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The relative role of visual and non-visual cues in determining the perceived direction of "up": Experiments in parabolic flight

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Abstract

In order to measure the perceived direction of "up", subjects judged the three-dimensional shape of disks shaded to be compatible with illumination from particular directions. By finding which shaded disk appeared most convex, we were able to infer the perceived direction of illumination. This provides an indirect measure of the subject's perception of the direction of "up". The different cues contributing to this percept were separated by varying the orientation of the subject and the orientation of the visual background relative to gravity. We also measured the effect of decreasing or increasing gravity by making these shape judgements throughout all the phases of parabolic flight (0*g*, 2*g* and 1*g* during level flight). The perceived up direction was modeled by a simple vector sum of "up" defined by vision, the body and gravity. In this model, the weighting of the visual cue became negligible under microgravity and hypergravity conditions.

Keywords: Perceived orientation; Microgravity; Hypergravity; Idiotropic vector

1. Introduction

Errors in the perception of the "up" direction, the direction opposite to that in which gravity is expected to pull, can be debilitating and may lead to postural as well as perceptual instability [1]. Under microgravity conditions where cues to self-orientation are impoverished, astronauts frequently experience 'reorientation illusions' in which they or their world appear to flip and the up direction becomes arbitrarily redefined [2,3]. This unsettling experience can lead to errors in recognizing objects, navigating within large structures, operating equipment, and reading signs. An understanding of the role of the available perceptual cues in determining the sense of body orientation may suggest strategies for countermeasures to these unwelcome effects.

A major frame of reference used to ascertain self-orientation is the orientation of the body, which has its own intrinsic sense of polarization to which the rest of perception is related. There are no perceptual sensors that provide body orientation directly and it is a

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curious reference frame in that it is constant relative to one's own consciousness. The body has components defined by the eyes, head and trunk that can move relative to one another but here we consider the whole ensemble as defining a single reference direction referred to as the *idiotropic vector* [4].

Cues to the orientation of the external world can be provided by visual and non-visual systems. The direction of gravity is sensed physically by the vestibular system. Proprioception and touch sensors contribute to this process by detecting forces and pressure consequential on the direction of the force of gravity. 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 [5]. Touch receptors detect pressure on the feet when standing and through the back and buttocks when seated. Vision provides intrinsic and extrinsic cues about the direction of gravity [6]. Intrinsic cues include the fact that many objects (e.g. faces) have an obvious "right way up". Other cues may be extrinsic: defined by the relative position of objects (e.g. a book placed on a table, a table on the floor or a scarf hanging from a hook). Environmental cues include the general structure of the visual frame, including the walls, ground plane and ceiling or sky.

Each of these cues provides information about the direction of "up". To arrive at a unified percept of up, the cues must be combined. Normally, the various cues are consistent with each other but under some conditions, such as when lying down or in microgravity, the cues can be widely disparate, incomplete or even missing. Previous work [4,7–9] has suggested that these cues can be weighted and vectorially summed to produce the perceived direction of "up". Are the cue combination rules the same under abnormal gravity conditions? In this study, we consider each cue as providing an estimate of perceived up and compare the weightings of each required under normal gravity, hypergravity and microgravity conditions.

2. Methods

2.1. 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 questions "which way would a ball fall?", "where is the top of an object?", "where is my head?", or "where is the light coming from?" can all evoke different answers. Here we define perceptual up as being opposite to the perceived direction of the pull of gravity. Various methods have been used to measure the direction of perceptual up (see [6] for a review). Such methods usually 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 they think "up" is. We exploited the observation that, in the absence of information about the origin of illumination, people interpret surface structure by relying on shading cues and using an assumption about the direction of illumination [10–12]. By measuring perceived surface shape, we thus obtained an estimate of the perceived direction of illumination which is closely connected to the perceived direction of "up".

Fig. 1 shows the test object we used. The test object consisted of four shaded disks presented in different orientations separated by 90°. Each of the four shaded disks can be interpreted as having a different three-dimensional structure depending on the perceived direction of illumination. When the shading is compatible with the perceived direction of illumination, the disk appears as a convex hemisphere. During rotation of the head or page, different disks appear more convex. The distribution of the decision as to which disk appears most convex reveals the perceived direction of illumination. For example, if two disks are equally likely to be chosen, it indicates that the perceived direction of illumination is midway between the directions indicated by the shading gradients on each of them.

2.2. Separating visual, gravity and body cues

We have previously separated visual, gravity and body cues by arranging the person in various ways either in a normally arranged environment or in a room that has been constructed so that it is pitched backwards by 90° [9,13]. In this tilted room, subjects lie on the physical floor (the back wall of the tilted room) with their feet touching one of the physical walls (the floor of the tilted room) and thus are upright visually

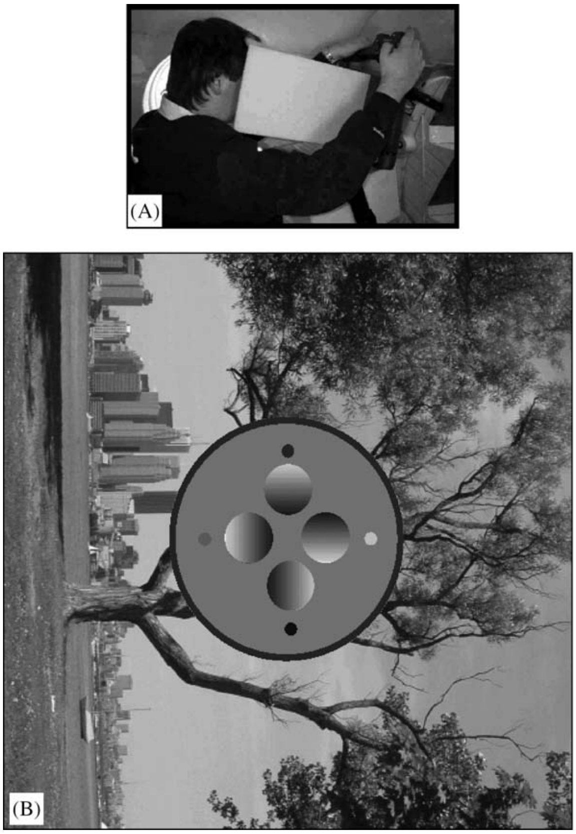

Fig. 1. The test stimulus. Subjects viewed a laptop screen through a shroud, square in cross-section (A). The image they viewed (B) consisted of four shaded disks differing only in their orientation superimposed on an oriented background. If light were interpreted as coming from the top of the page, then the top disk would be chosen. If it were thought to come from the top of the visual scene, then the bottom disk would be selected. If light were perceived to come from an intermediate location, then this would be revealed by the relative likelihood of choosing either of the disks on each side of this direction.

even though they are physically lying on their backs. In the tilted room, gravity and vision thus define different up directions. By placing the subject in different orientations in the tilted room and in the normal environment, the body-, visual- and gravity-based definitions of up can be placed in conflict. In order to accomplish a similar conflict in the constrained environment onboard a parabolic flight, a more manageable way of providing an unusually oriented visual environment was required. To achieve this, subjects viewed a photograph of a natural scene containing clearly polarized features such as the sky, ground plane and some trees. The photograph was presented on a laptop screen viewed at 35 cm through a square shroud (Fig. 1a) made out of foam that allowed an 18×18 cm ($29° \times 29°$) viewing area. The shroud prevented the subject seeing the visual orientation of the aircraft cabin. The test display (Fig. 1b) was superimposed on the photograph. The same photograph was used throughout the study.

The displays were viewed by subjects who were either seated upright in an aircraft seat (gravity direction aligned with the body) or lying on their left side on a foam mattress on the floor of the aircraft (gravity orthogonal to the body axis). In either case, subjects were restrained so that they could not move during aircraft maneuvers. The oriented photograph was displayed either aligned with or orthogonal to the body axis.

2.3. Parabolic flight

Parabolic flights were conducted using the NRC Microgravity Facility in Ottawa, Canada, onboard a modified Falcon 20 aircraft. Four flights were conducted in a single day to collect data for this experiment. During each 30-min flight four alternating 22-s duration periods of microgravity and hypergravity were experienced.

2.4. Procedure

Due to flight constraints, it was only possible to run a limited number of subjects in altered gravity conditions. We were limited to only three conditions with three or four subjects in each condition in flight. The authors served as subjects. All 24 possible spatial arrangements of the four shaded shapes (Fig. 1b) were presented. Each arrangement was shown in a random sequence that commenced as soon as possible after the aircraft had taken off and data collection continued until just prior to landing. Thus data was collected during level flight (normal gravity) and throughout the hyper- and microgravity phases of the flight. Subjects judged which of the four presented shapes was the most convex and indicated their choice using a game pad mounted in a frame that supported the computer with four buttons in the same configuration as the four disks of the display (Fig. 1b). Subjects took around

2 s to make each response and the next trial started the moment a button was pressed. We thus had a continuous record of subjects' performance under various conditions of gravity throughout the flight. Telemetry data from the aircraft synchronized to the displays were used to correlate measurements to the gravity condition under which they were collected.

Each subject ran one of the following conditions for the entire duration of a flight. Four parabolas were flown on each flight providing a total of 88 s of microgravity and 88 s of hypergravity. All subjects ran all conditions before the flight under normal gravity; only the subjects indicated by their initials after each condition ran those conditions in flight. The conditions (see inserts to Figs. 2, 3 and 4) were:

Condition 1: Upright with upright vision (DZ, RTD, MJ). Subjects sat upright with their heads in the shroud (Fig. 1a). They viewed the polarized picture with its top aligned with both gravity and their body axis. In this condition, the subject's body, the visual vector and the gravity vector (when defined) were all aligned.

Condition 2: Upright with visually defined top to right (HJ, LRH, PJ). Subjects sat upright, but the picture that they viewed through the shroud was tilted 90° to the right so that the top of the picture was orthogonal to the body and gravity axes.

Condition 3: Left side down with vision to subject's right, aligned with gravity (DZ, HJ, PJ, RTD). Subjects lay recumbent left side down on a supporting firm foam cushion on the floor of the aircraft. There was a spotter who did not participate in experiments during those flights who ensured that the subjects did not drift off the cushioned area during the microgravity phase of the flight. In this condition, the visual vector was aligned with the gravity vector and both vectors were orthogonal to the body.

Condition 4: Left side down with vision to the top of the subject's head (not run in flight). Subjects lay recumbent as in condition 3 but with the photograph oriented with its top aligned with the subject's head. Vision and body were thus aligned but orthogonal to the gravity vector.

Under microgravity conditions, conditions 2 and 3 should be equivalent. During the hypergravity and normal gravity phases, however, they should be very different, as the data bear out.

2.5. Analysis of results

For each condition, each subject recorded a string of time-stamped button presses indicating the shape they found the most convex for each trial. Only the set of four disks from which they had to choose (Fig. 1b) changed during a given trial. The orientation of the background imagery and body posture were constant for a given subject on a given flight. The responses were linked with inertial data from the onboard flight recorder, and responses were divided into normal gravity (effective gravity between 0.5 and 1.5g), microgravity (less than 0.5g) and hypergravity (more than 1.5g) phases. For each subject, the number of times each of the four disks was chosen as the most convex was represented as the lengths of four vectors whose directions corresponded to the direction of shading of each disk. These four vectors were summed to construct a 2D vector that indicated the perception of the direction from which illumination was perceived to come under that condition. The absolute number of responses for a given subject is immaterial to this analysis.

3. Results

3.1. Normal gravity

The total number of times that subjects chose each of the four shaded disks, under each of four normal gravity conditions is plotted in Fig. 2. All the experiments reported in this paper were performed with the subjects viewing the display through the shroud. For clarity we describe the data throughout this study relative to the true direction of gravity or to the orientation of the aircraft cabin.

When all of the up vectors were congruent (upright condition), the disk with the light coming from the up direction defined by all the cues, was consistently seen as most convex (chosen 79.6 $\pm$ 11% of trials). The other conditions showed influences of the body, gravity and visual vectors resulting in a response vector in between the directions of these stimulus vectors. These control data were very similar to the data pre-

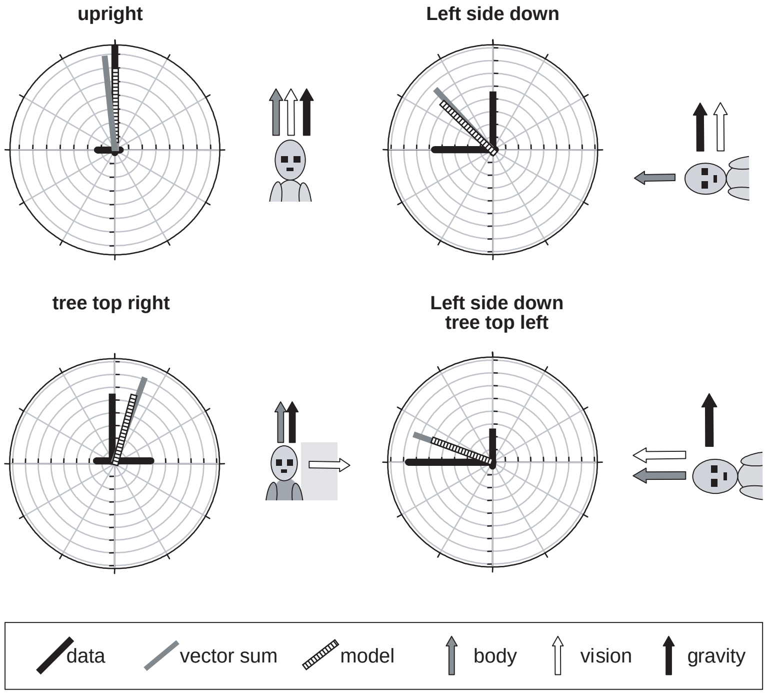

Fig. 2. Data obtained from ground-based controls and during periods of level flight. The black lines represent the number of times the shaded shape was chosen that had its light side oriented in each of the four directions. All data are shown oriented to the direction of gravity (black arrows on the inserts). The gray line is the vector sum of the four black bars (arbitrarily scaled) and the striped bar is the prediction from the weighted vector sum model with gravity = 1, body = 2 and vision = 0.85 (model 1). The four conditions used are shown in the inserts. The three arrows around each cartoon show the direction of gravity (black arrow), the body (gray) and vision (white) in each case.

viously reported using a full-field, visually polarized background [9,13]. There was no difference between the results obtained in periods of normal gravity during level flight with those obtained during control trials on earth.

3.2. Microgravity

The data obtained under microgravity are shown in Fig. 3. The data are very closely aligned with the body axis in all cases. There appears to be no discernable effect of vision. In fact, in the 'upright vision right' condition (center panel) it can be seen that there were almost twice as many more choices OPPOSITE to the visually specified direction than using the visual direction (25% vs. 14.2%)! Under microgravity, conditions 2 and 3 are very similar since the only thing that distinguishes them is the direction of gravity. The similarity of the data for these two conditions, indicates that the seat restraints and other physical cues to orientation within the seat (that might have been taken as gravity cues) did not seem to have a noticeable effect.

3.3. Hypergravity

The data obtained under hypergravity are shown in Fig. 4. Interestingly the data collected under hypergravity also show no discernable effect of vision. Comparing the central panel of Fig. 4 with the bottom left panel of Fig. 2 shows that the significant tilt of the response vector in the direction of the visual vector is not seen when the same condition is experienced under hypergravity. Similarly, comparing the bottom panel of Fig. 4 with the top right panel of Fig. 2, shows that the response vector is more closely aligned to the body vertical under hypergravity than under normal gravity.

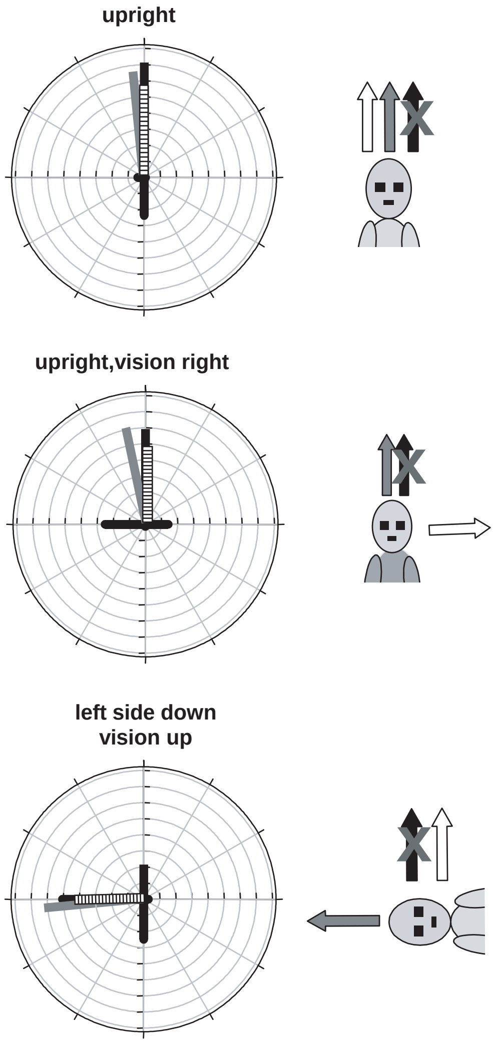

Fig. 3. Data obtained during the microgravity phase of the flight. The black lines represent the number of times the shaded shape was chosen that had its light side oriented in each of the four directions. The data are shown oriented relative to the aircraft cabin. The data in the lower two panels are equivalent, relative to the subject and can be superimposed by rotating through 90°. Conventions as for Fig. 2. Model fits use body only (model 4).

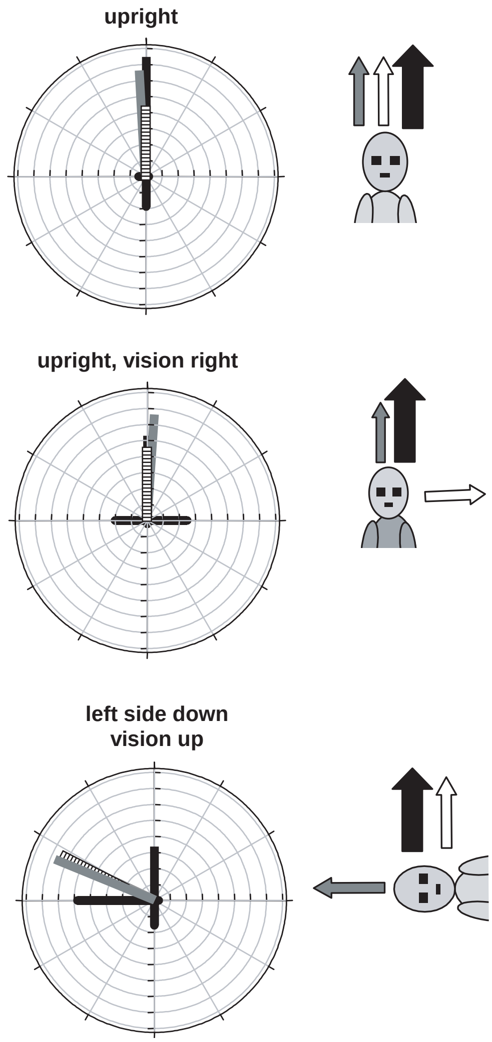

Fig. 4. Data obtained during the hypergravity phase of the flight. The black lines represent the number of times the shaded shape was chosen that had its light side oriented in each of the four directions relative to gravity and the orientation of the aircraft cabin. The gray line is the vector sum of the four black bars (arbitrarily scaled) and the striped bar is the prediction from our weighted vector sum model 5 in which vision is weighted 0 but gravity and the body retain the relative weightings they had in normal gravity.

4. Discussion

We have previously shown [9] that under normal gravity conditions and full-field vision, the direction of "up" can be convincingly modeled by a simple weighted vector sum between body, gravity and visual cues. These seem to be summed with weightings:

vision	gravity	body	
0.85	1.0	2.0	(model 1)

These relative weightings give more significance to the body than has been reported by Mittelstaedt (e.g. [4]). This may reflect the indirect nature of our probe compared to Mittelstaedt's more direct line-adjustment technique. Exploring these apparent differences is the subject of on-going research.

In the present experiment, we tested our model during variations in the force of gravity. By using parabolic flight we obtained measurements of the direction of perceived "up" during periods of microgravity and hypergravity. From our earlier results, our hypothesis was that under microgravity the data could be predicted using the weighting:

vision	gravity	body	
0.85	0	2.0	(model 2)

and under hypergravity

vision	gravity	body	
0.85	2.0	2.0	(model 3)

These hypotheses were generated with the idea that the weighting of the gravity term might be proportional to its strength and reliability [4,14,15].

Surprisingly, neither of these predictions turned out to be the case! Although our control data (Fig. 2) were in close agreement with our previous model (model 1—see model predictions superimposed on the data in Fig. 2), the predictions of models 2 and 3 were not met. Instead the best least-squares models for unusual gravity conditions were:

vision	gravity	body	
0	0	2.0	(model 4)

vision	gravity	body	
0	1.0	2.0	(model 5)

During microgravity the value assigned to the body vector is arbitrary, since it seems to be the sole determinant.

We find that the data can be well modeled by assuming that the visual vector is weighted at zero for both the microgravity and hypergravity phases of the flight. Under microgravity, this thus leaves only the body vector to generate the perceived direction of up, indicated in the data by the observation that subjects predominantly chose the disk with light coming from the direction of the top of the head and ignored the visual cue that had influenced the decisions substantially when making the same decisions under normal gravity. Under hypergravity we found that the significance or weighting of the gravity vector was not increased from the weighting relative to the body determined under normal gravity (i.e. 1:2). Increasing gravity did not seem to increase its significance in indicating the up direction.

There is another possible explanation, however, that must be entertained. That is that the alteration in decisions and the apparent ignoring of the visual cue under unusual gravity conditions were 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 will conduct control experiments under highly distracting circumstances on earth.

This study used only four probe directions and assumed that if the actual direction of perceived up fell between two probe directions then the choice of which disk appeared most convex would be made probabilistically depending on exactly where the resultant fell between them. Further analyses of individual subject's data, using finer gradations of test and using the method of adjustment by asking subjects to adjust the orientation of a disk to its optimal orientation, enabled us to verify that this assumption is valid under normal gravity conditions [9,13].

4.1. Implications for countermeasure design

Our results point to a rather disconcerting conclusion that under unusual gravity conditions, or in fact, possibly under any conditions of intense distraction, subjects tend to resort to using their own body as their primary reference frame and ignore external cues. This conclusion must be tempered by the fact that our visual images, although they were capable of affecting the sense of orientation under normal conditions, were highly impoverished. Furthermore parabolic flight creates only fleeting moments of microgravity with enormous amounts of stress and distraction around the transition time: extrapolating these results to conditions of maintained microgravity must be done with caution. Our visual display consisted of a small, flat photograph viewed at a fixed distance through a shroud that effectively blinkered our subjects. It might be that richer visual cues with stronger features than those that were presented here and which seem to be effective in normal gravity, such as larger field, higher contrast, stronger orientation cues, more depth or more effective parallax cues, are required to provide astronauts with a consistent and reliable cue to their orientation in the microgravity environment of a spacecraft. How these visual cues can be strengthened and enhanced to provide effective countermeasures for astronaut disorientation is the subject of ongoing research.

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