

The Role of Visual Cues in Microgravity Spatial Orientation

Authors

Charles M. Oman, Ian P. Howard, Theodore Smith, Andrew C. Beall, Alan Natapoff, James E. Zacher, Heather L. Jenkin

Experiment Team

Principal Investigator: Charles M. Oman¹

Co-Investigators: Ian P. Howard,² Theodore Smith,¹ Andrew C. Beall¹

Scientific Assistants: Alan Natapoff,¹ James E. Zacher,² Heather L. Jenkin²

¹Massachusetts Institute of Technology, Cambridge, USA

²York University, Toronto, Canada

ABSTRACT

In weightlessness, astronauts must rely on vision to remain spatially oriented. Although gravitational “down” cues are missing, most astronauts maintain a “subjective vertical”—a subjective sense of which way is up. This is evidenced by anecdotal reports of crewmembers feeling upside down (inversion illusions) or feeling that a floor has become a ceiling and vice versa (visual reorientation illusions). Instability in the subjective vertical direction can trigger disorientation and space motion sickness. On Neurolab, a virtual environment display system was used to conduct five interrelated experiments, which quantified: (a) how the direction of each person’s subjective vertical depends on the orientation of the surrounding visual environment, (b) whether rolling the virtual visual environment produces stronger illusions of circular self-motion (circularvection) and more visual reorientation illusions than on Earth, (c) whether a virtual scene moving past the subject produces a stronger linear self-motion illusion (linearvection), and (d) whether deliberate manipulation of the subjective vertical changes a crewmember’s interpretation of shading or the ability to recognize objects.

None of the crew’s subjective vertical indications became more independent of environmental cues in weightlessness. Three who were either strongly dependent on or independent of stationary visual cues in preflight tests remained so in flight. One other became more visually dependent in flight, but recovered postflight. Susceptibility to illusions of circular self-motion increased in flight. The time to the onset of linear self-motion illusions decreased and the illusion magnitude significantly increased for most subjects while free floating in weightlessness. These decreased toward one-G levels when the subject “stood up” in weightlessness by wearing constant force springs. For several subjects, changing the relative direction of the subjective vertical in weightlessness—either by body rotation or by simply cognitively initiating a visual reorientation—altered the illusion of convexity produced when viewing a flat, shaded disc. It changed at least one person’s ability to recognize previously presented two-dimensional shapes. Overall, results show that most astronauts become more dependent on dynamic visual motion cues and some become responsive to stationary orientation cues. The direction of the subjective vertical is labile in the absence of gravity. This can interfere with the ability to properly interpret shading, or to recognize complex objects in different orientations.

INTRODUCTION

When an astronaut ventures into space, the response of the body's gravity-sensing organs is profoundly altered. As soon as orbit is achieved, the spacecraft is literally falling around the Earth. The tiny stones in the inner ear balance organs—the otoliths—float into unusual positions, and tilting the head produces no sustained otolith displacement the way it does on Earth. The unusual signals from the otolith organs in zero-G are apparently not sufficient to produce major changes in the inner ear to eye reflexes that allow the eyes to stay fixed on an object while the body is moving. Also, although astronauts typically don't report sensations of "falling," they are susceptible to illusions about body orientation.

Some describe a paradoxical sensation of feeling continuously upside down ("inversion illusion"), often while seated upright in the cabin immediately after reaching orbit. The fact that fluids normally shift from the legs to the upper body and the viscera elevate upon entering weightlessness may also contribute to this sensation of being upside down. The inversion illusion can also occur with the eyes closed. Fortunately, susceptibility to this illusion usually only lasts a day or so before it subsides. Another much more common type of illusion—the "visual reorientation illusion" (VRI)—can occur when a crewmember is working upside down inside the spacecraft. It can also happen when a person is working upright, if the person sees another person floating upside down. In both situations, the ceiling of the spacecraft suddenly changes its subjective identity and seems somehow like a floor. The perceived port/starboard and forward/aft directions of the spacecraft may also reverse. VRIs usually happen spontaneously, but they can also be initiated or reversed by cognitive effort—i.e., by imagining a change in position. The sudden change in perceived orientation associated with VRIs is known to trigger attacks of space motion sickness during the first week in orbit. It is reportedly more difficult to keep your sense of direction when moving between spacecraft modules with differently oriented visual verticals. Mir station crewmembers say VRI susceptibility and sense-of-direction difficulties persist for months. Since dropped objects in space don't fall, it may seem surprising that astronauts have a sense of the vertical—as revealed by inversion illusions and VRIs—but most apparently do. Inversion illusions were first reported by Cosmonaut Titov in 1961, and VRIs were first described by Skylab and Spacelab crews (Oman, 1986) in the 1970s and 1980s. Some crews refer to both phenomena as "the downs."

What causes VRIs? On Earth, all of us occasionally visually reorient our sense of direction; for example, when we emerge from a subway station, catch sight of a familiar building, and realize we are facing in a different direction than we thought. Familiar objects provide important directional cues, but our sense of direction usually shifts only in a horizontal plane because gravity anchors our sense of which way is down. Laboratory experiments conducted on Earth in specially built tumbling rooms (Howard, 1994) have shown that tilting the room away from the normally upright position shifts the direction a subject will set a "down" pointer. The subjects tend to

point not toward the gravitational down but instead toward the principal visual axes of symmetry of the environment. If the room is furnished with familiar objects that have a clearly recognizable "top" and "bottom," such as a chair or a table, and both the room and the subject are tilted 90 degrees, many people report they still feel upright even though they are gravitationally supine. If the number of polarized objects is reduced and the room is slowly tumbled around the subject, most people initially feel tilted opposite to the direction of room rotation. Eventually, as a wall or a ceiling rotates into a position beneath their feet, that surface suddenly seems like a floor. The subject instantly feels tilted in the opposite direction.

This illusion corresponds to the VRIs described by astronauts. Rotating a strongly polarized room typically produces a sensation of full head-over-heels tumbling, with no VRIs. The hypothesis that emerged from these and other experiments (reviewed by Oman (Oman, 2002)) is that the subjective vertical (SV) direction—and the identity of surrounding surfaces—is determined by the interaction between signals from the body's gravity receptors and visual cues. Gravity direction cues come not only from the otolith organs, but also from receptors in the kidneys and the cardiovascular system. Individual subjects show a small but consistent headward or footward bias (Mittelstaedt, 1992). Visual cues include the principal directions defined by the major surfaces and symmetries of the surrounding environment (such as walls and ceilings), with the up/down axis of the visual environment identified based on two factors: (1) the gravitational polarity of familiar objects, and (2) a tendency to perceive the visual vertical as oriented along the body axis in a footward direction (known as an idiotropic orientation (Mittelstaedt, 1983)). If there are minor directional differences between the gravity receptor and visual cues to the vertical, the brain apparently compromises and the SV points in an intermediate direction. The remaining component of gravity is then perceived as a mysterious force, pulling the body to one side. (This illusion can be readily experienced in houses tilted by an earthquake.) If the disparity in direction of the gravity receptor and visual verticals is large, one sensory modality or the other typically captures the SV. Tilting the head away from the gravitationally erect position enhances the effect of visual cues. There seem to be consistent differences between individuals in the relative weighting assigned to visual vs. gravity receptor cues. Older individuals appear more susceptible to visually induced tilt. Scene motion enhances visually induced tilt for most subjects.

What determines the direction of the SV in weightlessness? The body's gravity receptors are unweighted in space, but the individual subject's headward or footward bias presumably remains. The bias may increase in a headward direction because of the zero-G fluid shift, though this effect may only last a few days. We hypothesized that with eyes open, the SV should align with the body axis if the crewmember has a strong idiotropic tendency. In a more visually dependent individual, the SV should align with one of the principal environmental axes of symmetry, depending on which way the person's feet are pointing (idiotropic effect) and on the orientation of polarized objects in the visual scene. Other crewmember's bodies are strongly gravitationally polarized, since they have a readily recognizable

top and bottom, and are consistently encountered upright in normal life. Hence VRIs should not occur in a visually familiar environment if everyone on board remains upright with respect to the deck. However, if the viewer floats sideways or upside down or another crewmember does so, the viewer may experience a sudden change in the direction of the SV. If unanticipated changes in the relative direction of the SV contribute to space motion sickness, one could speculate that idiotropic crewmembers should be less prone to space motion sickness, since they “carry down around with them.” These people may have more difficulty keeping track of objects and surfaces as they move about. If this is really so, it has potential implications for astronaut selection, training, spacecraft architecture, and space sickness prevention. Do crewmembers show consistent inter-individual differences in idiotropic vs. visual dependency? How can this be assessed? Harm et al. (Harm, 1999) retrospectively classified crewmembers based on postflight debriefings concerning illusions experienced in flight. Young and coworkers (Young, 1986; Young, 1996) had crewmembers insert their heads into a polka-dotted drum that rolled about the visual axis and report the amount of illusory angular self-motion (circularvection) they experienced. On Earth, upright subjects reported a paradoxical rolling/tilting sensation. In orbit, most astronauts felt continuous rotation. Wearing a bungee cord harness that pulled the subject to the deck inhibited the strength of circularvection in some subjects. Young concluded that astronauts become more visually dependent in weightlessness since they generally experience stronger sensations of angular speed in response to visual scene rotation. However, display limitations did not permit assessment of responses to linearvection stimuli, or to rotating and statically tilted, gravitationally polarized scenes. Scientific study of these illusions and sensations requires experiments on human subjects using controlled visual stimuli, which has been impractical on previous Shuttle flights. The virtual environment generator (VEG) display flown on Neurolab provided the first opportunity to study VRIs and related phenomena.

On Earth, the process of object recognition and shading interpretation depends on the gravitational orientation of the objects. For example, Rock (Rock, 1957) found that people more easily recognize nonsensical doodles if the doodles are shown in the same gravitational orientation as when previously seen. Howard and colleagues (Howard, 1990) showed that the illusory concavity or convexity people normally perceive when interpreting shading on a truly flat surface depends on a “light comes from above” assumption, where “above” depends on the relative orientation of the dark-to-light shading gradient to head orientation and to gravity. We predicted that if a subject experienced a VRI in weightlessness, it would not only change the subjective identity of surrounding surfaces but should also influence the recognition of complex figures, and the perceived convexity of gradient-shaded circles. Since many crewmembers say that they can cognitively initiate a VRI in weightlessness (i.e., “whichever way I decide is down becomes down”), on Neurolab we tested the hypothesis that figure and shading gradient recognition could even be changed just by cognitively altering the SV, without any physical movement or change in the visual scene content.

METHODS

Five related experiments were performed by four male Neurolab crewmembers, coded alphabetically A–D, who were aged 37–43 years old and had no visual or vestibular abnormalities. One of the subjects had participated in a 16-day flight two years earlier; the other three were making their first orbital flight. General experimental design and methods are described here. Specific procedures and stimuli for each experiment are detailed in the next section.

During all experiments, the subject wore a color stereo head-mounted display (Kaiser ProView-80; 640×480 resolution and 65 degrees×48 degrees field-of-view in each eye, 100% binocular overlap) equipped with a visor that completely excluded exterior views. Subjects viewed computer-generated visual scenes rendered by the NASA VEG, a custom Pentium/Windows NT real-time graphics workstation, described elsewhere in this book (see technical report by Oman et al. in this publication). A head tracker was not used to stabilize the visual environment, so subjects remained motionless during all trials. Experiment instructions were presented on virtual cue cards. Subjects initiated the trials and made subjective reports using a joystick strapped to their thigh. To eliminate directional sound cues, an area microphone mounted on the VEG front panel fed back ambient sounds monophonically to the subject’s binaural headphones.

Subjects practiced with the apparatus and performed portions of the experiments in mission simulations several times during the six months prior to flight. They completed each experiment as a subject three times preflight (approximately 90, 60, and 30 days before launch); once on the third or fourth day of orbital flight; again on landing day or the first day after landing, the second day after landing, and on the fourth and fifth days after landing. (The 90-day preflight session served as a training session for one subject, whose data were discarded. Limited testing was also performed on some subjects on the 16th flight day and on the day of return, as noted.) For purposes of statistical analysis, results from different sessions were usually pooled into epochs: preflight (“PRE”), inflight (“IN”), postflight days 0–2 (“EARLY”), and postflight days 4 and 5 (“LATE”). In each test session, the subject was tested under multiple conditions. During ground testing, the subject either was seated erect in a padded chair or lay supine or left shoulder down in a padded gurney bed. Inflight, the subject was tested free floating upright in the virtual visual environment, and also (depending on the experiment) either floating left shoulder down relative to the visual environment or while “standing” in a restraint harness. The harness was connected to a pair of deck-mounted constant force springs, which provided a “downward” position sense cue to the shoulders and hips. Conditions were necessarily nested by epoch. For operational reasons, the upright floating condition was always tested first. Results were analyzed statistically (Systat v.10) by subject, epoch, condition, and scene type or speed.

RESULTS

Tilted Room Experiment

The four subjects viewed the interior of a virtual spacecraft module, 7.1 m long, 2.1 m high, and 2.1 m wide. In successive trials, the scene was presented in different tilt orientations with respect to their head/body axis by an angle that varied over ± 180 degrees in four-degree increments, in randomized order. The presentation alternated between a scene (Figure 1A) that had identical left and right walls, and a ceiling and floor with similar (though not identical) details, and a second more visually polarized scene with readily distinguishable ceiling, wall, and deck surfaces, and an astronaut figure floating upright (Figure 1B) 2.5 m away from the viewpoint. Scene lighting was completely even, to eliminate directional effects. Subjects were instructed to look quickly around the scene at the beginning of each trial, and decide which surface seemed most like a “floor,” and which way objects would fall if gravity were present. Subjects then clicked a joystick button to make two green balls appear (as shown in Figure 1B, for example). The subjects indicated the SV by moving the outer ball into a position where the center ball would hit the subjective floor if it fell. If no falling direction was discernable, they were to point the outer ball at the subjective floor. In each of the pre- and postflight sessions, subjects performed 96 trials in both the upright and the supine conditions. In flight, subjects performed the same series of 96 trials in the floating condition. In the inflight restrained condition using the spring-loaded harness, 39 trials using the more polarized scene (Figure 1B) were performed.

To assess whether subjects had consistent differences in static (i.e., motionless scene) visual dependence, SV indications from individual subjects were plotted vs. the absolute value of scene presentation angle (Figure 2). Indications generally clustered along the diagonal (i.e., SV aligned with the head-to-foot axis) and/or pointed toward one of the four surfaces in the scene. Subjects sometimes gave responses in an intermediate direction, particularly in preflight testing, and for scene angles near 0, 90, or 180 degrees. For a particular range of scene angle, a subject’s

indications could fall in several different clusters. We think this is because when the subject glanced at the scene, several competing interpretations of the sensory cue set were possible, and which one that the subject chose in any given trial was probabilistic in nature. Indications within ± 5 degrees of the scene floor (angle=0), walls (angle=90), or ceiling (angle=180) surfaces were classified as visually captured responses. Those within ± 5 degrees of body axis (indication=angle) were classified as body dominated, presumably due to the effects of idiotropic and gravity receptor bias. In upright one-G testing, this occurs because of the gravitational down cue. Indications that were intermediate or ambiguous, in that they met both visual and body criteria, were classified as “other.” A static visual dependence (VD) coefficient was defined as the number of visual responses, minus the number of body axis dominated responses, divided by the total number of all responses. $VD=1$ indicated strong visually dependent response, while $VD=-1$ indicated a strong visual independence. Figures 3A–D show the mean VD coefficient for each of the four subjects, by epoch, for all trials.

Subjects B and C were strongly visually independent and remained so throughout the trials. They were not reliably affected by scene or posture manipulations. Subject A was moderately visually independent preflight but did show preflight sensitivity to postural and scene manipulations. This subject’s responses shifted dramatically toward strong visual dependence when floating in zero-G. When the constant force spring restraint harness was worn, responses became visually independent. After return to Earth, responses eventually returned to near-preflight levels. However, we noted some postflight carryover of visual dependence during tests on the first two postflight days, suggesting that the earlier inflight visual dependence was not the instantaneous result of the absence of gravity receptor and fluid shift effects. Subject D was moderately visually dependent preflight, and gradually became more so. None of the four subjects indicated or reported inversion illusions during our FD3 testing, though Subject A did experience an inversion illusion on FD1, and also on FD2 while performing another experiment in darkness.



Figure 1A. Tilted room experiment, weakly polarized scene.



Figure 1B. Tilted room experiment, strongly polarized scene.

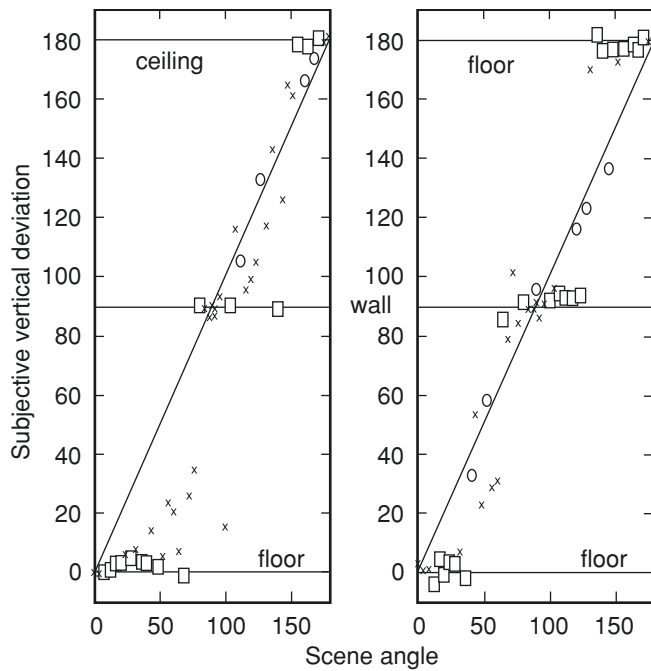


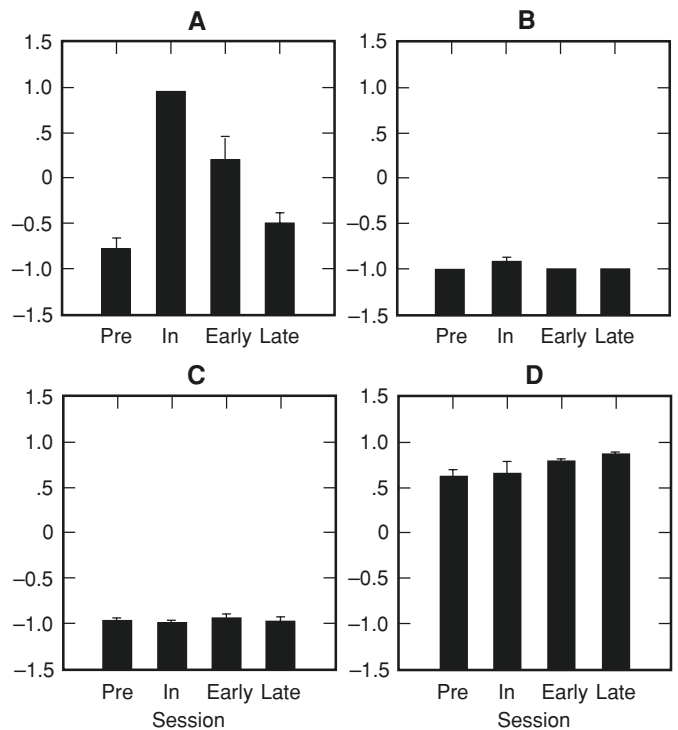
Figure 2. Scene tilt angle vs. absolute value of subjective vertical deviation from body axis: squares: visual responses; circles: body axis responses; crosses: other.

Overall, our tests confirmed that crewmembers show consistent differences in dependence on static visual cues to the subjective vertical. Clearly the effects of spaceflight on visual dependence varied among crewmembers. At least one of our subjects showed the hypothesized increase in dependence to static visual cues with some postflight carryover, and none of the four subjects exhibited increased visual independence inflight.

Tumbling Room Experiment

The four subjects viewed scenes, which rolled about their visual axis at 18 degrees/second. Scene rotation direction was alternated in successive trials. Three scene types were used: two spacecraft interior scenes (Figures 1A and 1B) and a polka-dotted cylinder interior (Figure 4). The latter was comparable to that used in earlier zero-G vection studies by Young et al. (Young, 1986; Young, 1996), and was expected to produce circular vection but not VRIs. The three scenes were presented in a fixed order that was repeated for a total of 12 trials. Subjects were instructed to indicate the onset of visual reorientation illusions by pushing the joystick trigger at the onset of each VRI; i.e., each time a scene surface changed subjective identity. Trial durations were 80 seconds for the polarized rooms, and 20 seconds for the dotted cylinder. At the end of each trial, subjects used a virtual indicator to report the magnitude of illusory rolling circular vection relative to perceived stimulus motion using a five-level ordinal scale (1 = no self-motion/full scene motion to 5 = full self-motion and no scene motion). Data from all three scenes were analyzed for the relative magnitude of circular vection experienced.

Data trials using the two spacecraft scenes were analyzed for the frequency of VRIs and the phase of their onset.



Figures 3A-3D. Static visual dependence (VD) coefficient vs. epoch for Subjects A–D. $VD=1$ indicates strong visual dependence, $VD=-1$ indicates strong visual independence. Error bars show ± 1 standard error.

Average roll circular vection magnitude of the four subjects is shown in Figures 5A–5D. Preflight roll vection was only moderate for three of the subjects, perhaps due to the relatively small visual angle subtended by the display. Subject D (who was the most visually dependent subject in the tilting room tests) had the strongest circular vection in preflight tests. Roll vection increased dramatically when free floating inflight as compared to preflight values for most of the crew. The apparent lack of effect for Subject D was probably because his preflight reports

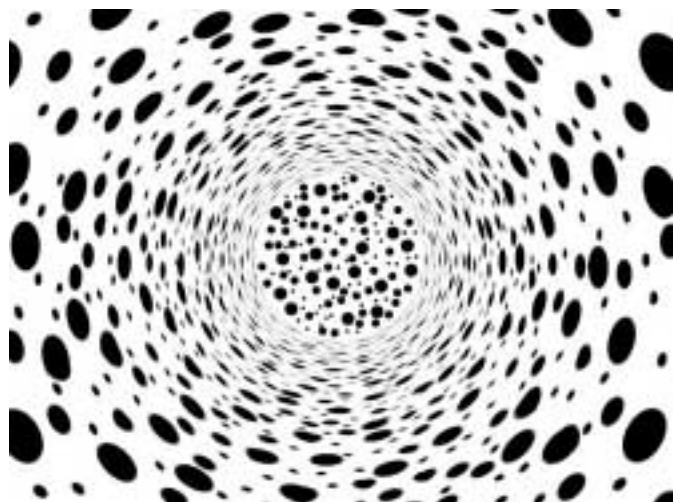
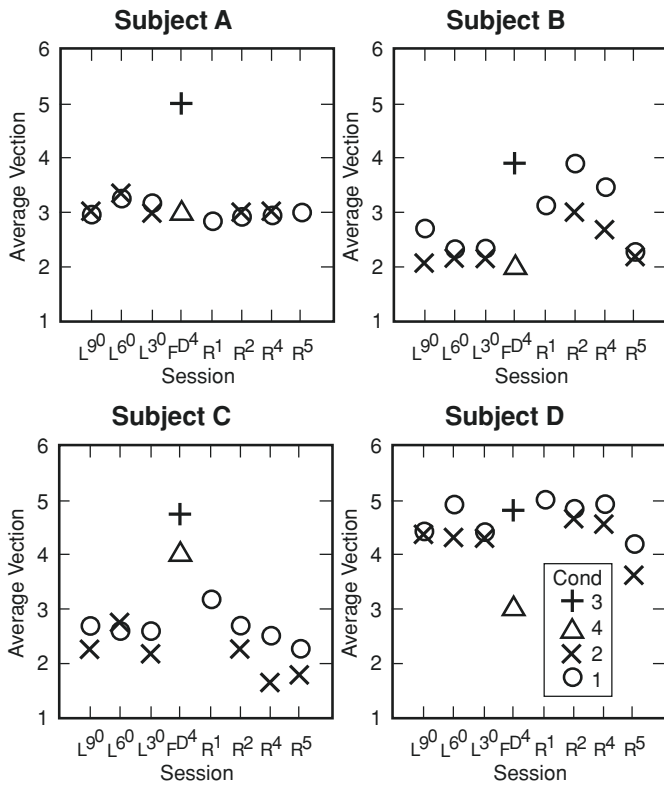


Figure 4. Tumbling room experiment. Dotted cylinder scene.



Figures 5A-5D. Tumbling room experiment average circular vection magnitude.

were also at a high level. Postflight vection returned preflight levels. Analysis of variance (ANOVA) demonstrated that vection reports were significantly ($p < 0.025$) higher with the dotted cylinder stimulus ($F(1,3)=30.8$) than with the room scenes. Wearing the spring-loaded restraint significantly ($p < 0.025$) decreased inflight vection ($F(1,3)=18.3$) as compared to the floating condition. Changing from the upright to the supine posture in one-G testing did not produce a reliable effect. Overall, results indicate an increased reliance on visual cues and a strong effect of position sense cues in flight in three of the four subjects.

Subject A almost always experienced complete tumbling under all conditions both in one-G and zero-G, so his data could not be analyzed for VRI effects. Changes in the clustering of VRI phase angles from Subjects B, C, and D were examined using a two-step procedure. Data from each trial were first screened for significant 90-degree and 180-degree tendencies by multiplying the phase angle data by two and four, and testing the resulting circular distributions for significant ($p < 0.05$) nonuniformity using a Rayleigh test. Changes in the percentage of 90-degree clustered data vs. 180-degree clustered data were then examined using a Kruskal-Wallis test. Significant 90- and 180-degree tendencies were consistently found. The effect of spaceflight (epoch) on VRI modal angle approached significance ($U=14$; $p < 0.058$). Individual differences may have masked effects. Ninety-degree tendency was greater inflight and early postflight, particularly for B and D. Tilted room VD for the individual subjects did not predict which tumbling room subjects would experience full tumbling or VRIs using identical scenes, which emphasizes the importance of scene motion cues in VRIs.

We were unable to demonstrate reliable effects of epoch, condition (upright/supine or floating/restrained), or scene type on VRI frequency for the remaining subjects (B, C, and D) as a group using Kruskal-Wallis, nonparametric rank ANOVA tests. However, effects may have been masked by the small group's heterogeneous response. Looking at the subjects individually, Subject C frequently reported VRIs in one-G but had very few in zero-G. Subjects B and D reported VRIs, but we could find no clear effects of epoch on VRI frequency.

Looming Linear Vection Experiment

Looming linear vection is the illusion of self-motion induced when the surrounding visual scene translates towards the viewer. The goal of this experiment was to determine whether subjects become more susceptible to looming linear vection in orbit. Each subject viewed a virtual corridor (Figure 6) that was 1.5 m wide and 3.0 m high from an eye height of 1.5 m. Background scene motion is more effective for eliciting motion illusions, so a black frame that did not move relative to the subject was provided in the foreground. In each trial, the corridor moved towards the subject at a constant speed for 10 seconds. Five different scene speeds (0.4, 0.6, 0.8, 1.1, and 1.6 m/second) were tested in randomized order, 12 repetitions each for 60 trials. At the start of each trial when the visual scene began to move, visual motion cues momentarily conflicted with gravity receptor cues, which indicated no physical acceleration. This cue conflict is believed to delay vection onset. We hypothesized that if subjects learned to respond more to visual than to gravity receptor cues in adapting to weightlessness, the latency of vection onset should be reduced. During the remainder of the constant velocity scene motion, no further cue conflict would be expected. Subjects may also become accustomed to constant velocity motion without physical effort in zero-G. If increased weight was given to visual cues in weightlessness, the vection sensation should seem more compelling and therefore be reported as a greater percentage of scene speed, thereby showing fewer spontaneous interruptions of vection (referred to as "dropouts"). We expected that using the constant force spring to provide a strong body axis force cue that firmly anchors the subject to the deck would inhibit vection, because such cues are entirely absent in weightlessness. Subjects were tested in both the upright and supine positions during pre- and postflight sessions, since cues from position sense and the relative orientation of gravity differed in the two positions.

Subjects were instructed to deflect the joystick in proportion to their perceived speed of self-motion. Immediately before starting the trials in each session, subjects practiced deflecting the joystick to specific numeric values, initially with feedback and then without feedback. Analysis revealed no evidence of consistent nonlinearities in joystick setting performance. Subjects were tested pre- and postflight in both upright and supine conditions. Inflight, subjects were tested on the fourth day of flight in both floating and spring-restrained conditions. Subject B got relatively little vection in preflight testing or when tested on FD4, but when retested on FD16 the subject reported strong vection. Subject D reported scene motion rather than self-motion in most preflight trials, so his data for this test were set aside.



Figure 6. Looming linear vection scene. Background scene moved toward subject. Black frame in foreground was stationary relative to the subject.

Typically (in coarse approximation), each subject would begin to deflect the joystick after a latency of about one second. The deflection would then increase to a maximum level that was often maintained for the rest of the trial, but was sometimes punctuated by vection dropouts. Dependent measures analyzed included latency to onset of joystick deflection (seconds), peak joystick deflection (percent), and the time integral of joystick deflection during the trial (seconds).

As we had hypothesized, inflight free-floating vection latency was shorter than in preflight testing on the ground. Latencies at the lowest speeds tended to be the most variable. Pairwise comparisons were significant (Mann Whitney test, $p < 0.05$) at all speeds for Subject A, at the two highest speeds for Subject B, and at the highest speed for Subject C's preflight upright data. Latency to vection onset decreased monotonically with scene speed (across all subjects, and for all epochs and conditions; Page test, $p < 0.05$). In our preflight tests, latencies did not differ consistently between the upright and the supine positions. Previous one-G studies on linear vection have collectively not shown consistent effect of upright vs. supine posture (Kano, 1991; Tovee, 1999).

Integrated joystick deflection and maximum joystick deflection both increased monotonically with scene speed under all conditions, but not in a linear way. Both responses were consistently reduced at the higher scene speeds. Though this could be a perceptual phenomenon, it could also be due to a speed-dependent change in joystick deflection strategy. Subjects told us that when indicating self-motion during a trial, they often tended to deflect the joystick in proportion to their vection as a percentage of the stimulus speed rather than using a consistent modulus across all speeds. We normalized peak joystick deflection values (Y) across scene speeds by dividing the values by the function $(1 - \exp(-v/V))$, where v was scene speed, and V was a constant parameter for each subject. V was taken as the median of all values of $-v/[\log(1-Y)]$ calculated for each preflight trial. V ranged from 1.9 m/second to 3.4 m/second. Since

all scene speeds were less than V and all trials were 10 seconds in duration, integrated joystick deflection divided by $10 \cdot (1 - \exp(-v/V))$ is a measure of average linear vection speed during each trial, normalized to that subject's preflight, low scene speed response. We refer to this metric as "normalized velocity."

Normalized velocity for Subjects A, B, and C is shown in Figure 7. As we had anticipated, inflight floating normalized velocity was generally greater in flight free floating than in preflight erect or supine. Pairwise comparisons of normalized velocity (or the integrated area measure) were significant (Mann Whitney test, $p < 0.05$) at all but the highest speed for Subject A, at the highest speed for Subject B, and at all speeds for Subject C. Inflight floating was significantly greater than inflight restrained at four out of five speeds for Subject A, and all speeds for Subject C. Both sets of results confirmed our hypotheses. The positive $p < 0.05$ finding in even two out of three (independent) subjects is significant at the $p < 0.00725$ level for a family of three subjects. Pairwise comparisons of preflight vs. early postflight showed significant effects at the highest speed for Subjects A and B, and the lowest speed for Subject C. Preflight erect vs. preflight supine, and preflight vs. late postflight showed no reliable effects. Subjects B and C tended to show larger responses at lower speeds in flight and postflight.

The quantitative analysis results are consistent with the subject's inflight and postflight oral debriefing reports.

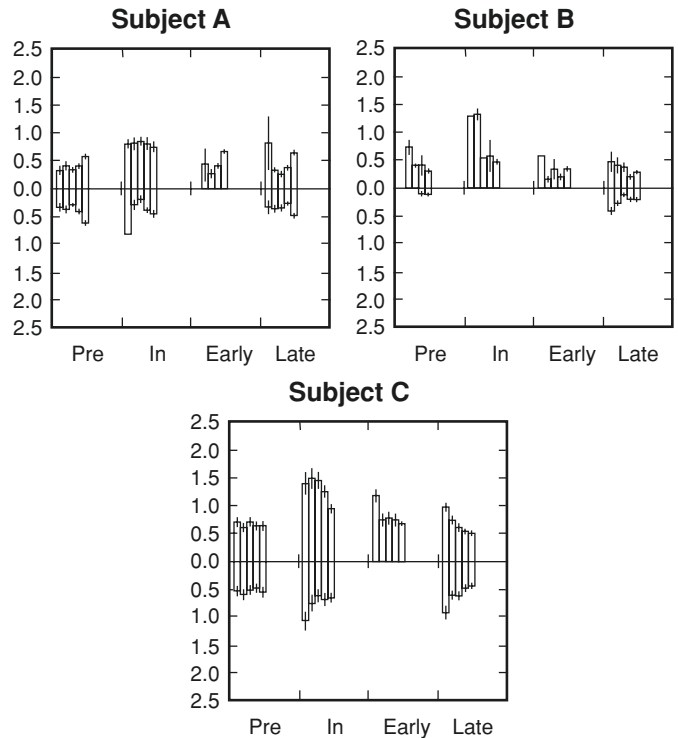


Figure 7. Normalized velocity response for Subjects A, B, and C. Data bars show mean values, error bars represent standard error of the mean. Data grouped by scene velocity for each of the four epochs (preflight, inflight, early postflight, late postflight). Erect and floating data are plotted upwards; supine and restrained data are plotted downwards. Subject A and B data from FD4 session, Subject C data from FD16.

On FD4, Subject A said: “ In the floating scenario, I got vection virtually instantaneously ... In the restrained position ... I felt that it was pretty similar to doing it on Earth. In fact my ability to get vection was probably less than it was in the one-G environment. It’s kind of like standing with your legs in a cement boot and you get the feeling that you’re supposed to be moving but you’re not really feeling any vection....” In a landing day debriefing, he added: “To me there was a striking difference doing the (floating) vection experiment in orbit as compared to the one-G controls prior to flight. Inflight, on FD4, I got vection virtually instantaneously at all speeds. It was strikingly impressive. It was a very cool sensation—felt like a ghost flying down a corridor—like in *Ghostbusters*—you even vect with low velocities.... Back here on Earth the tactile cues feel like being ... in a two-G pullup with a heavy weight on my head. This is a very strong cue saying you are in a stationary mode. Today (back on Earth) I didn’t get much in the way of compelling vection unless things are flying by. I felt 40% vection saturation today, 60–80% preflight, and 100% saturated vection in flight.”

On FD16, Subject B reported “linear vection much stronger than on the ground.... When floating I felt as if I would move forward into the rack.” On the day of return, he added: “Normally I don’t vectate much, but I had considerably more vection by the end of the flight.”

In a landing day debriefing, Subject C added: “Vection sitting upright today very different than inflight—it is like the preflight trials—not nearly as pure vection as inflight. The slow-speed vection was really dramatic inflight. It was fully saturated vection inflight. The slow-speed vection stimulus was basically the speed you move in the Spacelab—very much in place with what we were doing at the time. The tactile cue and the weight of hand may be inhibiting my vection today. The fast speeds today, I notice that I have an initial lurch forward and then settle down into a speed. Today I felt the slow speeds are in the 80–100% range and for the faster speeds in the 20–40% range.... Some of the slow ones were a little stronger than preflight. Slow speeds today felt more saturated.”

Shape-from-Shading Experiment

The goal of this experiment was to see whether the illusion of three-dimensional shape produced by two-dimensional shading depends on the direction of the perceived vertical, even in the absence of gravity. For hundreds of years, artists have used shading to create an illusion of concavity or convexity on a flat surface. The illusion presumably occurs because a real protuberance illuminated from one side produces the same retinal image as an indentation that is illuminated from the other side. Light normally comes from above, making the upper part of truly convex surfaces and the lower part of concave surfaces bright. If you position a truly flat gradient-shaded disc (Figure 8A) so that it is relative to your head, the light part of the disc is “above” the dark part and the disc seems convex. Rotating the disc 180 degrees makes the disc appear concave. The dominant factor in the shape illusion is clearly the orientation of the shading gradient with respect to your head. If the light and dark portions of the disk are oriented to your left and right, the disc appears flat (Figure 8B).

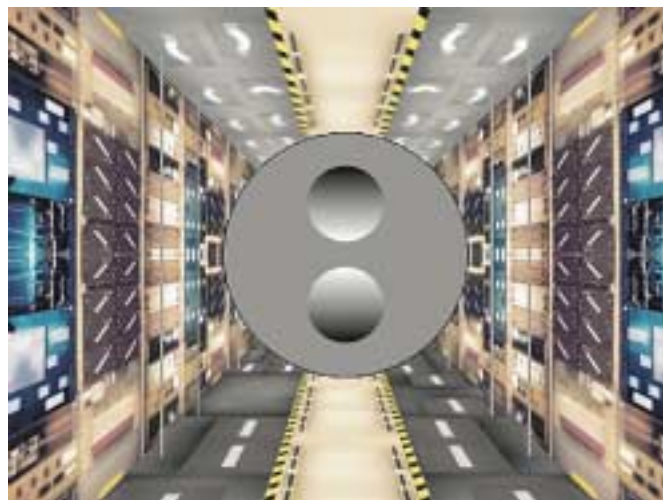


Figure 8A. Shape-from-shading experiment. Upright scene orientation. Shading gradient aligned with viewer body axis. Upper disc appears concave, and lower disc appears convex. Turn the page upside down. Does the illusion reverse?

However in this “neutral” orientation of the disc relative to the head, gravity has been shown to play a role. If the head and disc are then both tilted together, so that the light part becomes gravitationally above, the disc will again appear convex. Does this effect remain in weightlessness when the head is tilted, or if the subject does not physically move but simply cognitively initiates a VRI?

The experiment was conducted using the same spacecraft module scene as in the tilted room experiment (Figure 1A). Stimuli were pairs of gradient-shaded discs shown in various orientations, rendered on a 1.5-m-diameter gray circular easel located in the middle of the module, 3.0 m away from the subject (Figures 8A, 8B). The gradient-shaded discs, each subtending 20 degrees of visual angle, appeared alternately to the left and right or above and below each other. A forced-choice procedure was used: the subject decided which disc of the pair appeared more convex and moved an indicator square over the corresponding disc using the joystick. Each trial required about three seconds.

The experiment was conducted under three successive conditions: “upright,” “left-side-down,” and “VRI.” The first condition served as the control for manipulations of the SV in the latter two conditions. In the upright condition, the subject’s body axis was parallel to the walls of the virtual environment. In one-G tests, the subject sat upright in the laboratory. In zero-G tests, the subject floated upright in the Neurolab module. In the left-side-down condition, the virtual environment was rotated 90 degrees clockwise, so that the subject’s body axis was parallel to the floor and ceiling of the virtual environment (Figure 8B). In one-G tests, the subject lay left shoulder down on a gurney bed. In zero-G tests, the subject floated parallel to the deck of the Neurolab module. In the VRI condition, the visual background environment was again upright with respect to the subject (Figure 8C), but the subject was instructed to cognitively initiate a VRI so that the wall to his left seemed like a floor and he felt

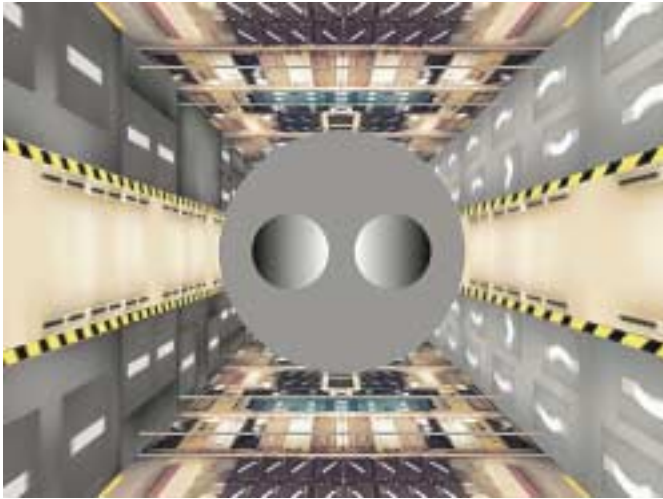


Figure 8B. Shape-from-shading experiment. Left-side-down background scene orientation. Shading gradient in neutral orientation as in Figure 8B. The convexity illusion is usually absent until you rotate your head and the page together, left shoulder down. Does the illusion of convexity reappear?

in a left-side-down condition. In one-G tests, the subject lay supine on a gurney bed; and in zero-G, the subject floated upright in the Neurolab module. At the beginning, middle, and end of the trials in each condition, the subject confirmed the direction of the subjective vertical using a green ball pointer, as in the tilted room experiment.

Forty-eight trials were conducted under each condition. Different sequences were used; but in each condition, 12 disc pairs had their shading gradients in the neutral direction perpendicular to the body axis. Our hypothesis was simply that if the subject changed the direction of his SV by changing from the upright to either the left-side-down or VRI condition, the percentage of convex discs oriented with the light side on the right should increase markedly, since in the latter two conditions up was to the subject's right. Twelve other disc pairs had shading parallel to the body axis. Responses to these allowed us to verify that the illusion was present in the upright condition, even in zero-G. Sixteen other pairs had one disc aligned with the body and one perpendicular to the body. These served as distracters and allowed us also to examine responses to conflicting stimuli.

With the shading axes perpendicular to the body, the percentage of light left responses for the group of four subjects increased in both the left-side-down and VRI (imaginary left side down while supine) both preflight, inflight, and postflight confirming that the cognitive reference frame, rather than gravity, contributes to the illusion of convexity when the shading gradient is perpendicular to the body (head) axis. Looking at subject responses individually, Subject B showed a strong light right bias over light left in the upright position, which biased group statistics. When the SV was manipulated to the left-side-down condition, light right responses increased relative to upright for Subjects A, B, and C preflight and inflight as hypothesized. In the VRI condition, light right responses increased for Subject A for all epochs, and for Subjects B and

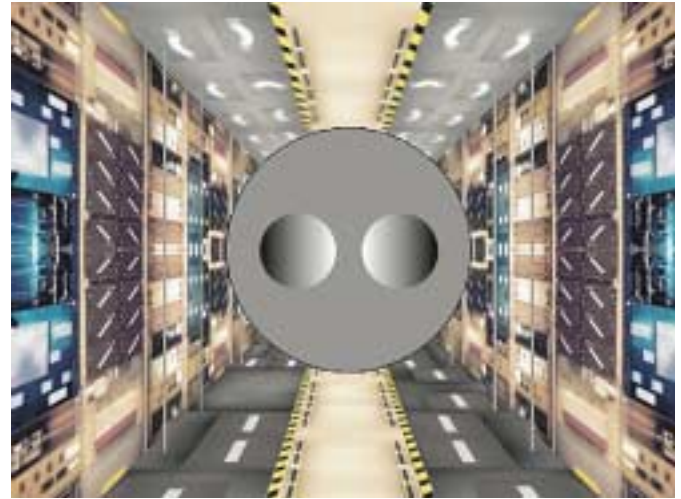


Figure 8C. Shape-from-shading experiment. Upright scene orientation. Shading gradient in neutral orientation, perpendicular to subject. In the VRI condition, when the subject simply decided the left wall was down, the illusion of convexity often reappeared—without any actual head tilt.

C preflight but not inflight. One possible explanation is that subjects sometimes were not always able to initiate the required VRI. Green ball subjective vertical indications in flight were not always in the expected direction inflight. Subject D reported he imagined the floor to his right rather than to his left. His light right responses to neutral stimuli consistently decreased for both manipulations, as one might expect. Subject A commented that VRIs were harder to initiate early postflight than preflight, because the direction of true gravitational down felt unusually strong; but Subject C found the reverse.

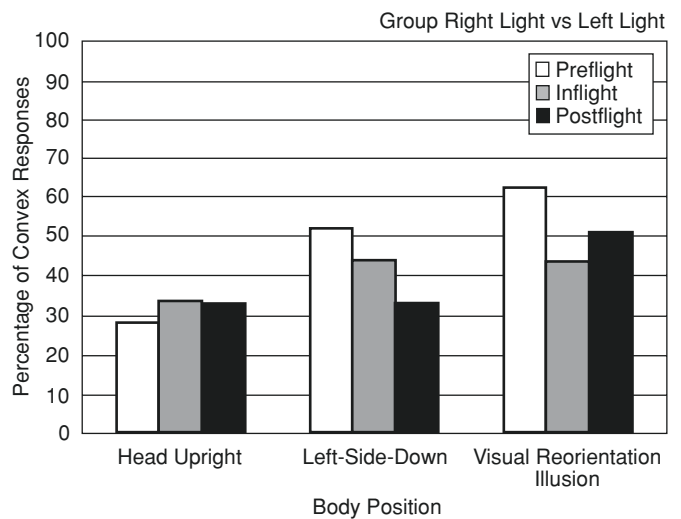


Figure 9. Shape-from-shading results. Percent of light right stimuli perceived as convex when paired with light left for Subjects A-D. In preflight testing (white bars), group responses showed an increase in light right responses, compared to light left, for both left-side-down and VRI conditions, as anticipated.

With the disc-shading axes parallel to the body, all four subjects reliably (95–100%) chose the light-on-top shading pattern in the upright condition regardless of gravity level, demonstrating that the shape-from-shading illusion persists even in zero-G. They also reliably chose the neutral (light-left) stimulus over convex (light-bottom) in all conditions.

Complex Figure Recognition Experiment

The goal of this experiment was to show that a subject’s ability to recognize a previously memorized complex figure in weightlessness depends on the orientation of the test figure to the perceived vertical, even in the absence of gravity. The experimental paradigm was analogous to the shape-from-shading

experiment previously described in that subjects learned sets of figures in an “upright” condition, and were then asked to recognize the sets after the direction of the SV was manipulated to left-shoulder-down and VRI conditions. As in the previous experiment, the subject indicated the direction of the subjective vertical using green ball pointers at the beginning, in the middle, and at the end of the trial sets under each condition.

Figures used in the experiment were black line drawings, subtending approximately 20 degrees of visual angle. Examples are shown in Figures 10A–D. Figures were drawn with either straight or curved lines that were either open or closed. The number of sides, branches, or loops varied. Different figure sets were used for each subject and session, with equal figure-type representation.



Figure 10A. Complex figure recognition experiment. Training figure example (closed curved type). Upright orientation. Subject was sequentially shown four such figures for five seconds each.



Figure 10B. Complex figure recognition experiment. Trial figure example. Upright orientation. One figure has been rotated 90 degrees clockwise. Shown for 0.5 second, then each figure was replaced with a black dot.

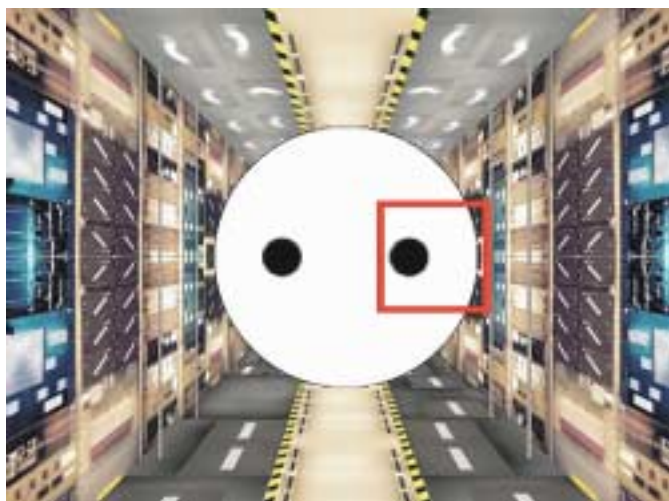


Figure 10C. Complex figure recognition experiment. Upright or VRI condition. After viewing each trial pair (e.g., Figure 10B), subject indicated which figure seemed most familiar by moving the indicator box with the joystick.



Figure 10D. Complex figure recognition experiment. Left-side-down condition. Open curved trial figure example.

The experiment was conducted using the same spacecraft module scene as in the shape-from-shading experiment, except that the circular easel provided a white rather than a gray background. In the “upright” condition, a series of four training figures (Figure 10A) was first shown for five seconds each. The subject was instructed to memorize these four shapes, without giving them names. Next, the subject fixated on a central cross, and a pair of test shapes (Figure 10B) appeared to the left and right or above and below the cross. Each test pair consisted of two versions of the training figure, one in the original orientation and the other rotated 90 degrees clockwise. After 0.5 second, the figures were replaced with marker dots. As in the shape-from-shading experiment, a forced-choice procedure was used. The subject had to indicate which figure looked “most like” one of the training figures using the joystick indicator (Figure 10C). Each trial required about three seconds. The subject completed 48 trials.

Next, the subject was again given a new set of four training figures to memorize for five seconds each. Then the subject physically turned into the same left-side-down position as was used in the shading experiment, and was repeatedly tested using a second set of 48 pairs of test shapes (Figure 10D). The visual environment in this orientation was thus rotated 90 degrees from the upright condition. The figure pairs were oriented so that one was in the same orientation with respect to the visual environment as when memorized (but therefore rotated 90 degrees clockwise with respect to the subject), and the other was in the same orientation with respect to the subject as when memorized (but therefore rotated 90 degrees counterclockwise with respect to the subject).

Finally, the subject and the visual scene were rotated back to the upright position, and the subject was given a third set of training figures to memorize. Then—without physical movement or a change in the visual scene orientation—the subject was instructed to initiate a VRI so that the left wall seemed like a floor, and he felt in a left-shoulder-down condition. The subject was again tested using a third set of 48 pairs of test shapes, one in the same orientation as during the memorization step and the other rotated 90 degrees counterclockwise with respect to the subject. Our working hypothesis was that in both one-G and zero-G, subjects recognize complex figures by recalling their features relative to the perceived “top” and “bottom” of the scene. We expected that the percentage of test figures that were presented upright with respect to the head in each condition would decrease in the left-shoulder-down and VRI conditions.

When tested on FD3, the percentage of body-upright test figures recognized decreased as expected from 78% (the control condition) to 55% in the left-side-down condition to 68% in the VRI condition. However, looking at the subjects individually, only Subject C’s data (Figure 11) truly followed the hypothesized pattern both on the ground and inflight, with a general trend to prefer body axis presentations. Unlike most other subjects in similar studies, Subject A consistently chose the body axis figure under all conditions in one-G, and there was no clear effect of the SV manipulation in any condition. Subjects B and D showed no effect of the SV manipulations in

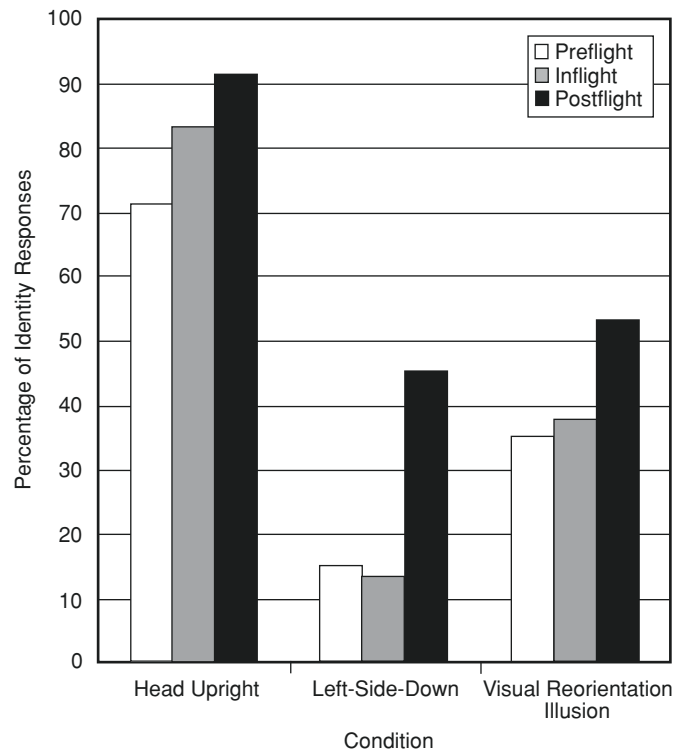


Figure 11. Complex figure recognition. Percent of previously memorized figures recognized by Subject C when presented upright with respect to head, by condition, and by epoch. A decrease was expected in left-side-down and VRI conditions relative to Head Upright, both in one-G and zero-G.

ground testing. We cannot generalize from these data, except to say that the expected effect of SV manipulation was clearly present in one subject preflight, inflight, and postflight.

DISCUSSION

With a very limited number of subjects, of nearly the same age and gender, usually tested only once in orbital flight, and always under conditions of time pressure and fatigue, we must be cautious in generalizing. However, our principal conclusions are:

Crewmembers differed in the extent to which their judgment of the subjective vertical was influenced by the orientation of motionless (static) surrounding surfaces and objects. Some subjects consistently reported subjective down as beneath their feet, while others reported down in a direction consistent with the surrounding visual environment. Subjects who were strongly statically visually dependent or independent on the ground remained so inflight. One moderately visually independent subject became more visually dependent during flight, and then returned to his preflight characteristic. None of our subjects became more statically visually independent as a result of spaceflight. The variety of responses among crewmembers suggests that there may be several ways to perceptually adapt to weightlessness.

In tests with tilted and tumbling scenes, most subjects experienced visual reorientation illusions so that the floor was the

surface beneath the crewmember's feet. With tumbling scenes, the angles at which VRI onset occurred tended to be 90 degrees or 180 degrees apart. Individual responses to motionless tilted scenes did not predict tumbling responses, which suggests that a scene's angular motion cues play an important role.

The magnitude of angular self-motion illusions produced by a rolling visual scene increased in zero-G for most subjects. One crewmember recalled occasionally making reaching direction errors during the first few days of flight because of VRIs.

The preponderance of our data on linear self-motion illusion (linear vection) produced by a scene translating toward the viewer shows small but statistically significant decreases in latency, and an increase in average vection magnitude consistent with the hypothesis that visual cues to linear motion become more compelling in weightlessness. This may account for anecdotal astronaut reports that spacecraft orbital motion relative to the Earth seems surprisingly vivid. Crews should be aware that moving visual images would produce motion sensations less effectively in ground simulators than in actual spaceflight, due to the vection-inhibiting effect of gravity. Because we had no opportunity to test most of our subjects more than once in flight, we can offer no firm conclusions as to how rapidly vection susceptibility increases upon reaching orbit. That Subject B had little vection on FD4 but was susceptible when retested on FD16 suggests that the effect may not necessarily be immediate, however.

Downward restraint reduces susceptibility to visually induced motion illusion, probably because it provides an unambiguous cue that the subject is not moving. Downward force cues are also reportedly effective in suppressing symptoms of space motion sickness (Oman, 1984).

Changing the relative direction of the SV in weightlessness either by body rotation or by simply cognitively initiating a visual reorientation illusion altered the illusion of convexity produced when viewing a flat, shaded disc for several subjects. It also changed at least one subject's ability to recognize previously memorized two-dimensional figures. This supports our hypothesis that there is a correlation between the surface the subject cognitively perceives as down and precognitive figure recognition and shading interpretation.

To measure these changes, we used the VEG head-mounted display to provide controlled, repeatable visual stimuli in both ground and flight testing since there was no other practical alternative—particularly for inflight testing. To what extent might our results have been affected by using this system? The VEG lacked a head tracker, which may have compromised the subject's sense of immersion. Although we used photorealistic textures, the spacecraft interior scenes had a cartoonish quality. The head-mounted display introduced some pixelization and visual distortion, and it constrained the subjects' field-of-view in a way that may have limited the effectiveness of the visual flow cues in our vection experiments. On the other hand, our subjects were physically motionless during all trials, so the lack of head tracking during the trials

themselves was arguably not important. Scenes were rendered in color stereo, which made pixelization less apparent and provided foreground/background motion cueing for the vection experiments. Most of the perceptual effects we were studying are mediated by peripheral vision, or other systems where visual acuity probably plays only a minor role.

Several of our subjects experienced symptoms of space motion sickness during their first days in orbit. Because of the limited number of subjects available and the uncontrolled nature of their daily activities, we made no attempt to correlate individual crewmember results with space motion sickness susceptibility under operational conditions. Although our experiments were deliberately designed to change the direction of the subjective vertical or the sense of self-motion sensation, our subjects described themselves as less susceptible than average to motion sickness, and none of our subjects reported symptoms during preflight or inflight testing. On the day of return to Earth, one subject had re-adaptation sickness, which was slightly exacerbated during the linear vection experiment.

Despite these limitations, results show that most astronauts become more dependent on dynamic visual motion cues and some also become more responsive to static orientation cues. The direction of the SV is labile, and shifts can cause disorientation and influence recognition of objects as well as interpretation of shading and shadows, and hence impact astronaut performance.

The scientific results and methods developed for this Neurolab experiment are currently being employed in the National Space Biomedical Research Institute to better understand spatial disorientation in orbit, and to develop countermeasures. A follow-on experiment to study the effects of long-duration flight aboard the International Space Station is in development. Our results broaden the understanding of how elderly people and vestibular patients who have altered inner ear balance function rely on visual and position sense cues to determine the direction of the subjective vertical, and why they find certain situations in daily life disorienting.

Acknowledgements

We thank our astronaut subjects, the VEG engineering team, the Neurolab mission and E136 experiment support cadre, our colleagues at MIT and York, and of course our families, without whose support this experiment would not have been successful—or even possible. Special thanks to: A. Al-Hajas, C. Amberboy, R. Allison, H. Anderson, F. Booker, L. Braithwaite, J. Buckey, M. Buderer, J. Cheng, G. Dalrymple, J. DeSouza, D. Grounds, H. Guitierrez, W. Hutchison, J. Homick, S. Johnston, J. Krug, K. Lawrence, A. Lee, A. Leyman, G. Lei, L. Li, G. Lutz, D. Merrick, T. Mills, A. Mortimer, K. Nguyen, M. Pickering, H. Rahman, J. Rummel, S. Sawyer, N. Skinner, A. Skwersky, C. Tovee, and J. van Twest. Supported by NASA Contract NAS9-19536 and Canadian Space Agency Contract 9F007-5-8515.

REFERENCES

- THE EFFECT OF RETINAL AND PHENOMENAL ORIENTATION ON THE PERCEPTION OF FORM. I. Rock and W. Heimer. *Am. J. Psychol.*, Vol. 70(4), page 493; 1957.
- A NEW SOLUTION TO THE PROBLEM OF SUBJECTIVE VERTICAL. H. Mittelstaedt. *Naturwissenschaften*, Vol. 70, pages 272–281; 1983.
- SYMPTOMS AND SIGNS OF SPACE MOTION SICKNESS ON SPACELAB-1. C. M. Oman, B. K. Lichtenberg and K. E. Money. NATO-AGARD Aerospace Medical Panel Symposium on Motion Sickness: Mechanisms, Prediction, Prevention and Treatment, Williamsburg, Va, NATO AGARD, pages 35/1–35/21; 1984.
- MIT/CANADIAN VESTIBULAR EXPERIMENTS ON THE SPACELAB-1 MISSION: 4. SPACE MOTION SICKNESS: SYMPTOMS, STIMULI, AND PREDICTABILITY. C. M. Oman, B. K. Lichtenberg, K. E. Money and R. K. McCoy. *Exp. Brain Res.*, Vol. 64, pages 316–334; 1986.
- MIT/CANADIAN VESTIBULAR EXPERIMENTS ON THE SPACELAB-1 MISSION: 2. VISUAL VESTIBULAR TILT INTERACTION IN WEIGHTLESSNESS. L. R. Young, M. Shelhamer and S. Modestino. *Exp. Brain Res.*, Vol. 64, pages 299–307; 1986.
- SHAPE FROM SHADING IN A DIFFERENT FRAMES OF REFERENCE. I. P. Howard, S. S. Bergstrom and M. Ohmi. *Perception*, Vol. 19, pages 523–530; 1990.
- THE PERCEPTION OF SELF-MOTION INDUCED BY PERIPHERAL VISUAL INFORMATION IN SITTING AND SUPINE POSTURES. C. Kano. *Ecol. Psychol.*, Vol. (3), pages 241–252; 1991.
- SOMATIC VERSUS VESTIBULAR GRAVITY RECEPTION IN MAN. H. Mittelstaedt. Sensing and Controlling Motion: Vestibular and Sensorimotor Function. B. Cohen, D. L. Tomko and F. E. Guedry, Eds. New York, *Ann. N.Y. Acad. Sci.*, pages 124–139; 1992.
- THE CONTRIBUTION OF MOTION, THE VISUAL FRAME, AND VISUAL POLARITY TO SENSATIONS OF BODY TILT. I. P. Howard and L. Childerson. *Perception*, Vol. 23, pages 753–762; 1994.
- TACTILE INFLUENCES ON ASTRONAUT VISUAL SPATIAL ORIENTATION: HUMAN NEUROVESTIBULAR EXPERIMENTS ON SPACELAB LIFE SCIENCES–2. L. R. Young and Mendoza. *J. Appl. Physiol.*, 1996.
- ADAPTATION TO A LINEAR VECTION STIMULUS IN A VIRTUAL REALITY ENVIRONMENT. C. A. Tovee. Cambridge, MA, Mass. Inst. of Tech. *Aeronaut. Astronaut.*, page 113; 1999.
- VISUAL-VESTIBULAR INTEGRATION MOTION PERCEPTION REPORTING. D. L. Harm, M. R. Reschke and D. E. Parker. In: C.F. Sawin, G.R. Tayler, W. L. Smith Eds. *Extended Duration Orbiter Medical Project*, NASA SP-534. NASA Lyndon B. Johnson Space Center, Houston, TX, pages 5.2-1–5.2-12, 1999.
- HUMAN VISUAL ORIENTATION IN WEIGHTLESSNESS. C. M. Oman. In: *Levels of Perception*. M. Jenkin and L. R. Harris, Eds, Springer Verlag., pages 375–398, 2003.