Perceived distance depends on the orientation of both the body and the visual environment

Laurence R. Harris Centre for Vision Research, York University, Toronto, Canada

Charles Mander Centre for Vision Research, York University, Toronto, Canada

Models of depth perception typically omit the orientation and height of the observer despite the potential usefulness of the height above the ground plane and the need to know about head position to interpret retinal disparity information. To assess the contribution of orientation to perceived distance, we used the York University Tumbled and Tumbling Room facilities to modulate both perceived and actual body orientation. These facilities are realistically decorated rooms that can be systematically arranged to vary the relative orientation of visual, gravity, and body cues to upright. To assess perceived depth we exploited size/distance constancy. Observers judged the perceived length of a visual line (controlled by a QUEST adaptive procedure) projected on to the wall of the facilities, relative to the length of an unseen iron rod held in their hands. In the Tumbled Room (viewing distance 337 cm) the line was set about 10% longer when participants were supine compared to when they were upright. In the Tumbling Room (viewing distance 114 cm), the line was set about 11% longer when participants were either supine or made to feel that they were supine by the orientation of the room. Matching a longer visual line to the reference rod is compatible with the opposite wall being perceived as closer. The effect was modulated by whether viewing was monocular or binocular at a viewing distance of 114 cm but not at 337 cm suggesting that reliable binocular cues can override the effect.

Introduction

Knowledge of absolute distance is required in order to convert visual images into the perception of objects of a particular size. However extracting absolute distance is not an easy task for the visual system. The problem can be solved monocularly from blur (Mather, 1997; O'Shea, Govan, & Sekuler, 1997) and accommodation cues (Mon-Williams & Tresilian, 1999) but these provide only crude estimates at best. Potentially more reliable cues come from binocular cues such as vergence (Mon-Williams, Tresilian, & Roberts, 2000) and disparity (Mayhew & Longuet-Higgins, 1982). However, interpreting disparities, especially for peripheral objects, requires knowledge of 3-D eye orientation, which is dependent on head orientation (Blohm, Khan, Ren, Schreiber, & Crawford, 2008). The ground plane serves as an important reference for distance estimation (Gajewski, Wallin, & Philbeck, 2014; Gibson, 1950; Wu, Ooi, & He, 2004) and the perceived orientation of the ground plane also depends on eye orientation (Howard, 2012) and hence head orientation. Therefore, we postulate that head orientation may affect the perception of distance. Head-position related errors have been reported when reaching for peripherally viewed targets (Blohm et al., 2008) and when judging distance while looking through the legs (Higashiyama & Adachi, 2006; Toskovic, 2010) giving support for this idea.

An effect of head position on perceived distance has long been thought to contribute to the moon illusion in which the moon looks smaller when directly above the observer than it does when it is seen on the horizon (see for example, Gauss, 1880, and many other studies reviewed comprehensively in Hershenson, 1989, and Ross & Plug, 2002). Although many of these studies are suggestive of head-related errors in perceived depth (Carter, 1977; Zinkus & Mountjoy, 1969), they are often confounded by differences in the visual scene (and therefore visual context) correlated to head orientation (Ching, Peng, & Fang, 1963; King & Gruber, 1962), by including elevated eye position (Wood, Zinkus, & Mountjoy, 1968) or by inadequate reporting methods (Bilderback, Taylor, & Thor, 1964). Experiments involving viewing the moon using mirrors

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have suggested that the moon illusion may not require a person to actually be looking in different directions but that visual context usually associated with a particular head orientation may be important (Rock & Kaufman, 1962). The vestibular system relies heavily on such visual context and past history (Merfeld, Zupan, & Peterka, 1999) to overcome its ambiguities and to determine head position, and can easily be misinterpreted as signaling incorrect body orientation (Howard & Hu, 2001). These observations suggest that visual context to head orientation may also influence depth perception.

Careful experiments under microgravity have more directly implicated the vestibular system in perceiving depth (Clément & Reschke, 2008). Perceived distances were consistently underestimated during either short-term exposure to microgravity using parabolic flight (Clément, Lathan, & Lockerd, 2008) or long term exposure on the International Space Station (Clément, Skinner, & Lathan, 2013) leading to perceptual distortions of three dimensional objects. In the absence of a gravitational reference it seems that objects appear closer than in the presence of orientation cues.

Despite these many studies implicating perceived orientation as contributing to depth perception and a strong theoretical basis as to why this should be (Blohm et al., 2008), quantitative experiments exploring the role of body orientation on depth perception controlling for the influence of visual cues to orientation are lacking. Here, we systematically altered both observers' physical and perceived orientation to assess the effect of head orientation on depth perception. Our hypothesis, based on the above observations, was that objects would appear closer when a participant lay down or when the visual scene was compatible with them lying down. We used the York Tumbling and Tumbled Room facilities to manipulate not only the actual orientation of an observer relative to gravity but also their perceived orientation. Surrounding a person with a realistic visual environment arranged orthogonal to gravity creates a compelling visual reorientation illusion in which a person feels that the room is upright (Howard & Hu, 2001). Measuring depth perception is always challenging as all methods introduce contaminating factors. Here we used an indirect method exploiting the relationship between perceived distance and perceived size. We had our participants adjust the length of a line until it matched a standard length provided by exploring the length of an unseen rod held in their hands. Performing this matching task requires subjects to convert visual information to physical length, which requires knowledge of absolute distance.

Methods

Participants

Ten participants took part in this study (five female, mean age 28 ± 3.6 years). They were either students or faculty in the lab or recruited from the York University Participation Pool in which case they received course credit for taking part in the experiments. All participants gave informed consent. All experiments were approved by the York Ethics Board and performed in accordance with the Declaration of Helsinki.

Stimuli

In order to measure perceived distance we used the indirect method of size constancy. In order to obtain the length of an object from its retinal image, distance needs to be taken into account. We compared the length of a visual line of variable length with a fixed-length unseen reference bar held in the hands. The bar was a metal rod 61 cm (2 in.) long and 1 cm in diameter. The bar was always held earth horizontal for both postures in both experiments and in all room configurations. The visual line was generated by a red laser reflected off a galvanometer that was positioned under computer control. The line was 0.5 cm wide and its length could vary under control of a QUEST adaptive procedure (Watson & Pelli, 1983) run by a computer. The bar was projected onto the far wall of one of two rooms: the York Tumbled Room and the York Tumbling Room. The York Tumbled Room is a room built rotated 90° relative to gravity with a matching control room of exactly the same size. It is 244 cm × 244 cm × 366 cm (8 ft × 8 ft × 12 ft) and decorated with features such as bookshelves, carpet, polarized wall paper, a door, pictures on the wall, and a window with a simulated view. It is arranged such that the back wall (244 cm × 244 cm, 8 ft × 8 ft) is on the true floor. When participants lie on this back wall they have the carpet of the "floor" beneath their feet and can see the far wall, complete with a door, opposite them as shown in the panorama in Figure 1. Participants stood or lay with their heads against the back wall so that viewing distance was about 337 cm (depending on the size of the participant's head). The York Tumbling Room is a cubic room 244 cm × 244 cm × 244 cm (8 ft × 8 ft × 8 ft) that is decorated with similar features to the Tumbled Room. In addition, the Tumbling Room contains furniture such as a laid table and chairs with a full-sized manikin sitting on one of the chairs. For the Tumbling Room experiment, participants were suspended in a chair in the center of the room so that viewing distance was about 114 cm, again depending on

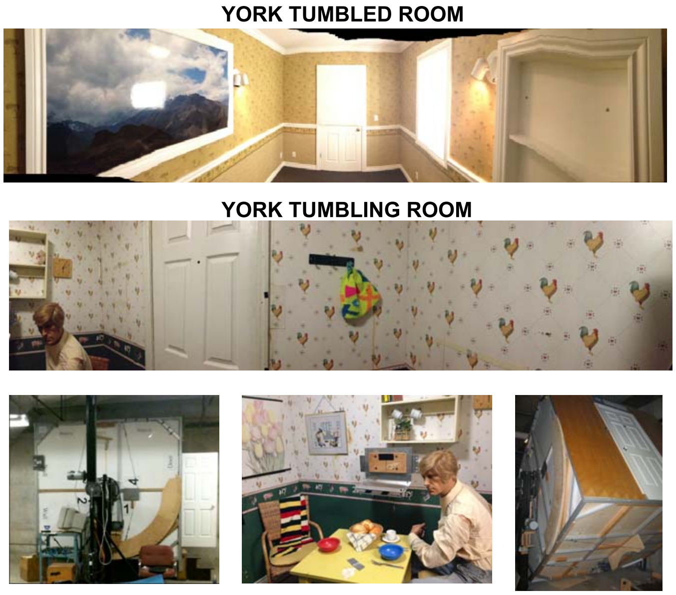

Figure 1. Photographs of the York Tumbled (top) and Tumbling (bottom) facilities. The Tumbled Room measured 244 cm × 244 cm x 366 cm (8 ft × 8 ft × 12 ft) and the Tumbling Room is 244 cm × 244 cm × 244 cm (8 ft × 8 ft × 8 ft). The panoramic views of each room were taken with the photographer on his back relative to gravity (photographs by the author, LRH).

the size of the participant's head. Views of the Tumbling Room, including a panorama of what they saw, are shown in Figure 1. For both the Tumbled Room experiment and the Tumbling Room experiment the viewing distance was constant for a given participant in all configurations in that room. A small intersubject variation was inevitable because of the different sizes of participants' heads.

The line stimulus was projected onto the wall directly opposite the participant aligned with their body axis. For the Tumbled Room experiment (and its identical control), the line was projected onto a screen fixed to the door (Figure 1). For the Tumbling Room experiment, it was projected next to the door or on the ceiling depending on the arrangement of the room. In both cases the position of the center of the line was randomly jittered over a range of ±10 cm between trials to prevent participants from lining up one or other end with any visible features in the room.

Procedure

For the Tumbled Room experiment, participants either lay on the physical floor that was the back wall of the room or stood in the control version of the room with their head against the back wall. Their feet were positioned on two foot pedals (Yamagoshi, Japan). The distance from the participant's eyes to the wall on which the bar was projected was within 2 mm of being the same for both rooms (measured by an ultrasonic measuring device: Zircon Sonic Measure DMS50L, California).

For the Tumbling Room experiment, the participant was strapped into a chair that could rotate in the pitch plane. Four combinations of the Tumbling Room and participant orientation were used: (1) both room and participant upright (facing door), (2) room tilted back 90°, participant on their back facing the door, (3) room upright, participant on their back facing the ceiling, and (4) room tilted forwards 90°, participant upright facing ceiling. These configurations are shown in cartoon form along the horizontal axes of Figures 2 and 3 for the Tumbled and Tumbling Rooms, respectively.

The experiment in the Tumbled Room and the experiment in the Tumbling Room were run separately. For each experiment, once a configuration had been adopted, participants were given the reference rod to hold and told to lift their foot from either foot pedal to start. They were told to hold the rod horizontally in front of their body and were prevented from seeing it by a cloth flap. The visual line was then presented for as long as the participant needed to judge whether the visual line or the reference rod was longer. They lifted their foot from one of the foot pedals to indicate their choice (left if the visual line appeared longer than the reference rod, right if shorter) and the next trial was immediately started. The length of the line was controlled by a QUEST adaptive algorithm (Watson & Pelli, 1983). The QUEST algorithm assumes the observer's psychometric function follows a Weibull distribution and adaptively determines the next line length to be presented on the basis of the participant's response to the previous trials. As the experiment goes on, knowledge on the observer's psychometric accumulates. We ran two QUESTs that approached the threshold from opposite directions (one starting with a long line, one with a short line). Each QUEST procedure terminated after 20 trials. Once the procedure was finished, the next room configuration for that particular experiment (either the Tumbled Room or the Tumbling Room) was selected (with the order of presentations within each experiment counterbalanced across subjects) and the procedure was repeated. All conditions were run twice, once with a monocular patch over the nondominant eye and once with both eyes open. All monocular and all binocular trials were run in blocks in an order counterbalanced across subjects.

Data analysis

The average of the two QUEST means was taken as the length of the bar when it was perceived as equal to

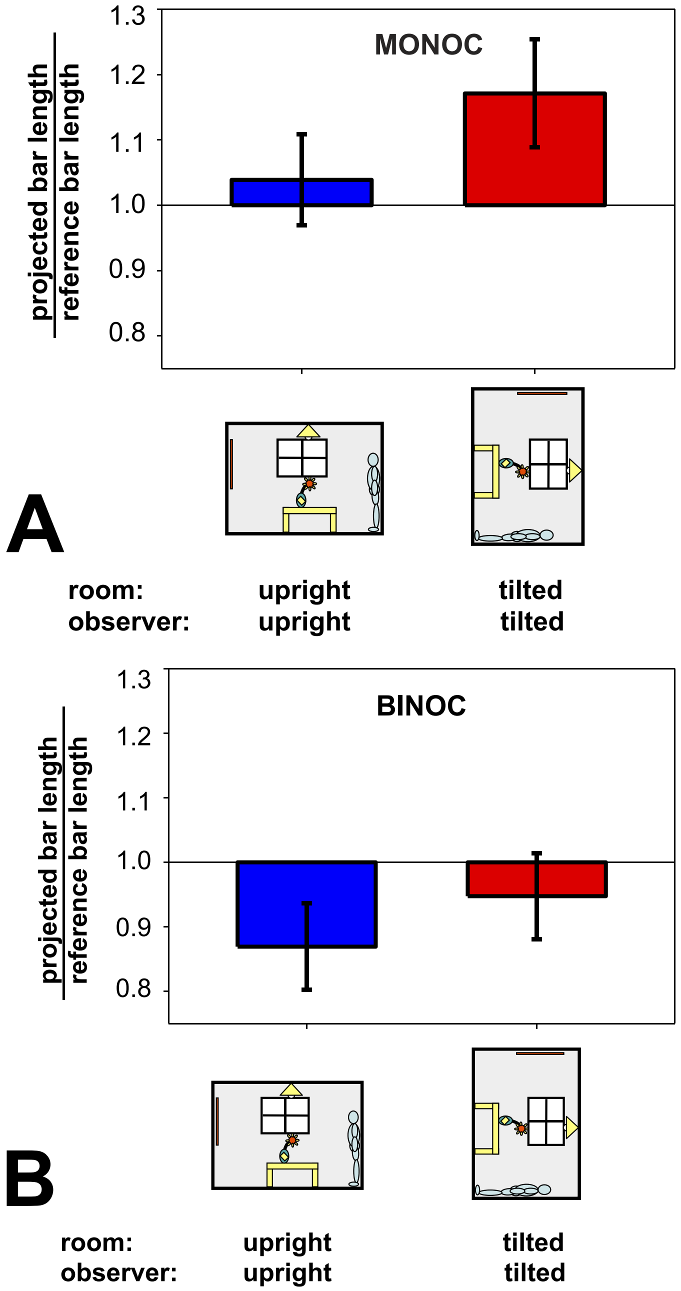

Figure 2. The length of a rod judged equal to the reference rod under monocular (A) and binocular (B) viewing in the York Tumbled Room (viewing distance ~366 cm, 12 ft). The lengths of the lines judged equal to the length of the reference rod are expressed as a ratio of the reference rod's actual length. Blue bars show ratios with the participant and room upright, red bars show data with the participant and room both tilted by 90°. Error bars are *SEM*s.

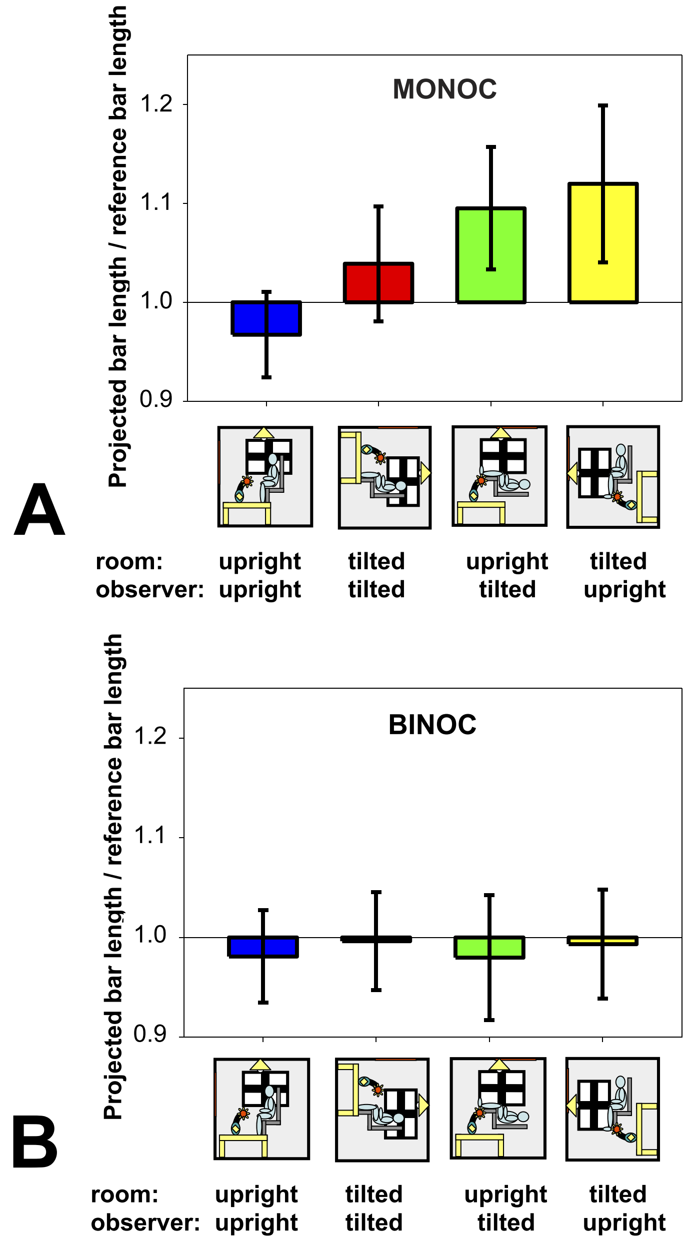

Figure 3. The length of a rod judged equal to the reference rod under monocular (A) and binocular (B) viewing in the York Tumbling Room (viewing distance ~122 cm or 4 ft). The length of the lines judged equal to the length of the reference rod are expressed as a fraction of the reference rod's actual length. As for Figure 2, blue bars show ratios with the participant and room upright, red bars show ratios with the subject and room tilted 90°. The Tumbling Room facility enabled two further conditions: Observer on back in an upright room (green bars) and observer upright in a tilted room (yellow bars). Error bars are *SEM*s.

the reference bar: the point of subjective equality (PSE). This length was divided by the length of the reference bar to provide a ratio where one corresponds to an accurate judgment. A ratio less than one thus corresponds to a line shorter than the reference being perceived as equal to the reference, and a ratio greater than one corresponds to a line longer than the reference being perceived as equal to the reference. The statistical analysis comprised repeated measures analysis of variances (ANOVAs). Mauchly's test of sphericity was used. Where the assumption of sphericity was violated we used the Greenhouse-Geisser correction to the degrees of freedom. For all tests, alpha was set at $p < 0.05$. All multiple comparisons were carried out with the false discovery rate p value correction (Benjamini & Hochberg, 1995).

Results

Experiment in the Tumbled Room

The lengths of the projected line judged equal to the reference rod are shown as ratios of the actual length of the reference rod for the experiment in the Tumbled Room (distance to back wall ~366 cm, 12 ft) in both the upright and tilted configurations, in Figure 2. A 2 × 2 between-within groups ANOVA revealed a significant main effect of condition, $F(1, 17) = 18.015$, $p = 0.001$, $\eta_p^2 = 0.514$, whereby the ratios for upright in the normal room (mean = 0.95, $SEM = 0.05$) were significantly lower than for supine in the Tumbled Room (mean = 1.06, $SEM = 0.05$). There was also a near significant difference between the monocular (mean = 1.11, $SEM = 0.07$) and binocular (mean = 0.91, $SEM = 0.07$) viewing condition, $F(1, 17) = 3.91$, $p = 0.064$, $\eta_p^2 = 0.187$. There was no significant interaction between viewing group and condition, $F(1, 17) = 1.191$, $p = 0.290$, $\eta_p^2 = 0.065$. In summary, under both monocular and binocular viewing conditions the length of the projected line judged equal to the reference rod was longer when the participants were supine than when they were upright.

Experiment in the Tumbling Room

The ratios of the projected line judged as being of equal length to the reference rod are plotted in Figure 3 for monocular and binocular viewing conditions with the observer and room tilted in various combinations. The first two conditions (both observer and room upright, blue bars, and both observer and room tilted, red bars) are the same as the conditions used in the Tumbled Room, except that the viewing distance was much shorter (122 cm, 4 ft compared to 366 cm, 12 ft in the Tumbled Room). A 2 (Viewing) × 4 (Condition) repeated measures ANOVA revealed a significant main effect of condition, $F(1.344, 12.092) = 5.971$, $p = 0.024$, $\eta_p^2 = 0.399$, but no significant effect of viewing, $F(1, 9) = 0.853$, $p = 0.380$, $\eta_p^2 = 0.087$, although there was a trend towards an interaction, $F(3, 27) = 2.444$, $p = 0.086$, $\eta_p^2 = 0.214$.

Comparing the same conditions as in the Tumbled Room experiment (both upright and both tilted) shows that the ratios were significant larger when tilted (1.02, SEM 0.04) than when upright (0.97, SEM 0.03), ($p = 0.005$ corrected, see Methods). Interestingly, this significant increase was also found when just the observer ($p = 0.005$, corrected) or just the room ($p = 0.014$, corrected) was tilted.

Under binocular viewing, none of the ratios for the conditions with the observer, room, or both tilted was significantly different from the upright-in-an-upright-room control condition ($p = 0.98$, 0.75, and 0.17, respectively), whereas for the monocular condition, all three experimental conditions were significantly different from the control condition ($p = 0.002$, 0.01, and 0.02, respectively).

Discussion

We have shown that the perceived length of a line judged equal to a reference rod held in the hands varies with orientation of an observer when they were either physically or perceptually tilted. When observers were, or thought they were, lying on their backs, the length of a projected line that matched the length of a reference rod held in their hand was longer than when it was seen at the same physical distance when they were upright. In order to make the required length comparison between the observed line and the rod held in their hands participants had to convert the retinal image of the line to a physical length. This conversion requires knowledge of the distance of the projected line. We interpret our data as revealing differences in this perceived distance caused by changes in perceived posture.

To convert retinal image size (in degrees) to linear distance (in cms) is simple trigonometry:

$$\text{Length} = 2.\text{d}.\tan(\text{theta}/2), \quad (1)$$

where d is the distance and theta is the retinal image angle. Leaving aside the interesting puzzle of how the brain might solve this nonlinear trigonometry and the fact that the angular size of an object would normally be obtained from a mixture of eye movements used to scan the object and retinal image size, not just the retinal image, the point is that if there were an error in estimating d, then this would translate into an error in estimating length. If the projected line seen as equal in length to the reference rod was actually longer than the rod, this would be compatible with the line being seen as closer. This is illustrated in Figure 4, which shows that ratio of the length of the reference rod to the length of the projected visual line is equal to the ratio of the perceived distance to the actual distance.

According to this calculation, the 12 ft (366 cm) viewing distance was perceived as 9.8% closer on

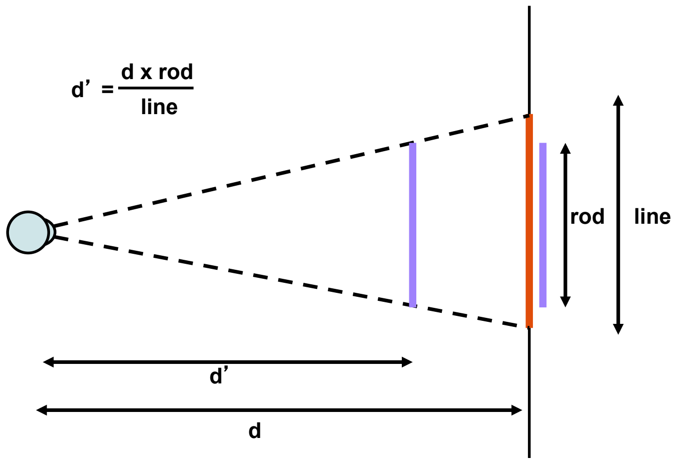

Figure 4. The ratio of the length of the line (red line) set equal to the length of the rod (purple line) is equal to the ratio of the actual distance (d) to the perceived distance (d′).

average (36 cm or 1ft 2 in.) when the observer was supine compared to when they were upright (pooling monocular and binocular data). The 4 ft (122 cm) viewing distance was perceived as 10.8% closer on average (13 cm or 5 in) when the observer was supine compared to when they were upright when viewing was monocular, independent of whether subjects were tilted or thought they were tilted because of the tilt of the room. Binocular vision in a fully lit, rich visual environment appears to be able to override the effect of head orientation at close distances (∼122 cm, 4 ft). However, at longer viewing distances (∼366 cm, 12 ft.), where binocular cues are less effective (Howard & Rogers, 2012), tilted head position consistently produced a reduction in perceived depth independent of whether viewing was monocular or binocular. This implies that binocular cues to distance, if strong enough, can work independently of head position.

It is possible that there may have been errors in estimating the length of the iron reference rod that were also dependent on the observer's orientation and the orientation of the surrounding room. However, the same rod was used throughout all experiments, held at the same orientation relative to the subject and to gravity, and subjects quickly formed an internal representation of its length that they then only confirmed by touch from time to time. This method is therefore akin to the method of single stimuli (McKee, Silverman, & Nakayama, 1986) although even an internal representation could be subject to distortion.

While this study might shed some light on the phenomenon of the moon illusion, it is clearly different in nature. The moon illusion literature is complex and wide ranging (Ross & Plug, 2002) and deals with an object (the Moon) of undefined perceptual size and distance. Rather, we feel that the present study is more related to the emerging central involvement of the head position system (involving an interaction of vestibular, visual, and proprioceptive cues) to visual perception. Gaze position (Gajewski et al., 2014) and the perceived orientation of the ground plane (Wu, He, & Ooi, 2007; Wu et al., 2004) are important contributors to perceived depth and both depend on head orientation. Already at the level of the primary visual cortex, responses have been shown to be modulated by changes in perceived depth even when actual depth remains constant (Murray, Boyaci, & Kersten, 2006). This might imply a role for the vestibular modulation of visual cortical responses that has been observed (Brandt, Bartenstein, Janek, & Dieterich, 1998; Seemungal et al., 2013).

Why might perceived distance depend on orientation?

The literature suggests various ill-defined theories for why head position might affect perception. For example, one theory, which can be traced back to Bishop Berkeley (Berkeley, 1732), suggests an effect of imagining the effort of walking along the distance in question (Proffitt, Stefanucci, Banton, & Epstein, 2003). Thus, uphill distances are perceived as longer. This theory would predict that distances perceived while lying supine should be perceived as longer as it would, presumably take more effort to move against gravity. However, our data are compatible with the opposite finding, namely that while lying supine, distances appear as closer, compatible with the "flattened heavens" interpretation of the moon illusion (Rock & Kaufman, 1962).

Why might distances, even for earthly targets at quite close distances, appear closer when viewed lying down? Correct depth perception relies on an accurate knowledge of the three dimensional orientation of the head and eyes (Blohm et al., 2008) in order to correctly interpret disparities over the whole visual field. Eye position does not seem to be affected by adopting a supine posture (Bockisch & Haslwanter, 2001) but knowledge of body orientation when lying supine is poor with large systematic errors and poor reliability (Jarchow, Wirz, Haslwanter, Dietz, & Straumann, 2003; Mast & Jarchow, 1996). Thus, a supine posture may not be so accurately calibrated against experience of depth. Misperceived distance may also be related to a corresponding misestimation of eye height above the floor of the room. Some participants anecdotally reported feeling taller when lying in the Tumbled Room. Perceived eye height (Wraga, 1999) and body size generally (Linkenauger, Witt, Stefanucci, Bakdash, & Proffitt, 2009; Stefanucci & Geuss, 2009; van der Hoort, Guterstam, & Ehrsson, 2011) contribute to the perceptual scaling of space. If participants felt they were taller than usual, then this could cause a perceptual rescaling of the size of the room a la Alice in Wonderland. When unsure of head position in the environment, either because of an unusual posture or in microgravity (Clément et al., 2013), the depth system may get recalibrated resulting in a rescaling of the apparent size of the environment with corresponding errors in size perception.

Keywords: vestibular, otoliths, distance perception, depth perception, tumbling room, posture and distance

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Corresponding author: Laurence R. Harris.
Email: harris@yorku.ca.
Address: Department of Psychology, York University, Toronto, ON, Canada.

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