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Chapter

SPATIAL ORIENTATION AND NAVIGATION IN MICROGRAVITY

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Abstract: This chapter summarizes the spatial disorientation problems and navigation difficulties described by astronauts and cosmonauts, and relates them to research findings on orientation and navigation in humans and animals. Spacecraft crew are uniquely free to float in any relative orientation with respect to the cabin, and experience no vestibular and haptic cues that directly indicate the direction of "down". They frequently traverse areas with inconsistently aligned visual vertical cues. As a result, most experience "Visual Reorientation Illusions" (VRIs) where the spacecraft floors, walls and ceiling surfaces exchange subjective identities. The illusion apparently results from a sudden reorientation of the observer's allocentric reference frame. Normally this frame realigns to local interior surfaces, but in some cases it can jump to the Earth beyond, as with "Inversion Illusions" and EVA height vertigo. These perceptual illusions make it difficult for crew to maintain a veridical perception of orientation and place within the spacecraft, make them more reliant upon landmark and route strategies for 3D navigation, and can trigger space motion sickness. This chapter distinguishes VRIs and Inversion Illusions, based on firsthand descriptions from Vostok, Apollo, Skylab, Mir, Shuttle and International Space Station crew. Theories on human "gravireceptor" and "idiotropic" biases, visual "frame" and "polarity" cues, top-down processing effects on object orientation perception, mental rotation and "direction vertigo" are discussed and related to animal experiments on limbic head direction and place cell responses. It is argued that the exchange in perceived surface identity characteristic of human VRIs is caused by a reorientation of the unseen allocentric navigation plane used by CNS mechanisms coding place and direction, as evidenced in the animal models. Human VRI susceptibility continues even on long flights, perhaps because our orientation and navigation mechanisms evolved to principally support 2D navigation.

Key words: vision; vestibular; spatial disorientation; navigation; inversion illusion, visual reorientation illusion, spacecraft architecture, head direction cells, place cells, height vertigo.

1. INTRODUCTION

In our normal lives on Earth, gravity furnishes a ubiquitous sensory cue that helps us keep the various self- and world-fixed coordinate frames we use for spatial perception, imagery, and actions in proper registration. We naturally locomote on two dimensional surfaces in a gravitationally upright orientation. Arguably the human nervous system has become somewhat specialized for terrestrial conditions, since – as reviewed in this chapter - astronauts and cosmonauts regularly experience occasional three dimensional orientation and navigation problems while in weightlessness, even long after the initial two to thee day period of susceptibility to space motion sickness has passed. The routine orientation and navigation problems experienced by astronauts probably have more to do with CNS spatial processing, imagery and perception – the central themes of this book – than they do with adaptation in the vestibular end organs or changes in vestibulo-ocular or vestibulo-spinal reflexes.

Dozens of crewmembers have served as subjects in various neurovestibular experiments in orbit. After their missions, all crewmembers are routinely debriefed on their operational experiences. However, only few are questioned in detail about orientation and navigation problems, and some are reluctant to raise the issue. Inevitably much of what is currently known is based on anecdotal but detailed descriptions provided by several dozen crewmembers, many of them scientist astronauts. Weightlessness is a unique environment. Though the reports are anecdotal, there is a great deal that can be learned from them that is of interest to neuroscientists. However some are unpublished, and others are scattered across the scientific and popular literature. My purpose in writing this chapter is to assemble and interpret them, including where possible many direct quotes, though preserving anonymity when required.

The organization of this chapter is straightforward: First, the two principal illusions of weightlessness - the "Visual Reorientation Illusion (VRI) and the "Inversion Illusion"- are described. Next, related extravehicular activity (EVA, or spacewalking) disorientation, height vertigo and 3D navigation problems are discussed. The final sections review several theories and experiments that provide insight into visual and body axis spatial orientation cue interaction, and the mechanisms of reorientation and 3D navigation. Based on evidence in animal models, it is argued that the exchange in subjective identity of floors, ceilings, and walls– one of the unique hallmarks of a Visual Reorientation Illusion - occurs when the CNS navigation reference plane coding azimuth and place erroneously aligns with the wrong spacecraft surface, due to the absence of gravity. Continued susceptibility to VRIs reflects the terrestrial heritage of human orientation, re-orientation and navigation mechanisms. Nonetheless, the crew reports and research reviewed here suggests ways to further reduce spatial orientation and navigation problems through improved spacecraft design and virtual reality based crew training.

1.1 Visual Reorientation Illusions

When an astronaut floats within the cabin of an orbiting spacecraft, the notion of a “gravitational down” is meaningless. Crew typically speak of the “visual down” reference defined by the orientation of surrounding wall, ceiling and floor surfaces, typically comprised of labeled racks and panels, readily recognizable from prior experience in ground simulators. In order to know which way to look or reach for remembered objects, or to move about in the cabin, astronauts must visually recognize landmark objects and surfaces, and correctly infer their self-orientation with respect to the cabin. Normally this process is automatic and effortless when they work with their feet oriented towards the familiar cabin floor. However, Skylab (Cooper, 1976; Johnston and Dietlein, 1977) and Spacelab astronauts (Oman et al, 1984, 1986, 87) reported that when moving about the cabin they frequently experienced disorientation. Two of the most common situations were when working upside down (relative to their normal 1-G orientation in training), or when floating right side up but viewing another crewmember floating upside down in the cabin. In either case, crew often experienced the striking illusion that the surrounding walls, ceiling, and floors had somehow exchanged identities. In the first situation, whichever surface was closest to their feet seemed like a generic floor. Surfaces approximately parallel to their body now seemed like walls, and overhead surfaces were perceived as ceilings. In the second situation, the orientation of the inverted crewmember determined the direction to the “floor”. In both cases, it was as if an internal mental coordinate frame responsible for perception of surface identity had rotated into a new orientation determined by available visual cues. Since the crew often felt “right side up” after such visual reorientations, we (Oman et al, 1987) termed these phenomena “Visual Reorientation Illusions” (VRI), in order to distinguish them from the less commonly experienced “Inversion

Illusion", detailed in Sect 2.2, wherein crew always feel continuously gravitationally upside down.

Sometimes the reorientation illusions were subtle, and crew were not aware of them till they reached or looked for a remembered object, or turned in the wrong direction. More often, the change in orientation perception was dramatic. One Skylab crewmember described it this way: "It was a strange sensation. You see brand-new things…It's really like a whole new room that you walk into…with the lights underneath your feet, and it's just an amazing situation to find yourself in". Another noted "All one has to do is to rotate one's body to [a new] orientation and whammo ! What one thinks is up *is* up". "It's a feeling as though one could take this whole room and, by pushing a button, just rotate it around so that the ceiling up here would be the floor. It's a marvelous feeling of power over space – over the space around one" (Cooper, 1976). A third said: "Being upside down in the wardroom made it look like a different room than the one we were used to. After rotating back to approximately 45 degrees or so of the attitude which we normally called "up", the attitude in which we had trained, there was a sharp transition in the mind from a room which was sort of familiar to one which was intimately familiar…We observed this phenomenon throughout the whole flight.". Another commented: "I can move into a given room sideways or upside down and not recognize it. You would tend to get locked into one frame of reference. When you rotated your body to another one, it took a little time for the transition to occur" (Johnston and Deitlein, 1977).

Areas of Skylab that had locally incongruent visual vertical cues also triggered VRIs, depending on where the astronaut was working or directed their visual attention. For example, the Skylab Multiple Docking Adapter (MDA) tunnel had a cylindrical interior, and control panels to operate telescopes and other systems mounted on the walls in a variety of different orientations. The MDA was deliberately designed this way because it provided an efficient use of wall space, and to determine whether crews could get along without a single visual vertical (Cooper, 1976). The almost unanimous verdict was that crews disliked working there. One said: "It is one of the biggest mysteries in the world when you go in there to find something." Another commented "There's been some thought about mounting some furniture on the floor, some on the walls, some on the ceiling, but this doesn't work out. You tend to orient yourself when you're in a room, even though you're in zero-g, and when you orient yourself, you should find everything is the same." (Johnston and Deitlein, 1977).

In the early 1980s, our MIT laboratory began to develop experiments on vestibular function, spatial disorientation and motion sickness which ultimately flew on four US Shuttle Spacelab missions between 1983 and 1993. The science crew of the first mission included a Skylab astronaut (O.

Garriott) who introduced us to these during illusions during repeated intervals of weightlessness on parabolic training flights. At our request, the crews made detailed notes on pocket voice recorders once they reached orbit. They documented for us in considerable detail the numerous circumstances that triggered orientation illusions aboard the Shuttle, emphasizing the previously unrecognized contribution of the illusions in causing space motion sickness. We summarized their reports in a series of papers (Oman et al, 1984, 1986, 1987, 1988). Our crews noted that the change subjective identity of surrounding surfaces was a perceptually distinct event. In this respect VRIs resemble other types of figure-ground illusions, except that what is being reinterpreted is the identity of surrounding surfaces, and implicitly, the viewer's own allocentric orientation with respect to an unseen environment beyond. VRIs typically occur spontaneously, but as with figure ground illusions, onset depends on visual attention and is therefore under cognitive control. One commented: "If you really want a surface to be "down", you can just look at it and decide that it is". Architectural symmetries and prior visual experience were important predisposing factors. For example, they noted that they frequently experienced VRIs when in the Shuttle flight deck, while the mid-deck beneath, or in the tunnel connecting the mid-deck to the Spacelab laboratory module. However, in the laboratory module, it usually required deliberate effort to make the ceiling and floor reverse, and making a wall seem like a compelling ceiling or floor was even more difficult. The crew noted that the mid-deck and tunnel areas had strong architectural symmetries, and that the science members of the crew had they received far less preflight training in the flight deck, mid-deck, and tunnel than the Spacelab laboratory module. They were intimately familiar the arrangement of the laboratory interior from two years of ground training in a high fidelity mockup. The implication was that visual vertical and surface identity cues are not entirely physically intrinsic, but depend on prior visual experience and familiarity with the spatial layout. Usually the only way to spontaneously experience a VRI while in the Spacelab laboratory was to float with feet towards the ceiling, or view a crewmember who was working that way.

Views of the Earth through the windows also provided powerful orienting cues. One of our Spacelab crewmembers commented: "Generally the visual verticals [in the laboratory module] kept me upright and oriented, and if I were to go and look out the window generally I would move myself around so that the Earth was down below me just so it was easier to see and understand where we were.. If I was upside down I would come away from there and for several seconds look around. The first time you think: things are kind of strange and misplaced, like the air lock is sitting on the floor or on the side or something. But as soon as [I] saw one familiar thing like the airlock then I was able to figure out where I was in relation to the Spacelab." This crewmember added that "working on the [inward] slanting panels on the upper half [of the laboratory module walls], let's say you are...pulling out a [stowage] box to get things out, and it wasn't more than a couple of seconds than the [upper panel] would become vertical to me, and I would look down and I'd see the [lower panel] wall.coming out at an angle, slanting in towards me, and it was ..a very strange sensation."

To some degree, non-astronauts can appreciate the VRI phenomenon simply by viewing rotated photographs (e.g. Figs 1-3), but astronauts and parabolic flight participants who have experienced 0-G VRIs firsthand say that when the gravity cue is truly physically absent, and the scene is real, the perceptual change in surface identity is far more distinct and the perceived self-orientation change far more compelling than when simply viewing a photograph.

Figure ***Error! No text of specified style in document.****-1.* Visual Reorientation Illusions are labile when visual cues to the vertical are ambiguous or conflict. Whether you feel upright or upside down depends on visual attention. Does your interpretation of the photograph change if you look at the face of the blue shirted crewmember ? If you turn both the page and your head upside down ? (NASA photo)

As detailed in Section 4.6, visual reorientation, path integration and place recognition are the fundamental modes underlying navigation in humans and many animals. In our everyday lives on Earth, our gravireceptive organs provide an absolute vertical orientation reference. Our semicircular canals contribute to our sense of direction, but cannot provide a corresponding absolute azimuth reference. Hence our sense of direction and place ultimately must be updated – reoriented - by visual cues. We all occasionally experience "direction vertigo" (Viguer, 1882; Jonsson, 2002), for example when we emerge from a subway, realize we are not facing in the expected direction, and reorient. However, living on Earth all our visual reorientations can occur only in azimuth since gravity anchors our perceptions of pitch and roll. Our sense of azimuthal direction reorients, but ceilings and floors do not change subjective identity the way they do for astronauts. At most we say the wall we thought faced west actually is actually the one facing east.

The focus of this chapter is on spatial orientation, not motion sickness. However, the early Shuttle crews made the important observation that VRI onset could trigger an immediate increase in nausea and sometimes even cause vomiting during the first several days in weightlessness. We (Oman et al, 1986) noted that VRIs are caused by a sudden change in perceived allocentric orientation, and that this happens without concurrent movement commands or vestibular and proprioceptive cues. Hence one would expect VRIs to be provocative, based on the sensory conflict theory for motion sickness. One Shuttle pilot recalled awakening in his seat, removing the cockpit window shades, seeing the Earth in an unexpected location above rather than below, experiencing a sudden change in spacecraft orientation - and therefore in self orientation - and vomiting moments later. Several Spacelab crew described sudden vomiting episodes after seeing a nearby crewmember floating upside down. One commented "[Early in the mission] I really needed…a good optical "down". It was really distressing when [a second crewmember] came floating into the [Spacelab] module upside down and tumbling and things – that didn't sit too well with my own perception of Spacelab. I felt like I needed a real visual "down", and it was the floor…and I didn't really have one of my own". Subsequent Shuttle crews have noted that after reaching orbit, when the entire crew remove their orange launch/entry space suits and leave them floating about the cabin prior to stowage, the resulting visual environment is extremely disorienting to everyone.

One astronaut deliberately created VRIs to obtain nausea relief: "When I went into the mid-deck..and I didn't feel really well, I knew a method how to get better by vomiting…I [went into the connecting tunnel] and turned around, just to make sure that I didn't know the orientation of Spacelab or the mid-deck, and then I'd close my eyes, [float back into Spacelab], open my eyes, and see something I didn't expect." Several crewmembers suggested that VRIs and space sickness could be reduced by the practique of deliberately ignoring visual landmarks, relaxing, and not trying to control their own orientation. Others noted that belting into a seat or standing up against a bungee harness seemed to reduce spontaneous VRIs and nausea.

It is interesting that Skylab crews had described orientation illusions but had not noted a relationship between them and space sickness, whereas to our subsequent Shuttle crews the causal relationship seemed unequivocal. Possibly this is because two of the three Skylab crews were largely confined to their seats in small Apollo ferry vehicles during the first days in weightlessness, when their susceptibility to space sickness was highest. The Shuttle crews could roam about freely immediately. It seemed clear that although VRIs caused disorientation, their nauseogenic potential was evident primarily during the first days in flight. Because of this, Oman et al (1984) first recommended that during the first several days while Shuttle crew are at risk of space sickness, for the good of all onboard, *all* crewmembers - symptomatic or not – should remain in a locally visually upright orientation. Subsequent Shuttle crews have followed this dictum, and operationally confirmed its efficacy.

With the exception of a questionnaire study (Kornilova, 1995, 1997) no comparably detailed descriptions of visual orientation illusions have yet appeared in the Soviet and Russian scientific literature. However, cosmonauts and designers of the Salyut, Mir and Russian ISS modules were clearly aware of the importance of providing at least a local visual frame of reference. Most Russian modules have a longitudinal floors, a rectangular interior cross section, ceiling lighting, and brown floors, tan walls and lighter tan or blue ceilings to help establish a locally consistent visual vertical in work areas within a module (Gurovskiy et al, 1980). In the ISS Zvezda module, the floor and ceiling rack labeling is symmetrically oriented about the surface midline. This way labeling on adjacent floors, walls, and ceiling are easily readable by crewmembers working upright. However, the local visual verticals of certain multi-compartmented modules (e.g. the Mir Priroda module) have adjacent work areas with oppositely oriented visual vertical cues.

NASA's 1995 Man Systems Integration Standard (MSIS 3000 Sect 8.4.3) for all future NASA spacecraft mandated that all NASA spacecraft be designed so color, lighting and equipment orientation provided unambiguous visual vertical cues that were consistent. The standard cited both Skylab and Spacelab experience and supporting ground research (e.g. Coss et al, 1989). However the rules were eventually changed for the non-Russian portions of ISS. Some early ISS designs Kitmacher (2002) featured large modules with parallel, "bologna slice" decks with globally congruent visual verticals, reminiscent of Skylab. Ultimately, however NASA designers opted for Shuttle payload bay sized modules with hatches at each end, connected by smaller "node" modules with hatches facing in all six directions. The interior of each NASA module have a square cross section, formed by four rows of superficially similar equipment racks running longitudinally. The front surfaces of these racks form the floors, walls and ceiling. The orientation and labeling of equipment mounted in the racks effectively creates dual visual verticals, oriented 90 degrees apart. One is defined by the equipment mounted on the walls, and the other by equipment on the floor and ceiling. To know which is the “true” visual vertical, the crew has to be familiar with the relative arrangement of specific equipment racks and permanently mounted equipment, or look for larger scale architectural cues. For example a row of lights running longitudinally between the ceiling and the walls outlines the ceiling. When viewed upright, the hatch openings at the ends of the module form a “**U**” rather than an “∩” , and the text on prominent emergency egress signs around the hatches (e.g. “TO NODE 1”) appears upright. Dual local visual verticals were not consistent with the general MSIS standard, but NASA adopted a special standard for ISS (NASA SSP5005, 1999) which deleted the troublesome requirements. Engineers apparently determined that disorientation due to architectural factors introduced only short-term medical and habitability problems, and that rack commonality and stowage volume efficiency should have priority. Early ISS crews noted the potential problem, and mounted movable equipment (e.g. laptop computers and foot restraints) so they worked upright with respect to the “floor” defined by their experience in ground training modules.

Early ISS astronauts also noted that the hatches in the node modules could sometimes be difficult to distinguish. Also, the Russian modules had smaller openings, necessitating a change in body orientation when transiting. If crews experienced VRIs when entering a node, they reoriented using remembered equipment items or signs as landmarks. One early ISS crewmember described how he had been detailed to mount an emergency egress placard on a US node hatch leading to the docked shuttle. He had a VRI after entering the node, and inadvertently attached the placard to an unused hatch leading to space. Fortunately another crewmember discovered the error.

Although space station crews eventually become intimately familiar with the interior of their spacecraft, it is clear that some degree of VRI susceptibility remains even after many months in orbit. Crews learn to live with the VRI phenomenon, and (as described in Section 3) rely on landmark and route strategies for navigation. One US astronaut who lived on Mir for six months recalled that in some areas where he routinely preferred to work visually upside down, VRIs actually seemed easier to get: “When I rolled upside down, I didn’t have to wait till my feet got near the floor before the ceiling became down. It happened even before I reached 90 degrees.”. Another US Astronaut who lived for months on ISS astronaut wrote: “There really isn't an up or down anywhere else here, but there is a direction we think of as the floor and a direction we think of as the ceiling in each module. Most of the labeling on panels and equipment is written so that it is right side up assuming this orientation, and also most of the lights are on the "ceiling" so they cast light "downwards." To add to the effect, there is a simulator back on Earth [where] we spent a lot of time in where we got used to one direction as the floor and the opposite direction as the ceiling….This isn't true for the Progress [cargo vehicle]. Since it is just a cargo container, we don't have a simulator that we have trained in on the ground, and since it is spherical there really isn't a flat surface to call the floor. So that means that work inside Progress can be kind of disorienting. This is especially true if doing close-up work on something (say unbolting a piece of equipment). In weightlessness your body may shift position without you realizing it while you are intently working, so that when you pop your head back up after finishing you may find yourself in a totally different orientation than when you started. I recall looking out the hatch and being momentarily surprised to see [another crewmember] in the Service Module running on the treadmill on the ceiling! Actually, it was me that had flipped upside down…. In space you need to remember that you aren't limited like you are on the ground to having your feet on the floor - they can just as easily be on the wall or on the ceiling. I find that when I am working in a tight space, I don't really think about any particular direction as up or down, but when out in an open space like in the middle of a module I do. If for instance I am up on the ceiling, by concentrating I can make myself think of the ceiling as the floor. I really think it is a matter of just familiarity what you call up or down. An example is the area around our weightlifting exercise equipment, which is located on the ceiling of the Node module. I've gotten so used to spending time there in that orientation that I am more comfortable there upside down. I've also gotten used to looking towards the Service Module while I am working out and seeing [my colleague] upside down - or at least the opposite way since from his viewpoint - it is me that is upside down" (Lu, 2005).

1.2 0-G Inversion Illusions

Many astronauts have some flying background and are familiar with the somatogravic illusions of aerobatic flight, including a sensation of flying upside down during an aerobatic pushover due to the associated "eyeballs up" acceleration. (Cheung, 2004) Since the US Shuttle thrusts into orbit in an inverted attitude, crewmembers experience "eyeballs-in and up" acceleration, it is not surprising that crewmembers report feeling upside down during the launch phase.

Immediately after main engine cutoff and the onset of weightlessness, almost all US and Russian crews experience momentary somersaulting sensations, and thereafter frequently feel upside down for a period of time ranging from seconds to several minutes (Gazenko, 1964; Yuganov, et al, 1966; Oman, et al, 1986). Cosmonaut Titov reported: ""the weight vanished as quickly as Vostok separated from the booster...and I felt suddenly as though I were turning a somersault and then flying with my legs up!.... Fortunately the sensation lasted only seconds"(Titov and Caidin, 1962). A similar illusion has been reported at the onset of the weightless phase of parabolic flight (Lackner, 1992). Almost all blindfolded subjects making their first flight experience somersaulting, or sometimes a paradoxical sensation of inversion without pitch. If vision is available, the incidence of the illusion is lower.

Figure ***Error! No text of specified style in document.***-*2.* Persistent 0-G Inversion Illusion – both self and vehicle seem upside down relative to an unseen external gravitational reference frame. The illusion is often reported in the Shuttle mid-deck, where walls of rectangular stowage lockers make up and down ambiguous (NASA photo)

For a small minority of astronauts and consmonauts, 0-G inversion illusions are more persistent, sometimes lasting for hours, and return sporadically during the first several days in orbit. Once crewmember said: "The only way I can describe it is that though I'm floating upright in the cabin in weightlessness, both the spacecraft and I seem to somehow be flying upside down ". Rolling upside down in the cabin does not eliminate the inversion sensation – only the spacecraft seems right side up. A

Spacelab crewmember said: “ I knew I was standing upright…in the normal way with respect to the orbiter, and nevertheless I felt upside down…despite the fact that everything was normally oriented around me. This gave me the intellectual interpretation that the orbiter was flying upside down….I just interpreted intellectually that the orbiter has to be upside down because you feel upside down and yet you see are the right way up..” Some have reported that the inversion sensation was more noticeable in the visually symmetrical Shuttle mid-deck than when on the flight deck. Certain of the afflicted have found that inversion illusion can be momentarily eliminated by standing in bungee cords, or looking at their own face in a mirror. However such methods have little practical appeal to busy crewmembers. Since 1978, Russian crews have worn “Penguin” suits that use elastic cords to load their bodies along the head-foot axis as a countermeasure against muscle and bone deterioration. In the early 1980s they also evaluated two other disorientation countermeasures, a cap that applied a load between the top of the head and the shoulders, and also sandals with insoles that could be inflated, applying pressure to the feet. The latter became known as “Cuban Boots” after the Cuban cosmonaut who first tried them. However, the extent to which these devices can reproduce haptic gravitational cues is unclear, and users reportedly still experienced illusions and space sickness (Reschke, et al, 1994b). Artificial cues that reinforce the perception that “down” is beneath the feet may render freely moving cosmonauts more susceptible to VRIs whenever they float inverted.

1.3 Distinguishing VRIs from 0-G Inversion Illusions

Prior to the first detailed descriptions provided by Skylab and Spacelab astronauts, VRIs were not distinguished from Inversion Illusions in the scientific literature. For example, Graybiel and Kellogg (1967) reviewed Titov’s early account of 0-G inversion illusion after orbital insertion (Sect. 2.2) but assumed Titov’s inversion sensation corresponded to the VRI produced by slowly rolling inverted in the cabin of an aircraft in parabolic flight. Prior to Skylab, crew accounts in the US and Soviet programs typically came from hurried debriefings or written questionnaires where terminology was rarely defined and or discussed. In some cases nuances were lost in language translation. Also, early investigators typically focused exclusively on perceived orientation with respect to the gravitational vertical, ignoring the changes in surface identify highlighted by Skylab and Shuttle crews. Consequently the distinction between inversion illusions and VRIs was overlooked in several otherwise comprehensive 1990s reviews (e.g. Lackner, 1992, Reschke et al 1994a,b). However as confirming descriptions of VRIs emerged from Shuttle (e.g. Mukai and Igarashi, 1995), Mir and ISS (e.g. Liu, 2003), the scientific and operational medical significance of the distinction between VRIs and Inversion Illusions has become more widely appreciated. Although both illusions are clearly influenced by visual and interoceptive cues, we (Oman, et al, 1984, 1986; Mittelstaedt, 1986; Oman, 2003) have noted that Inversion Illusions and VRIs differ in many important respects.

*Table **Error! No text of specified style in document.**-1.* Characteristics of VRIs vs.Persistent 0-G Inversion Illusions

Character	VRI	0-G Inversion Illusion
Perceived surface identity	Depends on orientation	Always veridical
Allocentric reference frame	Spacecraft	External gravitational frame
Perceived orientation	Usually feet towards “floor”, but can vary	Always gravitationally inverted
Role of visual cues	Required	Not essential
Duration	Seconds	Many minutes
Lability	Easily cognitively reversed	Reversible with haptic cues
Incidence	Almost universal	< 25% of crew
Prevalence	Can occur throughout flight	Rare after second day
Paradoxical sensation	Momentary	Continuous

As summarized in Table 1, the hallmark of a VRI is a visual attention dependent change in the perceived identity of surrounding surfaces, resulting from an angular reorientation of the internal mental allocentric reference frame used as the basis for perception of orientation and place. When an astronaut floats upside down in the cabin and then looks at their own feet, the ceiling surface beyond suddenly seems like a “floor”, and there is a corresponding illusory change in the identity adjacent surfaces. If the same astronaut is floating upright, but looks at a second astronaut floating inverted nearby, the surface beneath the second astronaut’s feet is often suddenly the “floor”. By contrast, a crewmember experiencing a persistent 0-G inversion illusion correctly perceives the identity of surrounding surfaces but feels continuously inverted with respect to an external gravitational reference frame, regardless of body orientation. Hence when floating inverted, such a person feels upside down in a gravitationally upright cabin. When floating upright, the entire cabin seems gravitationally upside down. Note that the orientation of the external gravitational reference frame is determined by body orientation, and not by the actual relationship to the unseen Earth. The inversion sensation continues even when body orientation is changed, and persists after the eyes are closed, whereas VRI sensations generally do not. Inversion Illusion sensations are difficult to reverse, whereas VRIs only occur with eyes open, are labile, and like figure-ground illusions are easily cognitively manipulated by redirecting visual attention. Crew typically look around for a known architectural visual landmark, reorient to it, and the surface identity illusion disappears after a few seconds.

Almost all crew experience a brief tumbling illusion upon reaching orbit, at the moment of booster engine cutoff. Persistent inversion illusions are far less common and prevalent only during the first several days of flight. The incidence of persistent inversion illusions among crewmembers is difficult to estimate from conventional crew reports. However, among twelve carefully debriefed science astronauts who understood the distinction, only two described persistent inversion illusions, and only during their first two days in orbit. By contrast, almost all astronauts admit to experiencing changes in subjective surface identity, and though susceptibility probably eventually diminishes, VRIs have been described throughout the duration of six month long missions aboard orbiting space stations.

VRIs create a momentary change or uncertainty in perceived orientation and place. Crews say VRIs are nauseogenic only during their onset. They are a significant space motion sickness stimulus only because VRIs occur often, as when crew leave their seats and move about in all degrees of freedom. The afflicted describe persistent 0-G inversion illusions as continuously nauseogenic, since the they feel continuously gravitationally inverted, regardless of their relative orientation with respect to the vehicle. Both of our science crewmembers who reported inversion illusions experienced space motion sickness, including vomiting.

2. EVA DISORIENTATION AND HEIGHT VERTIGO

Shuttle, Mir and ISS crewmembers have also sometimes experienced spatial disorientation episodes while performing spacewalks (“Extra Vehicular Activity”, EVA). EVA astronauts typically move about using handrails, trailing a backup safety tether. They stabilize their body with one hand while working with the other, or install foot restraints and use both hands. Since the body tends to drift while working, crews must remain conscious of their orientation, and be careful not to inadvertently bump antennae, optics, or other sensitive equipment. They must avoid thruster keep-away-zones. Working upright within the Shuttle payload bay is disorienting, since the area can be illuminated with flood lights, and the floor and side walls define a convenient visual reference frame. However when crews work on the rounded exteriors surfaces of the Mir or ISS modules, fewer global visual landmarks are available, particularly during the dark portion of each orbit, when the only lighting comes from helmet mounted lamps. Crews prepare for EVA by memorizing landmarks and routes during their preflight underwater neutral buoyancy training. NASA EVA teams also train using an interactive immersive virtual reality display system. Once in orbit they use a laptop computer graphics program to review anticipated translation paths (Homan, 2001; Walz, 2002). Nonetheless most EVA crews admit they occasionally become disoriented and sometimes must even radio for advice, or await daylight.

Figure ***Error! No text of specified style in document.**-3*. Floating inverted in Shuttle payload bay can cause EVA Height Vertigo (NASA photo)

Some EVA astronauts have described a 0-G form of height vertigo, apparently triggered by a VRI. Early reports came from Shuttle astronauts working in the open payload bay while it faced earthward. If the astronaut happened to float into an inverted orientation, looked toward their feet and saw the Earth moving by rapidly by several hundred kilometers away, their mental allocentric reference frame apparently jumped from the payload bay to the surface of the Earth below. Perceived orientation suddenly changed from floating inverted in the payload bay with the globe of the Earth “above” to hanging from a handrail with the surface of the Earth far “below” (Fig. 3) Height vertigo reports have also come from astronauts egressing from an ISS airlock through an Earthward facing hatch, or while standing in foot restraints on the end of the Shuttle remote manipulator arm, or while hanging on the end of a crane used on the Mir station to transfer crew from one module to another (e.g. Linenger, 2000). Some of the afflicted have extensive parachuting or rock climbing background, so it is hard to think that acrophobia is a contributing factor. In many respects the phenomenon resembles physiological height vertigo (Brandt et al, 1980) that people describe on Earth when standing at the edge of a cliff or the roof of a tall building. However, some astronauts say they also experience enhanced awareness of the spacecraft's orbital motion, and the sensation that both they and the entire vehicle are falling toward Earth. In some cases, the compulsion to "hang on for dear life" for fear they will fall to Earth is disabling. The most common etiologic factor is that the Earth's surface is perceived as beneath the body, rather than as a blue planet floating above. Veterans say the best defense against EVA height vertigo is to look at their hands, and concentrate on the vehicle as the frame of reference. Changing relative body position so the Earth is "above" should also be effective (Oman, 2002).

3. 3D NAVIGATION PROBLEMS

Navigation problems deriving from the peculiar visual architectural relationships between the interiors of docked modules on Apollo, Skylab, Mir and ISS have been consistently reported. A common theme is that crews transiting between modules are momentarily disoriented when the visual verticals in the modules transited are not coaligned. Spatial relationships between non-aligned modules are apparently difficult for the crew to visualize.

Figure ***Error! No text of specified style in document.**-4.* Russian Mir Space Station. In this picture, the Core module is behind, pointing upwards. The Priroda module is to the left, also attached to the central node mudule, and opposite the Kristall and the orange Shuttle docking module. Opposite the Core is a docked Soyuz. The cockpit interior of the docked vehicle is oriented at 45 degrees to the Core-Soyuz axis. (NASA Photo)

The first reports came during Apollo, where astronauts in the Command Module (CM) on their way to the Moon normally sat facing the docked Lunar Module (LM). The primary visual axes of the LM cockpit were pitched back 90 degrees and yawed 90 degrees right with respect to the CM cockpit. One Apollo crewmember recalled: "..whenever I went from one spacecraft to the other through the connecting tunnel between the CM and the LM I was visually disoriented until I looked at a familiar spacecraft panel. Instantly my mind reoriented itself and I went about my business. In this case my mind apparently had a "learned" orientation from lying on my back during training in the command module simulators that was 90 degrees different from that learned while standing on my feet during training in the lunar module simulators" (Schmitt and Reid, 1985).

Skylab astronauts encountered similar problems. One noted "I get you know, [one local vertical] embedded in my mind, and I whistle [out of the workshop] through the docking adapter and into the command module [docked facing the other Skylab modules] and zingy ! All of a sudden it's upside down…" He felt the disorientation might be dangerous, since an astronaut might throw a switch the wrong way." (Cooper, 1976).

Disorientation and navigation problems were also common on the Russian Mir space station, due to its complex three dimensional architecture. Mir research modules were connected at 90 degree angles to a central, 6 ported spherical "node". The visual verticals of many Mir modules were not co-aligned. For example the visual vertical in the Priroda science module was opposite to that in the Core module station control center. The visual vertical in the Kristall science module was oriented at 90 degrees to the Core. Crewmembers said that even though they intellectually knew the physical arrangement of the modules, and though had a small physical model of the Mir exterior onboard, the interior arrangement was so complicated that they could not readily mentally visualize it. Several observed they could not point in the direction of familiar interior landmarks in other modules the way they knew they could in their homes on Earth. When moving between modules they learned to use landmarks and rules to navigate. One crewmember recalled: "I learned that to go into Priroda, I needed to leave the [Core module] upright, go through the hatch to my left, and then immediately roll upside down so that Priroda would be right side up". Another said: "Even though you knew the modules went in six different directions, it felt like the node was a vestibule in a single story house…. You eventually just learned what to look for and do to get to your destination."

A third said: “After I first boarded Mir, I decided to go back to the Shuttle, but discovered I didn’t know which way to go, since I hadn’t left behind any bread crumbs!”. To assist Shuttle visitors, Mir crew fashioned red velcro arrows, and positioned them on the walls pointing toward the Shuttle.

In 1997, Mir crews successively had a fire, a near collision and a collision with a Progress robot resupply vehicle. The collision caused a depressurization and power loss. In both cases when collisions were imminent, crew tried to locate the inbound spacecraft visually, but could not readily keep track of its allocentric direction when moving from module to module and window to window. The power loss required the crew to reorient the entire station using thrusters on a docked Soyuz spacecraft. Crew in the Mir Core control center discovered they had great difficulty mentally visualizing the orientation of another crewmember in the differently oriented Soyuz cockpit, and performing the 3D mental rotations required to formulate appropriate verbal control instructions (Burrough, 1998) These events convinced the space agencies that in could be critical in certain emergency situations for crew to be able to maintain their allocentric orientation and be able to make complex three dimensional spatial judgments.

Fortunately no comparably serious emergencies have yet occurred on the ISS. The primary Russian and US modules orbited so far (2006) are arranged in a straight line. Although some modules have multiple visual verticals (Sect 2.1), their principal visual verticals - as defined by the crew’s gravitational orientation during training in ground simulators - are coaligned. However crews have reported difficulties visualizing spatial relationships between these principal modules and other vehicles which often dock at 90 degrees to the main plane of ISS, such as the Shuttle, Soyuz crew vehicle, and also the Progress and Multipurpose Logistics Modules which deliver supplies. Other modules and vehicles will eventually be added at 90 degree orientations. As on Mir, visiting Shuttle crews are vulnerable to becoming lost. In emergencies, crewmembers must plan to leave ISS in different directions, since each of the Soyuz vehicles can only accommodate three people in custom fit couches, and visiting Shuttle crews must leave through a different hatch. Small relocatable luminescent signs (Smart, et al, 2001) point the way to the various docked vehicles, but in conditions of reduced visibility, crew must remain oriented and be able to find their way. Since the ground mockups are not all connected in the actual flight configuration, egress routes and landmarks cannot be fully rehearsed. ISS crews and visitors do partial walkthroughs on the ground, and sometimes rehearse in orbit. Laptop based VR emergency egress trainers for 3D egress route rehearsal under simulated impaired visibility are also under development (Aoki, et al, 2006).

4. RELATED THEORIES AND EXPERIMENTS

The concluding sections of this chapter review the physiologic and cognitive factors known to influence human perception of the gravitational vertical and surface identity, and the mechanisms of visual reorientation and 3D navigation. Notional models for sensory cue interaction based on ground laboratory experiments of Mittelstaedt, Howard, as well as more recent results from human and animal experiments conducted in parabolic and orbital flight. Taken together, these results account for many of the phenomena described in previous sections. It is argued that astronauts remember landmarks within spacecraft modules relative to a 3D allocentric coordinate frame that in terrestrial life defines a 2D navigation plane and thus the identities of floors, walls, and ceilings. The changes in perceived surface identity that occur during a human VRI are the direct result of a rotation of the astronaut's internal local allocentric frame. If the navigation planes of adjacent spacecraft modules are incongruently aligned, inter-module navigation and spatial judgment abilities are impaired.

4.1 Gravireceptor bias

On Earth, human perceptions of static tilt result from a synthesis of gravireceptor, body axis, and visual cues. Mittelstaedt (1987, 1997) showed that gravireceptor cues originate not only from the vestibular otolith organs in the inner ear, but also from receptors located in the trunk (e.g. kidneys and cardiovascular system). He also noted that when a person lies horizontal, the gravitational component acting along the head and body axis is eliminated. However a residual gravireceptor bias evidently remains in either a head ward or foot ward direction: Subjects with a head ward bias do not feel horizontal in darkness unless their body axis is tilted a few degrees head upward. The bias may originate in the saccular otoliths or in truncal receptors. Mittelstaedt argued that the perceptual effects of the residual gravireceptor bias should also be manifest in orbit. Those astronauts with a head ward bias in 1-G should experience persistent 0-G inversion illusions and be more susceptible to space sickness. Of five astronauts Mittlestaedt tested in 1-G, the two who had head ward biases reported inversion illusions in space. However, 1-G bias did not predict acute inversion illusions in brief parabolic flight (Glassauer and Mittelstaedt, 1992). Also, half of a large control population had a head ward bias, so evidently the 1-G bias over-predicts the incidence of persistent inversion illusions actually reported in orbit with eyes open. Nonetheless, it makes sense that a net gravireceptor bias acting along the body long axis could determine susceptibility to persistent inversion illusions in orbital flight. Perhaps fluid shift effects fully manifest only in orbital flight alters the effective gravireceptor bias from that measured in 1-G (Oman, 2002). The associated sensations of head fullness from fluid shift resemble those from whole body inversion in 1-G. Fluid shift typically begins even before launch, since crew typically sit on the launch pad with feet elevated, sometimes for hours.

4.2 Body Axis and Visual cues

On Earth, if subjects lying horizontal in a dark room are asked to rotate a luminous line to the gravitational vertical, they will set the line tilted about 30 degrees in the direction of their foot to head axis – the well-known Aubert illusion (Aubert, 1861). If the room lights are turned on so the gravitational vertical cue is supplemented by visual vertical and horizontal cues from the room, the Aubert effect is much reduced, but still present. Conversely, if the entire surrounding visual environment is tilted with respect to gravity, subjects feel compelling illusions of self tilt. Witkin et al (1948) showed that when a person sits upright in a darkness and views even a tilted, dimly lit square frame, the perceived vertical is biased away from true gravitational vertical in the direction of the frame axis of symmetry. The magnitude of the effect was shown to be an personal characteristic, and formed the basis of Witkin's well known "Rod-and-Frame" test of visual field dependency.

Mittlestaedt (1983) referred to the tendency for the perceived vertical to align with the body as an "idiotropic" effect, and introduced the idea of using weighted vectors to represent the visual, body axis and gravireceptor cues involved. Young et al (1986) and Parker and Harm (1993) advocated similar models. Subsequent experiments (e.g. Mittelstaedt, 1989; Dyde, et al, 2006) have shown that the magnitude and interaction of the visual and body axis vectors derived from experimental data depends on how the perceived vertical direction is measured. Though vector models provide a conceptually useful way of describing the relevant stimuli, the cue interaction is arguably (Sect 4) mathematically nonlinear and the result of top-down processing.

To investigate cue interaction beyond the 30 degree gravitational tilt angles used by Witkin, Howard and colleagues constructed a small cubic room mounted on a horizontal axle that could be fully tumbled with a human subject inside. The gravitational orientation of the subject could be independently manipulated. The room was furnished with a table, chair, door, and other everyday objects. Howard and Hu (2001) showed that the normal effect of visual cues on gravitationally erect subjects is dramatically enhanced if the subject's body axis is tilted away from the normal gravitationally upright position. For example, if both the subject and the room are both tilted 90 degrees from the gravitational vertical, two thirds of adult subjects will judge they are gravitationally upright.

What properties of the visual scene influence the strength of the visual vector ? Howard and colleagues (Howard and Childerson, 1994, Howard and Hu, 2001, Howard et al, 2005, Jenkin et al 2006) argue that at least five scene properties contribute to perceived tilt:

1. "Intrinsic polarity" cues: Many familiar objects, such as desks, trees, and people are almost always seen in a consistent orientation with respect to gravity. Intrinsically polarized visual objects can strongly influence perceived orientation. Intrinsically polarized objects have identifiable principal axis with one end perceptually the "top" and the other end perceptually the "bottom". Large, readily recognizable environmental surfaces presumably also fall into this class, such as a lawn, water surface - or the earth viewed from orbit. The orientation of the human body – either another person, or a downward glance at one's own torso and legs - also provides a significant intrinsic polarity cue.
2. "Extrinsic polarity cues": Objects that lack intrinsic polarity can acquire polarity by their placement relative to other supporting objects in the scene. Examples include objects hanging or lying on shelves, tapered objects that would fall over unless they were large end "down".
3. Environmental symmetry cues: The walls, ceilings, floors, and large stationary objects present in most scenes define axes of symmetry. Howard (1982) referred to these as "frame" cues to emphasize the correspondence to the luminous frame used in Witkin's experiments.
4. Background location: Polarized objects are more effective when placed in the background rather than the foreground of the visual scene.
5. Field of view: the more polarized objects and surfaces the observer is able to see, the stronger the effect.

Although these five factors are known to influence the magnitude of the visual effect, it is important to note that frame and polarity cues are perceptual, not physical quantities. They depend on the visual attention, expectations and the prior experience of the observer. Ultimately the model for cue interaction is empirical: For a given subject and visual scene, if one manipulates the orientation of the visual scene, body axis, and gravity, it is possible to fit a mathematical model to data and estimate the component visual, body axis and gravitational vectors. However one cannot physically measure scene polarity or symmetry cues, and use it to predict the magnitude of the visual vector.

4.3 Top-down processing and surface identities

In many situations involving ambiguous sensory cues, the resulting perceptions show evidence of “top down” processing. Prior assumptions or equivalently an internal mental model determines what is perceived. For example there are typically multiple axes of symmetry in a visual scene, and which one provides the dominant “frame” cue depends on where the subject expects the vertical to be. Howard and Childerson (1994) placed subjects gravitationally upright inside an unfurnished cubic chamber, and then rolled the chamber about the subject’s visual axis. Presumably the chamber’s surfaces provided only visual symmetry cues. Significantly, these subjects reported a sensation of oscillating tilt, not full rotation as in a fully furnished room. We (Oman and Skwersky, 1997) have repeated these experiments, and noted that subject reports of “oscillating tilt” are linked to a change in the perceived identity of the chamber surfaces. Apparently the subjects assume that the surface nearest their feet and most closely aligned with gravity is a “floor”, the opposite surface is a “ceiling” and the intermediate surfaces are “walls”. However as the “floor” surface rotates away from the horizontal, the wall on the opposite side becomes more horizontal. Eventually, the identity of the surfaces becomes ambiguous. As chamber rotation proceeds, the original “floor” suddenly switches subjective identity and becomes a “wall”, and simultaneously wall on the opposite side becomes the new “floor”. Since the new “floor” is oriented 90 degrees from the previous one, the subject suddenly reports feeling tilted in the opposite direction. As the rotation proceeds, tilt sensation oscillates. The “oscillations” have a paradoxical quality, since there is no concomitant change in vestibular cue. Apparently at the perceptual level the interior surfaces of the chamber are generic visual objects whose perceived wall/ceiling/floor attributes are determined not only by specific polarized objects on them, but also by top-down assumptions as to the expected orientation of the vertical (e.g. gravitationally down and beneath the feet). It is interesting that some subjects tested seated gravitationally erect in Howard’s furnished, highly polarized tumbling room also experience oscillating tilt and not full rotation. Presumably gravity and body axis cues dominate over the rotating polarity cues. Subjects are aware of the paradoxical surface attributes and say “that surface which I can see is actually a ceiling now seems like a floor”. Thus, surface identity seems linked in top-down fashion to an unseen allocentric reference frame, determined by gravitational, body axis, and object polarity cues. The correspondence between their reports and the VRI descriptions of Skylab and Spacelab astronauts is obvious.

The top down linkage between allocentric orientation, perceived tilt, and perceived surface identity has been explored in other experiments. For example, Mast and Oman (2004) showed that if subjects view an ambiguously polarized room (Fig. 5) tilted at 45 degees, top down processing determines perceived object and surface identity and the direction of the perceived vertical in the scene, and this in turn influences even low level visual processing, such as the horizontal-vertical line-length illusion.

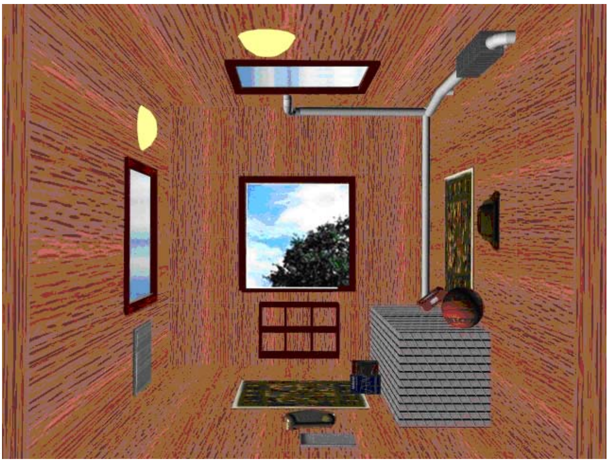

Figure ***Error! No text of specified style in document.**-5.* Room with ambiguous frame and polarity cues (Mast and Oman, 2004). View the figure upright and rotated 90 deg. clockwise. Which surface seems to be the floor ?

4.4 Human visual orientation experiments in orbit

On several missions early in the Shuttle era, our laboratory (Young, et al 1986) studied how the absence of gravity and footward force applied with bungee cords influenced illusory rolling sensations induced with a rotating dot display. In weightlessness, crews gave greater weight to visual flow and haptic cues. However the response varied between subjects, suggesting crew differed in "perceptual styles. Parker and Harm (1993) summarized comments from several other Shuttle astronauts, and concluded that some astronauts apparently increased the weight given to static visual cues, while others apparently became more idiotropic. During the 1998 "Neurolab" Shuttle mission, (Oman, et al, 2003) we studied VRI and motion illusion susceptibility, visual vs. idiotropic tendencies and the interdependency of self-orientation and visual shape perception among four astronauts, who wore a head- mounted display (Fig. 6). We tested the crew on several occasions preflight and postflight and on the third or fourth day of the mission. None of our subjects reported persistent inversion illusions during testing in flight.

In one experiment, our subjects indicated the direction of subjective "down" while viewing a virtual spacecraft interior tilted with respect to their body by an angle that varied randomly over successive trials. Responses were classified as aligned with scene architectural visual axes, body (idiotropic) axes, or other.

Figure ***Error! No text of specified style in document.****-6.* 1998 Neurolab Shuttle mission experiments on individual differences in visual orientation and shape perception. (Oman et al, 2003). The head mounted display provided controlled visual stimuli in the otherwise cluttered and busy laboratory.

Most all the inflight responses were closely aligned to either the visual scene or idiotropic axes. Comparing an average measure of visual vs. idiotropic dependency across mission phases (Fig. 7), we saw clear differences between subjects consistent with the notion of individual perceptual styles. Those astronauts who were strongly visually dependent or independent prior to flight remained so in orbit. Three of the subjects (A,B &C) were visually independent preflight. One (A) became more visually dependent inflight, showing greater orienting response to scene polarity, and then reverted postflight indicating an adaptive response. However the other two remained idiotropic when tested inflight – consistent with the high incidence of VRIs under operational conditions in orbit. For practical reasons we could not measure VRI susceptibility to real scenes under operational conditions to compare with our data, nor was the mission long enough to determine whether VRI susceptibility (real or virtual) decreases in orbit eventually. Perhaps one day these answers can be obtained aboard ISS.

In a second experiment, three of four subjects who viewed rotating polarized or dotted scenes while free floating experienced stronger roll motion illusion than on the ground, confirming Young et al's earlier finding. When the scene motion corresponded to virtual motion down a long hallway, perception of linear self motion increased dramatically. Other experiments (Young, et al 1996; Liu et al 2002) in parabolic flight have shown that the linear and angular motion illusion enhancement happens immediately upon entry into 0-G. It may be that 0-G more immediately and consistently enhances the perceptual weight given to visual flow cues as opposed to static frame and polarity cues. This phenomenon could also explain the enhanced sensation of orbital motion occasionally described by EVA astronauts, and the persistence of VRI reports on long duration missions.

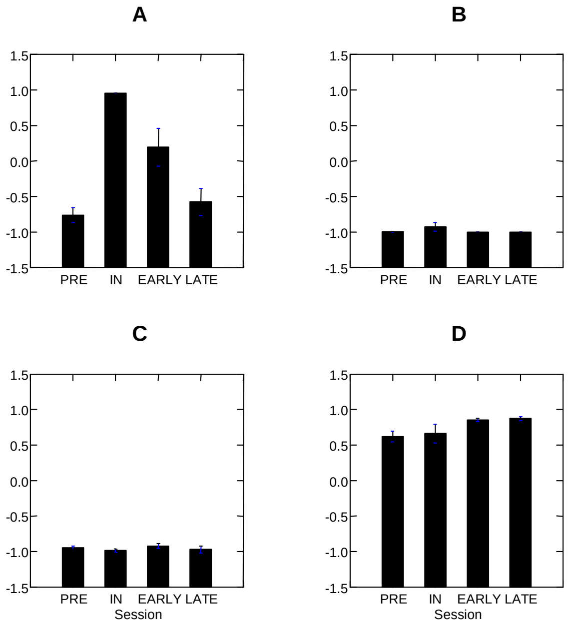

Figure ***Error! No text of specified style in document.**-7.* Visual-idiotropic dependency coefficient for Neurolab subjects A-D by mission phase (pre=preflight, in=idays 3-4 in orbit, early= first 3 postflight days, late=postflight days 4-5. A value of +1 indicates strong visual dependence, and -1 indicates strong idiotropic dependence. See Oman, et al (2003) for details.

In a third experiment, when our subjects viewed a physically flat but gradient shaded disk, three out of four experienced a change in illusory disk convexity after cognitively initiating a VRI so perceived self orientation changed from floating perpendicular to parallel to the deck. That such a change in perceived object convexity occurred after a VRI would be expected, since as every art student knows, perceived convexity/concavity of surfaces is known to be based on a "light comes from above" assumption. The result demonstrated the interdependency of shading interpretation and self-orientation perception, even in weightlessness.

4.5 Visual reorientation, mental rotation and perspective taking

Visual reorientation mechanisms allow people to recover their sense of location and direction after becoming momentarily disoriented, both in normal terrestrial environment (Wang and Spelke, 2002), in orbital flight, and in desktop virtual reality experiments and games, where vesibular cues confirming visual motion are missing. In order to reorient or remain oriented while free floating within a spacecraft cabin, astronauts must be able to recognize visual landmarks from an arbitrary relative orientation. Hence spatial orientation in 0-G likely depends on individual ability to recognize individual 3D objects after rotation (Shepard and Metzler, 1971) and to correctly mentally visualize the appearance of an object array after an imagined change in location or viewing direction (Huttenlocher and Presson, 1979). Individual 3D mental rotation and imaginary perspective taking abilities are experimentally distinguishable personal characteristics (Kozhevnikov and Hegarty, 2001). In mental rotation tests, error rates and response times increase with visual rotation angle. Mental rotation abilities of the genders overlap, but on average men perform better. Among women, spatial abilities vary across the menstrual cycle (Hausmann, et al 2000). There is no public data on individual differences among astronauts, but among MIT graduate students, we routinely see large inter-individual variability in these skills. Leone, et al (1995) tested the 3D mental rotation performance of five Mir cosmonauts, and showed that individual abilities are unchanged in weightlessness as compared to on the ground. Imaginary perspective taking ability has not yet been tested in orbit. However in ground experiments, Creem et al (2001) showed that self-rotations are more easily imagined about the body axis, perhaps because in our upright terrestrial lives, most imagined rotations take place about that axis. They also demonstrated that the subject's orientation to gravity has little effect on imaginary perspective taking.

We tested the abilities of several large subject groups to visualize the direction to objects inside a simulated space station node after large changes in relative viewing angle (Oman et al; 2002, Richards et al 2003; Shebilske, et al, 2006). We consistently found that performance correlated with several well known tests of 2D and 3D mental rotation abilities. Most subjects said that they memorized the environment from a prototypical orientation. Many invented rules to help them mentally reconstruct the space, such as memorizing opposite or adjacent pairs of objects. As with many spatial tasks, performance improved with practice. Most – but not all – eventually performed adequately. Manipulation of the subject's orientation to gravity had little effect on performance, nor did it in Creem's experiments Most subjects described the mental rotation/visualization task as "something done in your head". Collectively these findings suggest that 3D orientation ability in weightlessness probably varies between subjects, even among the highly select astronaut population, but should improve with experience and training, particularly if people are taught strategies for choosing and remembering appropriate landmarks. Validated tests of 3D mental rotation and perspective taking abilities may be helpful in identifying particularly vulnerable individuals, and in customizing their training.

4.6 3D Navigation

Wang and Spelke (2002) argue that both humans and many animals navigate - keep track of their orientation and position - via similar fundamental neural mechanisms supporting reorientation, place recognition, path integration, and cognitive map formation. Most experimental studies have focused on terrestrial navigation in a 2D horizontal plane. Path integration involves continuous updating of position and orientation relative to a starting point using vestibular and motoric cues, and without reference to fixed environmental landmarks. When people encounter a novel environment, they first identify landmarks and associate individual landmarks with specific actions, such as turning left or right, and eventually learn a sequence of landmarks and actions as a route (Siegel and White, 1975). Route knowledge consists of declarative topologic rules that becomes automatic with practice. Most older children and adults recognize common landmarks on interconnected routes and develop an ability to take shortcuts, to point to unseen landmarks, and even do so from a different, imagined location. This kind of ability requires configurational environmental knowledge is frequently described as a "cognitive map" (e.g. Tolman, 1948), though this not meant to imply a person actually has a mental image of a cartographic map. The physiological basis of cognitive maps and how they are acquired is the subject of debate (e.g. Wang and Spelke, 2000; 2002). There is evidence (e.g. Sadalla, et al, 1980; Colle and Reid, 1998) that configurational knowledge is hierarchical. Local objects are coded relative to room landmarks, which in turn are coded relative to buildings, and so on up to larger geographic scales. Even local room scale spatial mental models are based on conceptions rather than perceptions, and people imagine local object locations using a spatial framework employing both salient environmental axes and their body axes to establish referent categorical directions. Most adults employ a mix of landmark, route, and cognitive map based navigation strategies, often resorting to landmark and route techniques when unsure of their orientation, or simply out of convenience. Particularly when disoriented, astronauts apparently do the same.

The ability of astronauts to physically perform actual physical three dimensional wayfinding/navigation tasks has not yet been tested in orbit. However performance in simulated navigation tasks in 3D mazes has been tested in several non-immersive virtual reality experiments conducted on the ground (Aoki et al, 2003; 2005; Vidal, et al, 2004) and also in 3 cosmonauts aboard the International Space Station (Vidal et al, 2003). Though the Aoki and Vidal maze architectures and methods differed in details, all routes required a succession of 90 degree turns in various directions through a virtual maze. Both sets of experiments showed that subjects generally had difficulty building a correct mental representation of their path whenever the path required a body rotation other than in yaw (azimuth). There was no major difference between Vidal's ground and orbital flight results. Practice generally improved performance, particularly with the complex configurations. Vidal et al (2004) concluded that "although humans can memorize 3D-structured environments, their innate neurocognitive functions appear to be specialized for natural 2D navigation about a gravitationally upright body axis Aoki, et al (2003) explained explained their results by assuming that whenever their subjects made a pitch rotation, they "did not recognize the rotation of their frame of reference". Although Vidal and Aoki did not specifically ask their subjects about changes in subjective surface identity, or explain their results in terms of VRIs, one can account for both by assuming that whenever subjects made a 90 degree turn in pitch or roll, and entered the next maze segment, they experienced a VRI, and as result failed to correctly rotate their unseen allocentric navigational reference frame as a result of scene movement. Subjects may be able to reconstruct their orientation and position relative to a global allocentric frame by remembering the direction of successive turns, but this requires a series of mental rotations that likely becomes increasingly prone to error as the number of turns increases. Unfortunately, (Sect 2.1) it is usually impractical to design spacecraft with globally congruent visual verticals, or hatches large enough so astronauts can avoid pitches resulting VRIs when transiting through them.

In virtual reality based 3D orientation training experiments (Richards, et al 2003; Benveniste, 2004; Oman, et al 2006) subjects responded fastest when module interiors were presented in a visually upright orientation and looking in a specific direction. This suggests that subjects remember each module's landmark arrangement from a canonical viewpoint that establishes a local reference frame. When modules were attached to each other with local reference frames incongruently oriented, and the subjects had to make spatial judgments between them, they required several seconds longer, suggesting subjects mentally interrelated the two modules though some kind of 3D mental rotation process. If Mir and ISS crews had to perform complex mental rotations to interrelate module interiors, this may explain why they found it so difficult to maintain their allocentric orientation relative to the entire station. When first learning the actual flight configuration in orbit, if they experienced an unrecognized VRI when transiting between modules, their sense of direction would be mis-oriented relative to the larger coordinate frame of the station. Their mental cognitive map of the station interior would then be incomplete or erroneous, as in the case of the Mir astronaut who felt he was living in a single story house (Sect. 3). In terrestrial situations, miscoding of the orientation of a local cognitive map with respect to a larger scale one can create "wrong door" disorientation in room scale environments (Lackner and DiZio, 1998), and "direction vertigo" on building and city scales. Once learned, such miscoding can be difficult to unlearn (Jonsson, 2002). Therefore it may be important to teach astronauts the actual flight configuration of their spacecraft interiors very early in the ground training process. Preflight virtual reality training where astronauts learn the allocentric relationships between visually incongruent spacecraft modules – for example using "see through" walls or miniature 3D models of the station interior and exterior (e.g. Marquez, et al 2002) - and where they learn rules relating specific adjacent/opposite landmark pairs both within and between modules should be a useful 0-G disorientation countermeasure.

4.7 Animal experiments in 0-G

Does the CNS actually maintain an internal allocentric coordinate frame in weightlessness that establishes a "floor"-like navigation plane ? Over the past two decades, the neural basis of spatial memory in humans and animals has become better understood based on electrophysiological studies in animals, and functional neuroimaging in humans. Portions of the limbic system, including the hippocampus, post-subiculum, thalamic nuclei, and entorhinal cortex function together to interrelate various external (e.g. visual) and internal (e.g. vestibular and haptic) sensory cues and determine place and direction relative to the environment. Wiener and Taube (2005) provide a comprehensive review. One type, "head direction" cells (Taube, 1998), are found in several limbic areas and consistently discharge as a function of a rat's head direction in the spatial plane the animal is walking in, independent of place or head pitch or roll up to 90 degrees. The direction of maximum response ("preferred direction") varies from cell to cell. The range of firing is typically about 90 degrees. The preferred directions of the entire ensemble of cells reorient in unison when distant visual landmarks in the room are rotated about the animal. Comparable cells have also been found in primate. Head direction cells in turn provide the essential azimuthal reference input to at least two other classes of limbic cells: "grid cells" (Hafting, et al, 2005) and "place cells" (Best et al, 2001) that ensemble code various attributes of the rat's location- also in the two dimensional plane of the animal's locomotion. (It is important to note that though these particular cell classes respond in a 2D plane, the animals show 3D orienting behavior. Presumably there are other as-yet-undiscovered limbic cell classes that code other orientation or place attributes in third dimension defined by the orientation of this 2D locomotion plane - e.g. height, elevation angle or roll angle).

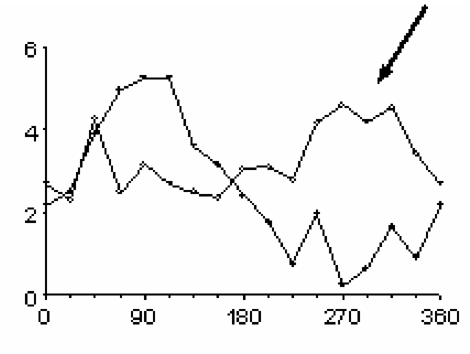

*Figure **Error! No text of specified style in document.**-8.* Rat head direction cell directional tuning curves on cage ceiling and floor during 0-G parabolic flight. Data recorded on ceiling indicated with arrow. (Taube, et al, 2004)

A critical question is the extent to which gravity anchors the orientation of the response plane of these cell classes. In 1-G laboratory experiments, head direction cells usually maintain directional tuning when the animal climbs a vertical wall, but if the rat crawls inverted across a gridded ceiling, many cells show reduced directional tuning, or lose it entirely (Calton and Taube, 2005). In parabolic flight experiments, we monitored rat head direction cell responses while animals in a visually up-down symmetrical cage successively experienced 1G, 0G and 1.8G (Taube, et al, 2004). Allocentric directional tuning was maintained in 0-G while the animal crawled on the familiar floor of the cage, despite the absence of gravity. When we manually transferred the rat to the ceiling in 0-G, most cells lost directional tuning, and statistically showed an increase in overall background firing level, which could reflect an instability in orientation perception. We predicted that if the rat occasionally experienced a VRI and adopted the ceiling rather than the floor as the navigation reference plane, but continued to use a primary visual landmark to determine azimuth, the preferred firing direction should flip across the visual axis of symmetry of the cage. Bursts of firing in other than the original preferred direction occurred on the ceiling in several animals, and in some animals were 2-3 times more frequent in the expected ceiling-preferred directions than in the original floor-preferred directions. Fig. 8 shows the ceiling and floor tuning curves for one such cell, which shifted through about 180 deg in azimuth. Such shifts in azimuth may correspond to the common human perception during a 180 degree VRI that one is in a familiar but somehow mirror-reversed place, since objects remembered on the left are now to be found on the right.

In a related experiment conducted in on the Neurolab Shuttle mission, Knierim, et al (2000; 2003) recorded place cell activity as trained rats walked across three surfaces defining the corner of a cage. Their path required a yawing 90 degree turn while on each surface, followed by a pitching 90 degree turn to move onto the next surface. After a total of 3 yaws and 3 pitches, they returned to the original starting point. The investigators' original hypothesis was that in 0-G only the yaw rotations would be taken into account, and the animal would have to yaw 360 deg. and traverse four successive surfaces to do it before the same place cell would fire again. However, when tested on the fourth flight day, one animal's place cells responded in only a single area of the 6 turn track, suggesting this animal had incorporated the pitch rotations, and was maintaining a 3D allocentric sense of place within the cage. In the other two animals, place cell fields were abnormal, with one of them exhibiting symmetric firing fields on each successive surface. We suggested that this would fully be expected if the animal experienced the equivalent of human VRIs: After each pitch back, the view of the track ahead was virtually identical on each surface, so they might have the illusion of traversing the same one turn segment of the track three times in succession. The third animal did not exhibit consistent place fields – which might be expected if it was disoriented, and simply following the track using a route strategy. However when tested after five more days in weightlessness, the place fields of the second and third animals appeared unimodal, suggesting they had learned to orient to the entire cage, rather than successive locomotion surfaces.

Taken together, these experiments show that even in the physical absence of gravity, limbic head direction and place cells in animals responses define a two dimensional navigation plane parallel to the "floor" of the animal's environment. In 0-G if the animals crawl or are placed on adjacent or opposite surfaces, direction and place tuning can disappear or change in ways suggesting the navigation plane has reoriented into alignment with the adjacent or opposite surface. We cannot ask animals their perceptions of surface identities, but the neural behavior of their limbic navigation plane in 0-G does correspond to that posited for humans, based on the character of 0-G disorientation and VRIs.

So far head direction and place cell responses have been characterized only in terrestrial animals. It is interesting to speculate about what we will ultimately find in other vertebrate species. Birds, marine mammals and cartilaginous fish rely on dynamic lift to oppose gravity, and usually fly/swim upright. Most bony fish have gas bladders which ballast them upright. Certain species – notably the marine mammals – apparently have the ability to remain allocentrically oriented while performing multiple graceful rotations about axes perpendicular to gravity, yet it is ecologically important for them to remain allocentrically oriented with respect to the ocean surface or bottom. Do marine mammals have a more robust ability than rodents and humans apparently do to maintain allocentric orientation when gravitationally inverted or in weightlessness ? To what extent can vertebrate limbic neural networks reorganize during life to respond to new environmental challenges ?

4.8 Sensory integration in weightlessness

The theories and experiments reviewed in Sects 4.1-4.7 account for many of the perceptual phenomena described Sections 1-3.. As detailed in Oman (2003), one can formally combine Mittelstaedt's original notions of gravireceptor bias and body axis (idiotropic) cues with Howard's concepts for visual frame and polarity cues into a model for sensory cue interaction. However, several new assumptions are required. One is that the net gravireceptor bias may be different than that measured in 1-G. The second - and more important – assumption is that though sensory cues can be represented by vectors, their resultant is not simply a mathematical vector sum. Rather, they are interpreted in nonlinear, top down fashion based on visual attention and the assumed orientation of an internal 3D coordinate frame that codes the remembered location of local cabin landmarks, and that assigns corresponding surface identities. When an astronaut floats visually upright in a familiar cabin, the internal mental coordinate frame is properly anchored, surface identities are correctly perceived, and objects are in remembered locations. However, if the visual scene has multiple axes of visual symmetry and/or polarized objects have inconsistent visual orientations, as shown in the Figure 9 example, the perceived orientation and surface identity is multistable and depends on body orientation and visual attention. The internal mental coordinate frame can alternate between a veridical orientation, and one that does not correspond with reality. When it does, the astronaut notes a change in perceived cabin surface identity, the hallmark of a VRI. Frequently VRIs are triggered when the astronaut looks at his own legs, since their intrinsic visual polarity is aligned with the body axis rather than environmental polarities.

Figure ***Error! No text of specified style in document.****-9.* VRI in the ISS US Laboratory module. The equipment and labeling on the true floor and ceiling are oriented 90 degrees counterclockwise from those on the true walls and floor. The square cross section of the module means the major physical axes of symmetry are also 90 degrees apart. When a crewmember floats in this body orientation, which surface is perceived as a floor depends on visual attention. VRIs due to such ambiguities can only be prevented by attending to learned landmarks.

To the extent that object polarities result from prior terrestrial experience in an upright body orientation, experience viewing an environment from multiple body orientations may eventually reduce polarity effects. One of the goals of preflight virtual reality based training is to accelerate this process. However the continuing occasional susceptibility of long duration astronauts to VRIs suggests that certain types of polarity are innate, and that the disorienting body axis orientation effect does not disappear entirely.

If asked to indicate the direction of “up” or “down”, most astronauts will point perpendicular to the perceived floor. “I take my down with me, and it attaches to whatever surface seems beneath me”. A few with very strong idiotropic tendencies may report “down” seems aligned with their head to foot axis, even though paradoxically if they change their body orientation, they never feel that they are stationary and the spacecraft is rotating around them.

When VRIs occur, the internal mental coordinate frame aligns with local axes of the spacecraft cabin interior. In contrast, during inversion illusions or an episode of EVA height vertigo, the internal mental reference frame jumps beyond the spacecraft. The latter two are the only situations in which astronauts describe strong “gravitational vertical” perceptions. EVA height vertigo occurs when crew have a wide view of the Earth in their lower visual field, and extrinsic visual polarity and haptic cues are consistent with supported by/hanging from the spacecraft. The external reference frame jumps “down” to the Earth, and suddenly there is a strong perception of height. Inversion illusions are likely when strong head ward gravireceptor bias cues (perhaps from fluid shift during the first several days of flight) are strong enough to overcome environmental visual polarity and foot ward body axis cues regardless of relative body orientation. In this situation, the only sensory interpretation possible is that there must be an unseen gravitational coordinate frame, far beyond spacecraft cabin and aligned so “down” is always in the foot-to-head direction. Hence when floating upside down in the cabin, they feel gravitationally inverted. When visually upright, they feel upright but the entire spacecraft seems gravitationally upside down.

How people mentally represent physical space is often determined by conceptions, not direct perceptions (Tversky, 2003). On Earth our spatial knowledge of the layout a familiar building is generally derived by concatenation of our spatial knowledge of the layout of the individual rooms, and we cannot see through the walls. This process is relatively effortless, since all the “floors” lie in the same plane. Most people can point in the direction of the front door of a building regardless of what room they are in. Unfortunately, for engineering reasons, all spacecraft from Apollo to ISS have required crews to work in areas with incongruently aligned coordinate frames. Anecdotal reports from astronauts and evidence from virtual reality simulations (e.g. Aoki; Vidal, Benveniste) suggests that crews have great difficulty concatenating their knowledge of incongruently aligned local coordinate frames, and often cannot correctly point in the direction of unseen landmarks in distant modules, such as the emergency exit. Crews probably have difficulty maintaining a spacecraft-fixed rather than local-module fixed internal coordinate frame, since the latter are more useful when working in individual modules. This way, labels appear upright, and objects are in remembered places. When transiting between modules, crews usually deliberately initiate a VRI and work in the local coordinate frame. Another goal of virtual reality based preflight orientation training is to teach crewmembers the relationships between important landmarks in different modules relative to a single spacecraft-fixed allocentric navigation frame.

Will astronauts who live in weightlessness for years eventually lose their susceptibility to VRIs, inversion illusions and height vertigo, and be able to interrelate the reference frames of adjacent modules or work areas, regardless of orientation ? When the first human children ultimately are born and mature in weightlessness, will their spatial abilities and neural coding be fundamentally different than ours ? Or will they – like today's astronauts – still show evidence of their terrestrial evolutionary heritage ?

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REFERENCES

Aoki, H., Ohno, R., and Yamaguchi, T. 2003, A study of spatial orientation in a virtual weightless environment. Part 2 Causes of spatial cognition errors. *Journal of Architecture, Planning, and Environmental Engineering*, **563**:85-92

Aoki, H., Ohno, R., Yamaguchi, T. 2005. The effect of the configuration and the interior design of a virtual weightless space station on numan spatial orientation. *Acta Astronautica* **56**, 1005-1016.

Aubert, H. 1861. Eine scheinbare Drehung von Objekten be Neigung des Kopfes nach rechts oder links. Vrirchows Archiven **20**:381-393

Benveniste, D. 2004. Cognitive conflict in learning three-dimenaional space station structures. SM Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, September, 2004

Best, P.J., White, A.M., and Minai, A. 2001. Spatial processing in the brain: the activity of hippocampal place cells. *Annu. Rev. Neurosci*. **24**:459-86

Brandt, T., Arnold F, Bles, W. and Kapteyn T.S. 1980 The mechanism of physiological height vertigo I: Theoretical approach and psychophysics. *Acta Otolaryngologica* **89**:534-40.

Burrough, B. 1998 *Dragonfly: NASA and the crisis aboard the MIR*, Harper Collins, New York

Calton, J.L. and Taube, J.S. 2005 Degradation of head direction cell activity during inverted locomotion. *Journal of Neuroscience* **25**:2420-2428

Cooper, H.S.F. Jr. , 1976 *A House In Space*, Holt, Rinehhart and Winston, 184 pp.

Coss R.G., Clearwater Y.A., Barbour C.G., and Towers S.R.. 1989 Functional décor in the International Space Station: body orientation and picture perception. NASA TM 102242, November, 1989

Cheung, B. 2004, Nonvisual illusions in flight. in: *Spatial Disorientation in Aviation*, FH Previc and WR Ercoline, eds. Volume 203, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, pp. 243-281.

Colle H. A. and Reid G. B. 1998. The Room Effect: metric spatial knowledge of local and separated regions. *Presence*. **7**:116-128.

Creem, S.H., Wraga, M, Proffitt, D.R. 2001 Imagining physically impossible self-rotations: geometry is more important than gravity. *Cognition* **81**:41-64

Dyde, R., Jenkin, M.R. and Harris L.R. 2006. The subjective visual vertical and the perceptual upright. *Exp. Brain Res*. In press.

Gazenko O (1964) *Medical studies on the cosmic spacecraft Vostok and Voskhod*. NASA TTF-9207

Glasauer, S. and Mittelstaedt, H. 1992 Determinants of orientation in microgravity. *Acta Astronautica* **27**:1-9.

Graybiel, A. and R. S. Kellogg, 1967. Inversion illusion in parabolic flight: its probable dependence on otolith function. *Aviat., Space and Env. Med.* **38**(11): 1099-1013.

Gurovskiy, N. N. Kosmolinskiy, F.P., and Melnikov, L.N, 1980. *Designing the Living and Working Conditions of Cosmonauts*. Moscow, Mashinstroyeniye.

Hafting, T. Fyhn, M., Molden, S. Moser, M.B. and Moser E.I. 2005. Microstructure of a spatial map in the entrohinal cortex. *Nature* **436**:801-806

Hausman, M, Slabbekoorn, D, Van Goozen, S., Cohen-Kettenis, P. and Gunturkun, O. 2000. Sex horomones affect spatial abilities during the menstrual cycle. Behavioral Neuroscience **114**:1245-1250.

Homan, D. 2001, NASA Johnson Space Center VR Laboratory DOUG software, personal communication

Howard, I. P., 1982. *Human Visual Orientation*. Toronto, Wiley.

Howard, I.P. and Childerson, L. 1994, The contribution of motion, the visual frame and visual polarity to sensations of body tilt. *Perception*, **23**:753-762.

Howard, I.P. and Hu, G. 2001, Visually induced reorientation illusions. *Perception*, **30**:583-600.

Howard,, I.P., Hu, G., Saxe, R. and Zacher J.E. (2005) Visual orientation in a mirror world tilted 90 degrees. *Perception* **34**:7-15

Huttenlocher J and Presson, C. 1979, The coding and transformation of spatial information. *Cognitive Psychology*, **11**:375-394.

Jenkin, H.L., Zacher, J.E., Oman, C.M. and Harris L.R. 2006. Effct of field of view on a visual reorientation illusion: does the levitation illusion depend on the view seen or the scene viewed ? (Abstract) 7th Symposium on the Role of the Vestibular Organs in Space Exploration, Noordwijk, the Netherlands, June 8, 2006

Johnston, R.S. and Deitlein, L.F. 1977 *Biomedical Results from Skylab* NASA SP-377, US Government Printing Ofiice, Washington DC

Jonsson E. , 2002. *Inner Navigation: Why we get lost and how we find our way*. Scribner, New York.

Kitmacher, G.H., 2002, Design of the Space Station habitable modules. 53rd International Astronautical Congress. 10-19 Oct, 2002. Houston, TX. Paper IAC-02-IAA.8.2.04. http://www.spacearchitect.org/pubs/IAC-02-IAA.8.2.04.pdf

Knierim, J.J., McNaughton, B.L. and Poe, G.R. 2000. Three –dimensional spatial selectivity of hippocampal neurons during space flight. Nature Neuroscience **3**:209-210.

Knierim, J.J., Poe, G.R., and McNaughton, B.L. 2003. Ensemble neural coding of place in zero-g. In: *The Neurolab Spacelab Mission: Neuroscience Research in Space: Results* *from the STS-90 Neurolab Spacelab Mission*. J.C. Buckey, Jr. and J.L. Homick, Eds. NASA SP-2003-535. p.63-68.

Kornilova, L.N. 1997 Orientation illusions in spaceflight. *J. Vestibular Research*, **7**:429-439

Kornilova LN, Muller Kh and Chernobylskiy LM, 1995 Phenomenology of Illusory Reactions in Weightlessness. *Fiziologii Cheloveka*, 21:50-62

Kozhevnikov, M. and Hegarty, M. 2001. A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory and Cognition*, **29**(5):745-756.

Lackner, J.R., 1992 Spatial orientation in weightlessness. *Perception* **21**:803-812.

Lackner J.R. and Graybiel, A, 1983 Perceived orientation in free-fall depends on visual, postural, and architectural factors. *Aviat. Space. Env. Med.* **54**(1):47-51

Lackner J. R. and DiZio P., 1998 Spatial Orientation as a Component of Presence: Insights Gained from Nonterrestrial Environments. *Presence*. **7**:108-115.

Leone, G., Lipshits, M., Gurfinkel, V. and Berthoz, A. 1995. Is there an effect of weightlessness on mental rotation of three-dimensional objects ? *Cognitive Brain Research* **2**:255-267.

Linenger, J. 2000, *Off the Planet*. McGraw Hill, New York

Liu A, Duda K, Oman C, Natapoff A. 2002 Effects of parabolic flight zero-gravity on looming linear vection.. Journal of Vestibular Research **11**(3-5): 325

Lu, E , 2005 Ed Lu's Journal Entry #12: Which Way is Up ? NASA Johnson Space Center press release, Sept. 2003. http://www.edlu.com/whichWay.pdf

Marquez JJ, Oman CM, Liu AM, Beall AC 2002 Spacecraft in miniature: a tool for the acquisition of mental representations of large environments. Journal of Vestibular Research **11**(3-5): 338

Mast, F.W. and Oman, C.M. 2004, Top-down processing and visual reorientation illusions in a virtual reality environment. *Swiss Journal of Psychology* **63**(3):143-149

Mittelstaedt, H., 1983, A new solution to the problem of the subjective vertical. *Naturwissenschaften* **70**:272-281

Mittelstaedt, H., 1987 Inflight and postflight results on the causation of inversion illusions and space sickness. Proc. Norderney Symposium on the Scientific Results of the German Spacelab Mission D-1. Norderney, Germany, 27-29 August, 1986. P.R. Sahm, R. Jansen, and H.M. Keller HM Eds. German Ministry of Research and Technology, Bonn, Germany.

Mittelstaedt, H. 1989. Interactions of form and orientation. In: *Spatial Displays and Spatial Instruments*, Ellis, S.R. and Kaiser, M.K., eds. NASA Conference Publication 10032. p.42.1-42.14

Mittelstaedt, H, 1996, Somatic gravireception. *Biological Psychology* **42**:53-74

Mukai, C. and Igarashi, M. 1995, Microgravity and space motion sickness. *Journal of Otolaryngology, Head and Neck Surgery* **11**(7):967-972

NASA, 1995, Man-Systems Integration Standards (MSIS). NASA Johnson Space Center Bioastronautics/Habitability and Human Factors Office.

NASA Space Station Program Office, 1999 Flight Crew Integration Design Requirements SSP 50005, NASA Johnson Space Center, Houston TX.

Oman, C.M. 2003 Human visual orientation in weightlessness. In: *Levels of Perception*, L. Harris and M. Jenkin, Eds. Springer-Verlag, New York. P. 375-398

Oman, C. M. 1987. The role of static visual orientation cues in the etiology of space motion sickness. *Proceedings of the Symposium on Vestibular Organs and Altered Force Environment*., Houston, TX, October, 1987, honoring A. Graybiel. ed: M. Igarashi. NASA/Space Biomedical Research Institute. p.25-37

Oman CM, Benveniste D, Buckland DA, Aoki H, Liu A, and Natapoff A. 2006 Spacecraft Module Visual Verticals And Training Affect Spatial Task Performance. *Habitation* **10**(3/4):202-203

Oman, C.M. and Skwersky, A, 1997. Effect of scene polarity and head orientation on illusions in a tumbling virtual environment." Aviat, Space Env. Med **68**:(7): 649

Oman, C.M., Howard, I.P., Smith T., Beall, A.C., Natapoff, A., Zacher, J.E., and Jenkin H.L. 2003. The role of visual cues in microgravity spatial orientation. In: *The Neurolab Spacelab Mission: Neuroscience Research in Space*: Results from the STS-90 Neurolab Spacelab Mission. J.C. Buckey, Jr. and J.L. Homick, Eds. NASA SP-2003-535. p. 69-82.

Oman, C. M., B. K. Lichtenberg, and Money, K.E. 1984. Symptoms and signs of space motion sickness on Spacelab-1. NATO-AGARD Aerospace Medical Panel Symposium on Motion Sickness: Mechanisms, Prediction, Prevention and Treatment, Williamsburg, Va, NATO AGARD CP-372. Later published as:

Oman, C. M., B. K. Lichtenberg, and Money, K.E. 1990. Symptoms and signs of space motion sickness on Spacelab-1. *Motion and Space Sickness*. G. H. Crampton, ed.. Boca Raton, FL, CRC Press. p.217-246.

Oman C.M, Lichtenberg B.K, Money K.E, McCoy R.K 1986 M.I.T./Canadian vestibular experiments on the Spacelab-1 mission: 4. Space motion sickness: symptoms, stimuli, and predictability. *Exp Brain Res* **64**: 316-334.

Oman, C.M., Shebilske, W.L., Richards, J.T. Tubre, T.C., Beall, A.C. and Natapoff, A. 2002. Three dimensional spatial memory and learning in real and virtual environments. *Spatial Cognition and Computation* **2**:355-372.

Parker, D.E. and Harm, D.L. 1993, Perceived self-orientation and self-motion in microgravity, after landing and during preflight adaptation training. *J. Vestib. Res.* **3**:297-305

Reschke M.F., Bloomberg J.J., Paloski W.H., Harm D.L., and Parker D.E., 1994a Physiologic adaptation to space flight - neurophysiologic aspects: sensory and motor function. In: *Space Physiology and Medicine*, eds. A. E. Niccogossian, C.L. Huntoon, and S.L. Pool, 3rd ed, Lea and Febiger. pp. 261-285.

Reschke M.F., Harm D.L.,Parker D.E., Sandoz, G.R., Homick, J.L. and Vanderploeg, J.M. 1994b Physiologic adaptation to space flight - neurophysiologic aspects: Space Motion Sickness. Chapt. 12 in: *Space Physiology and Medicine*, eds. A. E. Niccogossian, C.L. Huntoon, and S.L. Pool, 3rd ed, Lea and Febiger. pp. 228-255.

Richards, J.T., Oman, C.M., Shebilske, W.L., Beall, A.C., Liu, A.M., and Natapoff, A. 2003. Training, transfer, and retention of three-dimensional spatial memory in virtual environments. *Journal of Vestibular Research* **12**(5/6) 223-238

Schmitt H.H. and Reid D.J. 1985, Anecdotal information on space adaptation syndrome. University Space Research Association Division of Space Biomedicine, Houston, TX Report, July 1985.

Tversky, B. 2003. Structures of mental spaces: how people think about space. *Environment and Behavior.* 35: **1**:66-80

Walz, C. (2002) Expedition Four: Spacewalking, ISS Style, http://www.spaceflight.nasa.gov/station/crew/exp4/eva/spacewalking.html

Sadalla E. K., Burroughs W. J., and Staplin L. J. 1980. Reference points in spatial cognition. Journal of Experimental Psychology: Human Learning and Memory. 6:516-525.

Shebilske, W.L., Tubre, T, Tubre A.H., Oman, C.M., Richards, J.T. 2006 Three-dimensional spatial skill training in a simulated space station: random vs. blocked designs. Aviation, Space and Environmental Medicine (in press)

Shepart, S. and Metzler, D. 1971 Mental rotation of three dimensional objects. *Science* 171:701-703.

Siegel, A. W. and White, S.H. 1975. The development of spatial representations of large-scale environments. *Advances in child development and behaviour*. H. W. Reese. New York, Academic Press. 10: 9-55.

Smart K, Bowen C. Carr D., and Novak J. 2001 ISS emergency egress- a system for crewmember pathway indication. SAE Technical Paper 2001-01-2184, 31st International Conference on Environmental Systems, Orlando, FL. July 9, 2000.

Taube J.S. 1998, Head direction cells and the neurophysiological basis for a sense of direction. *Prog Neurobiol* **55**:225-256.

Taube, J.S., Stackman, R.W., Calton, J.L., and Oman, C.M. 2004. Rat head direction cell responses in zero-gravity parabolic flight, *J. Neurophysiol*. **92**:2887-2997

Tolman, E.C., 1948, *Cognitive Maps in Rats and Men*. Psychol. Rev. 55, 189-208

Titov, G and Caidin M. 1962 *I am Eagle !* Bobs-Merrill.

Viguier, C. (1882) Le sense de l'orientation et ses organs chez les animaux et chez l'homme. Revue Philosophique **14**:1-36.

Wang, R.F. and Spelke, E.S. 2002. Human spatial representation: insights from animals. Trends in Cognitive Sciences, **6**(9)376-382

Wiener, S.I. and Taube, J.S. 2005. *Head Direction Cells And The Neural Mechanisms Of Spatial Orientation*. MIT Press, Cambridge, 480 pp.

Witkin, H.A. and Asch, S.E. 1948. Studies in space orientation: IV. Further experiments on perception of the upright with displaced visual fields. *J. Exp. Psych*., **38**:762-782

Young, L.R., Oman, C.M., Watt, D.G., Money, K.E., Lichtenberg, B.K., Kenyon, R.V. and Arrott, A.P. 1986. MIT/Canadian vestibular experiments on the Spacelab-1 mission: 1. Sensory adaptation to weightlessness and readaptation to one-g: an overview. *Exp. Brain Res*. **64**:291-298.

Young, L. R., Mendoza, J. C., Groleau, N. & Wojcik, P. W. 1996, Tactile influences on astronaut visual spatial orientation: Human neurovestibular experiments on Spacelab Life Sciences 2," *Journal of Applied Physiology*, **81**(1):44-49.

Yuganov, EM, Gorshkov AI, Kasyan II, Bryanov II, Kolosov IA, Kopanev VI, Lebedev VI, Popov NI and Solodovnik FA. 1966, Vestibular reactions of cosmonauts during the flight in the Voskhod spaceship. Aerospace Medicine **37**: 691.