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Relative role of visual and non-visual cues in determining the direction of "up": Experiments in the York tilted room facility

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Abstract. Perceiving a direction as "up" is fundamental to human performance and perception. Astronauts in microgravity frequently experience reorientation illusions in which they, or their world, appear to flip and 'up' becomes arbitrarily redefined. This paper assesses the relative importance of visual cues in determining the perceived up direction. In the absence of information about the origin of illumination, people interpret surface structure by assuming that the direction of illumination is from above. Here we exploit this phenomenon to measure the influence of head and body orientation, gravity and visual cues on the perceived up direction. Fifteen subjects judged the shape of shaded circles presented in various orientations. The circles were shaded in such a way that when the shading was compatible with light coming from above, the circle appeared as a convex hemisphere. Therefore, by finding which shaded circle appeared most convex, we can deduce the direction regarded as "up". The different cues contributing to this percept were separated by varying both the orientation of the subject and the surrounding room relative to gravity. The relative significance of each cue may be of use in spacecraft interior design to help reduce the incidence of visual reorientation illusions.

1. Introduction

The perceived direction of "up", the direction along which gravity pulls, is fundamental for many aspects of perception and not only determines our ability to move around within an environment but also helps to identify objects within it. Figure 1 demonstrates the significance of the "up" direction to object identification. Distortion of the facial features is not evident with the page in its normal orientation but become readily apparent when the page is rotated "upside down" and the faces become "upright" (after [12]).

Errors in the perception of the up direction can be debilitating and may lead to postural as well as perceptual instability [6]. Astronauts in microgravity frequently experience reorientation illusions in which they or their world appear to flip and the up direction becomes redefined arbitrarily [9,10]. Not only can this be unsettling but it can also lead to errors in recognizing objects, navigating within large structures, operating equipment and reading signs. In order to help understand how reorientation illusions come about and to develop tests to assess the effectiveness of various visual polarization cues to help overcome them, we have assessed the relative contributions of the body, and visual and non-visual cues to the perception of the "up" direction. Each cue can form part of a complete three-dimensional reference frame but here we consider them as providing just a reference direction. Since we hope to give relative

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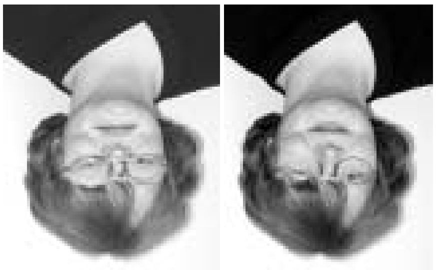

Fig. 1. The left and right views of the first author's face appear normal (and similar) when viewed in this orientation. Large structural changes are easily overlooked in the upside-down face, but these changes become readily apparent when the face is presented in its normal upright orientation. This figure is based on the Thatcher Illusion [12].

magnitudes to the weightings of these directions, we will refer to them as vectors pointing in the direction of up as specified by each system.

The body axis

The body has components defined by the position and orientation of the eyes, head and trunk. In the experiments reported here these all remain aligned and we consider the whole as a single reference direction referred to as the idiotropic vector [8].

The direction of gravity

The direction of gravity is sensed by the vestibular system and by proprioception and touch sensors. The changes in force needed by muscles when they are working with or against gravity can also provide a cue to the direction of gravity [7]. Touch receptors detect the force that the weight of the body applies to support surfaces through the feet when standing and back and buttocks when seated. The direction of gravity can be detected with a resolution of less than 5 degs [3].

Visual cues

Vision, also, provides information about the direction of gravity by providing orientation cues associated with individual objects, groups of objects or the structure of the environment [4]. Intrinsic cues include the fact that many objects have an obvious "right way up" (e.g. faces). Other cues may be extrinsic: defined by the relative position of objects (e.g. a book placed on a table, or a scarf hanging from a hook). Environmental cues include the general structure of the frame within which the visual display is provided, including walls, ground plane, and the ceiling or sky. For these experiments as in normal life, all these visual cues were arranged to be consistent with each other providing a single, visual "up" vector.

The effectiveness of each of these cues has traditionally been investigated by removing other factors as much as possible. However other cues can never be removed completely and in any case the systems sensitive to each cue normally interact with each other. Our experiments look at the relative contribution of each of the body, gravity and visual cues presented simultaneously but arranged to indicate different directions of up.

Determining which way is up

How can one ascertain a subject's perceived direction of up? Adopting different criteria can produce very different estimates. Under some conditions the interpretations "which way would a ball fall?", "where is the top of an object?", "where is my head?", "where does light come from?" could all evoke different answers. Here we define up as the perceived direction of the pull of gravity. Various methods have been used to measure this including simply pointing or aligning a rod with the subjective vertical or horizontal (eg. [8,14], see [4] for a review). Such methods involve drawing subjects' attention to the idea of "up" – a concept of which we are not normally aware – and therefore involve cognitive factors.

To reduce the influence of cognitive factors we used a task that requires knowledge of "up" but which does not require a subject to consider consciously where "up" is. In the absence of information about the origin of illumination, people interpret surface structure by using shading and some assumption about the direction of illumination [1,2,11]. This assumed direction is influenced by both the orientation of the retina and the true vertical which the subject can sense by visual and non-visual means. Normally all of these cues, the retina, visual orientation cues and the acceleration of gravity, are aligned but here we separate them to reveal the relative strengths of their contributions to perception.

Figure 2 shows the test object we used. The test object consisted of four shaded disks presented in different orientations separated by 90 degrees. Each of the four shaded disks seems to have a different three-dimensional structure depending of the perceived direction of illumination. When the shading is compatible with the perceived direction of light, the circle appears as a convex hemisphere. In the example given in Fig. 2, assuming that the top of the printed page corresponds to the reader's personal idea of "up", the shaded disk near

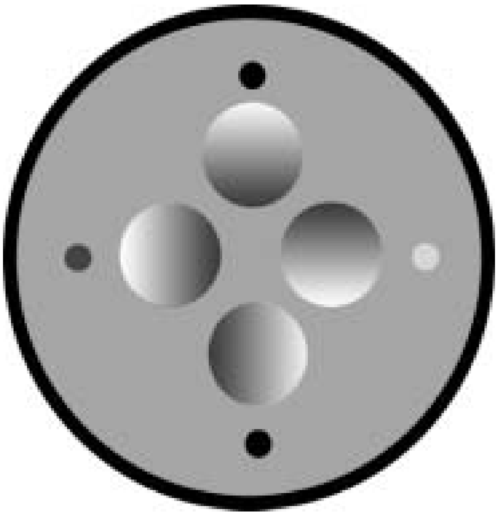

Fig. 2. Test shapes. The four shaded disks differ only in their orientation. Under the assumption that the disks are lit from above and that the page is 'upright', the disk near the top marker should appear most convex, while the disk near the right marker should appear most concave. Subjects indicated which disc appeared most concave by pressing a button from a similarly configured button array.

(a) True structure

(b) Subject's view

Fig. 3. The York Tilted Room. The room is an 2.5 m $\times$ 2.5 m $\times$ 2.5 m room that has been constructed 'tilted' relative to the normal direction of gravity. The contents of the room are highly polarized so as to provide strong intrinsic and extrinsic cues about the visually defined up direction. In this room, the visual up is orthogonal to the gravitational up.

the top marker will appear most convex. It is shaded as if it were a three-dimensional convex shape lit from the top of the page. During rotation of the head or page, different discs will appear more convex and the disc that appears most convex at any one time reveals the perceived direction of illumination.

By finding which shaded disk appears most convex during viewing under our various conditions, we can deduce the perceived direction of illumination and the relative weightings of the cues that determine it. From these studies we can therefore predict the perceived direction of illumination and the perceived direction of "up" in unusual environments and also the visual and non-visual cues to the perceived vertical.

2. Method

2.1. *The York tilted room*

In order to separate visual and gravity reference directions, we constructed a tilted room at York University in which the visual cues about the polarity of the room are set at 90 degs to the direction of gravity. This room is a 2.5 m cubic physical room in which the wallpaper, furniture, and other physical structures, including a full-sized manikin in life-like pose (not shown in this view), are used to provide strong, realistic, polarized visual cues. What appears as the visual floor is actually constructed on a physical wall, and one of the visual walls is actually constructed on the physical ceiling (Fig. 3). All the visual cues in this room indicate an "up" direction that is orthogonal to the physical direction of gravity. By arranging subjects in various orientations both within and outside the tilted room, the relative importance of the body, visual and gravity "up" vectors to the overall perception of the direction of up can be assessed.

2.2. *Procedure*

Fifteen subjects (5 female) participated in the experiment (age range 18–49 years). Subjects were drawn from the York University graduate student population and from researchers in the laboratory. Displays like that shown in Fig. 2, were presented on a laptop computer screen. The computer's screen was always arranged with the top towards the top of the subject's head except for the inverted condition in which the bottom was towards the top of the subject's head. All 24 possible spatial arrangements of the four shaded shapes were used. Each arrangement was shown 8 times in a random order for a total of 192 trials per condition. Each trial took 3–5 secs and the whole set of 192 trials took between 10 and 15 mins.

Subjects were instructed to inspect the four shaded disks and to indicate which one of the four shapes appeared most convex. They made their choice using a game pad connected to the computer with four buttons in the same configuration as the display. Subjects pressed the corresponding button to indicate which shaded disk appeared most convex.

Observers cycled through the following four conditions (see left hand columns of Fig. 4) in an order counterbalanced between subjects.

Condition 1: Upright

Subjects sat upright in a normally lit, regularly configured upright room. In this condition the subject's body, the visual vector, and gravity were all aligned.

Condition 2: Right side down

Subjects lay recumbent on their right side in an upright room with their heads supported by a firm foam pillow. The gravity and visual vectors were orthogonal to the body vector.

Condition 3: Right side down in tilted room

Subjects lay recumbent right side down on a pillow in the tilted room. The visual vector was aligned with the body vector and both vectors were orthogonal to gravity.

Condition 4: Inverted

Subjects were inverted by lying on their stomach on a low table in a normal room. They leaned forwards and looked over the edge of the table with the top of their head pointing towards the ground. They looked backwards under the table where the laptop was placed in line with their direction of gaze. Under this condition the body vector (we are only concerned with the head and eyes) was opposed to both the gravity and the visual vectors that now pointed through the bottom of the head.

Table 1
The percentage of times (with standard errors) that each of the four shaded discs was chosen for each of the four conditions. The discs have been identified by their orientation relative to gravity as in Fig. 4

Direction of light relative to gravity:	0 up	90 right	180 bottom	270 left
a) subject upright	83.4 $\pm$ 4.2	6.0 $\pm$ 0.4	0.9 $\pm$ 1.8	9.7 $\pm$ 2.4
b) subject inverted	2.3 $\pm$ 1.0	14.3 $\pm$ 6.8	72.2 $\pm$ 2.9	11.1 $\pm$ 4.2
c) subject right side down	45.3 $\pm$ 6.5	50.3 $\pm$ 6.5	3.2 $\pm$ 0.3	1.3 $\pm$ 1.0
d) subject right side down in York Tilted Room	23.8 $\pm$ 3.1	68.8 $\pm$ 4.3	4.5 $\pm$ 1.3	3.0 $\pm$ 1.4

3. Results

The mean number of times that subjects chose each of the four shaded disks under each of the four conditions is plotted in Figs 4(a)–(d) and listed in Table 1. For clarity we describe the data relative to gravity.

When all of the up vectors were congruent (upright condition Fig. 4(a)), the disc with the light coming from the up direction defined by all the cues, was consistently seen as most convex (chosen 83.4 $\pm$ 4.2% of trials). By contrast, upside-down observers (Fig. 4(b)) predominantly chose discs with light coming from the top defined by their own (inverted) body i.e. light coming from the floor in real world co-ordinates (chosen 72.2 $\pm$ 2.9% of trials).

In a normally oriented room, right-side-down observers were approximately equally likely to choose discs lit from the top of their bodies (real-world right; chosen 50.3 $\pm$ 6.5% of trials) or from real-world top (chosen 45.3 $\pm$ 6.5% of trials). By contrast, right-side-down observers inside the tilted room showed a clear preference for the disc lit from the top of their heads (which now corresponded also to the visual up: chosen 68.8 $\pm$ 4.3% of the time) rather than the disc lit from the gravity-defined up (chosen in 23.8 $\pm$ 3.1% of trials).

4. Discussion

The variation of subject responses over the four conditions demonstrates the relative importance of the different cues in determining the perceived direction of illumination. For the conditions when vision, body and gravity were aligned and the conditions when the head was inverted, our results replicated those of previous studies confirming the importance of the head orientation [5,13]. When upright, subjects chose the disc with the light coming from above, as defined by all three

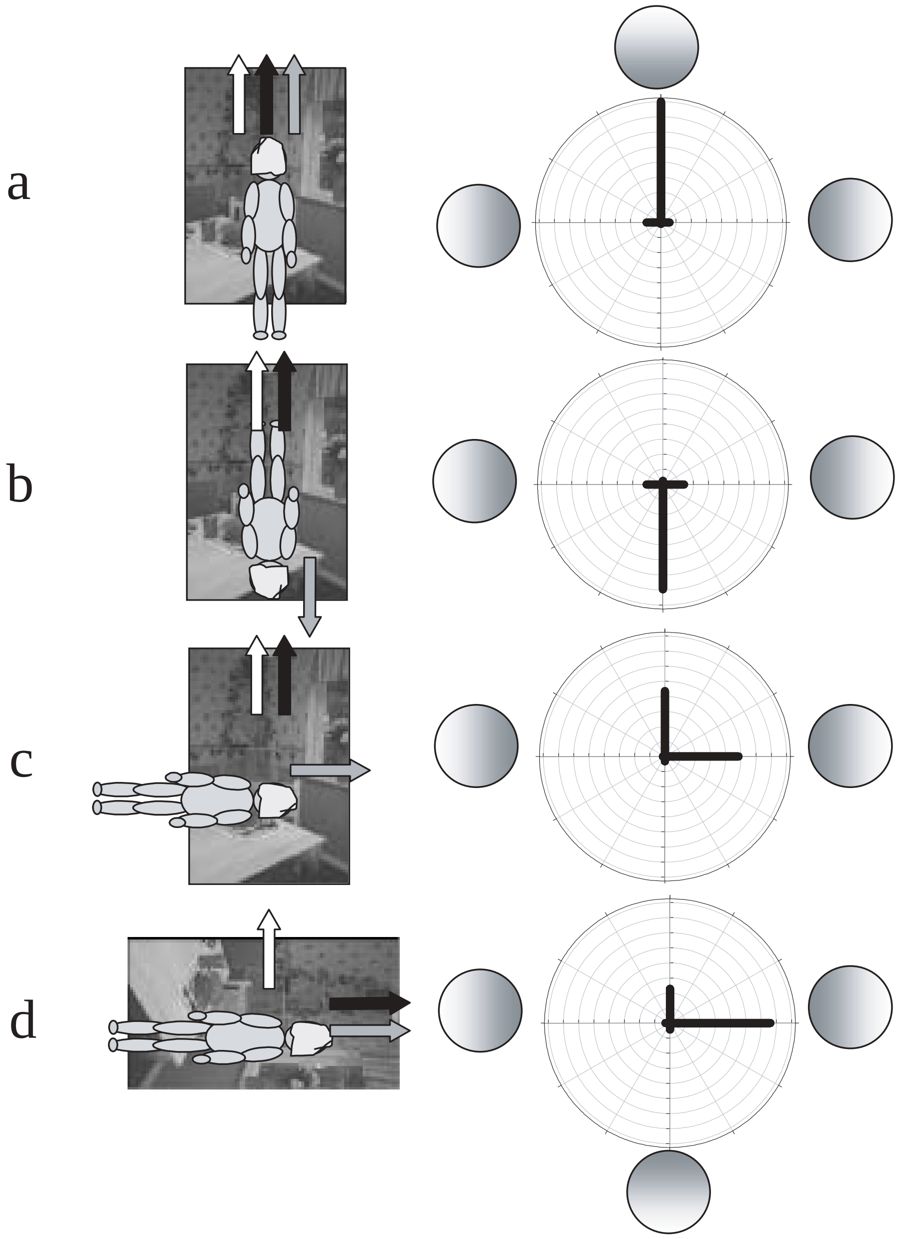

Fig. 4. The experimental conditions (left) and results (right). Subjects made their judgements while upright (a), inverted (b), or right side down (c) in a normal room or while lying right side down inside the York Tilted Room (d). The directions of gravity, body, and vision were separated by these arrangements as indicated by the superimposed arrows (white arrow, gravity; black arrow, visual; grey arrow, body). On the right are the number of times each of the shaded circles (shown as inserts around the graphs) was chosen as appearing the most convex. The plots on the right and experimental configurations on the left are all shown oriented relative to gravity. Thus the upwards pointing arm of the polar histograms correspond to the number of times that the shaded circle with light coming from the gravity-defined up direction (shown at top) was chosen. Standard errors are given in Table 1.

cues, as being the most convex. When upside-down, subjects chose the disc with the light coming from the top relative to their head as being the most convex. Thus even when both gravity and vision are combined in opposition to the body vector, the body vector dominates in determining the perceived direction of illumination. This result may be analogous to a reorientation illusion experienced by astronauts in microgravity [9], confirming that reorientation illusions can be replicated under normal gravity conditions when a suitable probe is used.

The strength and usefulness of this study comes from the two other conditions that were tested. For right-side-down observers in a normal room, body cues were orthogonal to both visual and gravity cues. Under this condition, observers chose discs with the light coming from the body-up direction only slightly more often (50.3 compared to 45.3%) than the disc with the light coming from the direction of up defined by the combined visual and gravity vectors. This suggests that the strength of the body vector is only slightly less than the vision and gravity vectors combined and allows us to make a quantitative estimate of the relative strength of their weighting. When right-side-down inside the tilted room, body and visual cues were in the same direction but orthogonal to gravity. This condition resulted in the disc with the light coming from the visual and body directions being chosen much more often than the disc with light aligned with the gravity (68.8 compared to 23.8%).

Treating these two ratios as a pair of simultaneous equations and setting the weighting of gravity arbitrarily equal to unity, we can model the data as resulting from three vectors with the following relative weights:

$$\text{body} : \text{gravity} : \text{vision} = 2.05 : 1 : 0.85$$

This study used only four probe directions. The model assumes that if the resultant direction fell between two probe directions that the choice would be made probabilistically depending on where between them the resultant fell. Further analyses of individual subject's data and using finer gradations of test will enable us to determine whether the model's predictions hold for individuals or only for populations.

In this description we are implying that the three cues determine the perceived direction of illumination by a weighted geometric sum. Since the perceived direction of illumination results from a combination of body and gravity cues, it also allows us to assess the relative contribution of visual and non-visual cues to the perceived upright. The ratios above indicate that in determining the direction of upright (as opposed to illumination) the non-visual (gravity) and visual cues are weighted

$$\text{gravity} : \text{vision} = 1 : 0.85$$

or that non-visual cues are about 18% more powerful than visual cues in determining the perceived vertical. If this is so then, when inverted, the gravity and vision cues would almost balance, creating a volatile situation that might be tipped one way or another by altering the strength of one or other cue.

4.1. Implications for space craft design and astronaut training

Astronauts in microgravity usually have to rely on only vision and body cues and as such all relative directions ('left', right' 'above' and 'below') become not only subjective, but potentially transient. Encouraging crews to adhere to specified body orientations may help avoid ambiguities associated with instrumentation use and navigation, especially within larger orbiting structures.

However, our results indicate that body orientation cannot establish the direction of up: the visual environment must do this alone in the absence of other gravity cues. The interior design of space vehicles that require free movement and efficient navigation within them, could therefore usefully include polarization cues incorporated within craft structure and instrumentation. Tests of the type described here could be used to assess the effectiveness of these cues before they are tested in space.

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