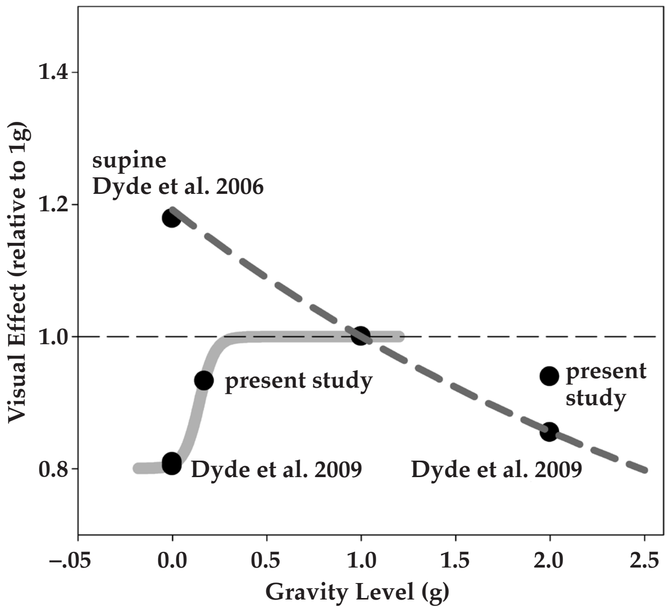


**Figure 5.** The effect of gravity state on the magnitude of the visual effect. The dashed curve predicts the influence of vision (magnitude of the visual effect) plotted as a function of gravity level. The weighting assigned to the gravity cue has been set as proportional to the actual g value while the weightings of the visual and body cues relative to each other was maintained. All effects are plotted relative to the visual effect at 1g. Superimposed on this theoretical curve are data points measured under lunar gravity (present study), microgravity (6), hypergravity (present study and 6) and while lying supine (5) as indicated. The thick grey sigmoid plotted through the points corresponding to 1g, lunar g (present study) and 0g (6) diagrammatically indicates a threshold for the reduced effect of vision at between 0 and 0.17g.

gravity and expect the relative visual weighting to be increased (as it is when lying supine). Other factors may include a loss of proprioceptive cues because of wearing a bulky space suit with a limited view of the body, the reduced field of view available through the space suit's visor and the lack of normal visual cues to up in the sparse lunar landscape. Understanding how altered gravity states affect perception and the assessment of moon upright is an important part of our preparations to return to the moon.

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