Assessing the perceptual consequences of non-Earth environments

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Summary: This white paper summarizes the need to measure the perceptual consequences of long-term exposure to reduced gravity environments. Such information is essential to establish astronaut comfort, optimum operational performance and for the design of appropriate living spaces.

As part of the human spaceflight program, humans will live and perform in the challenging environments that space travel and visits to mars and the moon present. Our perceptual systems have evolved to operate with the constants and constraints that exist on Earth. It is important that we understand the limitations and changes that result from living in these unusual environments.

Our normal Earth-bound lives have provided a set of constants such as the continuous pull of gravity, the fact that the sky is generally lighter than the ground, that trees grow roughly vertically, that the horizon is level with our eyes and many more. Perception takes place in the context of these constants. As a demonstration, figure 1 shows an example of the well-known Thatcher illusion [1]. First view the figure with the page held upright. The two images appear normal and relatively similar when viewed in this orientation but when the page is rotated 180 degrees structural differences become readily apparent. Recognition of faces is dependent on their orientation relative to the viewer. Now rotate the page until it just becomes apparent which face is distorted. This angle will change depending on the orientation of the body relative to gravity. Even recognizing when a face is distorted depends on the context provided by gravity!

The perceptual conundrum that an astronaut faces when operating in microgravity is illustrated in Figure 2. Many of the ‘natural’ perceptual cues that underlie our everyday existence are lost in outer space. Here an astronaut is operating in the Shuttle payload bay. The astronaut’s field of view is limited by the space suit. The lack of gravity leads to unusual activity in the various gravitoreceptors within their body. The space suit also limits haptic feedback normally felt
through the skin, and the lack of gravity provides unusual perceptual cues to the idiotropic (literally “introspective”) senses including those associated with joint weighting and normal muscle tension. Finally, the visual environment itself is unnatural. The normal visual cues (ground, sky, surroundings) are missing, but more even more subtle effects are present. For example, the lack of an atmosphere in space or on the moon eliminates the normal scattering of blue light from the atmosphere which changes the apparent colour of objects with depth.

Given the critical nature of gravity to a wide range of perceptual systems it is perhaps not surprising that astronauts operating in microgravity have reported a wide range of perceptual effects [2]. One important perceptual effect that is often reported in microgravity is the visual reorientation illusion (VRI) in which astronauts suddenly experience walls, ceiling and floor surfaces changing identities [3]. VRI’s have been reported on Skylab [4], Spacelab [5] and continue to be reported to this day. A related perceptual effect is that the perceived direction of up may vary with head tilt differently to how it varies under normal gravity (see below). Illusions of this type can be dangerous because they can lead to errors in operating equipment (misinterpreting the orientation of a toggle switch) or navigating to emergency stations (turning left instead of right). However, we still cannot predict these perceptual phenomena or completely minimize their effects.

Probes for measuring perceived orientation.

Long before the development of spaceflight and the need to understand the perceptual effects of living in outer space, it was recognized that the definition of “up”, or equivalently “down”, or which surface is the floor, were fundamental questions on Earth. For example, in our normal
day-to-day environment, one could imagine asking subjects a very simple question like ‘where is the floor?’ [6] and use this to measure the perceived direction of up, but other probes are possible too including the use of luminous lines [7], shaded disks [8], and ambiguous characters [9]. These can all be used to assess the effect of combined environmental cues to the perception of up on broader perceptual tasks.

Each of these probes has advantages and disadvantages. For example, the luminous line probe requires the subject to judge the orientation of a line relative to the perceived direction of gravity -- a judgement that is meaningless when gravity is absent. But to illustrate perhaps the simplest of these consider the probe that asks a subject to indicate which surface in their environment is the floor. The floor is that surface in an environment that provides physical support. In a normal environment the floor might be sensibly defined as the surface most closely aligned with the gravity-defined horizontal. It turns out that this is not the only factor taken into account in making this decision.

Given a probe, or a set of probes, it is then possible to quantify the processes that underlie our perception of which way is up, and from this begin to understand the conditions that lead to VRI’s and similar perceptual problems in unusual gravity environments.

**Which way is up?**

The direction of up can be modeled in a number of ways. Perhaps the most straightforward is to amalgamate the various perceptual systems that transduce information about the direction of up into three broad categories; a measure of the direction of up obtained from the visual sense, a measure of the direction of up obtained from gravity-defined cues and most importantly the otolithic division of the vestibular system which in collaboration with somatosensory cues provides cues as to the direction of gravity, and body-centric (idiotropic) cues, cues obtained from the frame of reference anchored in the long axis of the body. Mittelstaedt [10], and more recently Dyde et al. [9], have argued that the direction of up can be modeled in terms of a weighted vector sum of cues as to the direction of up provided by these three broadly defined sources of information (see Figure 3).

This weighted vector sum model has proven to be effective in modeling the perceived up direction and assessing the significance attached to each cue under a range of conditions including ground-based [9], short-duration microgravity [11] and neutral buoyancy [12]. Different environmental conditions result in different emphases being placed on the three components that make up the model. Within the context of this model, illusions such as VRI can be seen as a consequence of a change in weighting of the available vectors.
When the body, visual cues and gravity are misaligned, the perceived direction of up is not aligned exactly with any one of these cues but is a compromise ‘best guess’ derived from the weighted sum (figure 3). Changes in the weighting of the cues, such as can occur when gravity is not present or is present at an unusual level, can lead to a distorted perception of upright and potentially disastrous consequences.

In space, which way is up?

Surprisingly little is known about the full effects of the range of unnatural perceptual cues that can be encountered in space travel and how they act and interact with the perception of up.

Visual cues. Astronauts operating in space habitats are presented with unusual and often uniformly textured environments. Rack space is always a premium in spacecraft and as a consequence cues provided by consistent alignment of equipment are often sacrificed. Highly polarized scenes with natural objects are key to providing a visual up [13, 14]. The lack (or at least reduction) of “intrinsically polarized” objects [15] in the artificial environment found within spacecraft further reduces the visual cues available to define a coherent direction of up.

When inferring 3D structure from shading information, the brain exploits the fact that on Earth light comes from above [16]. Lighting in the interior of space habitats is often designed to provide equal illumination on all surfaces and in all directions thus providing no coherent cue to up based on lighting. The lack of a coherent lighting direction means that shape-from-shading judgements are likely to be inconsistent with the judgements that would have been made on Earth of the same object. Indeed, this is the basic premise behind the use of shape-from-shading judgements as a probe to determine the direction of up [8, 17].

As astronauts move outside of their habitat onto the surface of planets or float above space structures, further complications come into play. In addition to many of the effects that occur indoors, astronauts are now faced with views of long distances that are not coloured naturally by the blue shift found on Earth. Astronauts are also faced with the significantly reduced field of view provided by their environmental suits. Given the critical importance of visual cues in the perception of self orientation when gravity is not present, the limited field of view found in space suits is likely to further reduce the ability of vision to provide an effective cue as to the direction of up [18].

Haptic cues. The haptic system contributes to the sense of orientation on Earth by indicating pressure points where the body touches support surfaces. The microgravity environment reduces such cutaneous pressure and also unloads joints which can result in a loss of limb position awareness [19] and contribute to disorientation [20]. The effect of such a reduction can be assessed from the weighting assigned to body cues in the determination of up.

Body cues. The body provides a frame within which questions like “which way is up?” can be answered. Normally we have at least a partial view of our body and we can usually find where our feet are. It takes an unusual environment indeed to break this fundamental idiotropic
representation. Wearing a space suit, unfortunately, provides such an environment in which an astronaut cannot see their body and where visual cues to the “floor” may not be useable. Disorientation is induced when this situation is simulated on earth [21].

**Gravity cues.** Short-duration microgravity studies have demonstrated that when gravity is effectively removed for short periods of time humans tend to rely more on the perceived orientation of their body rather than visual cues [11]. Surprisingly, this also appears to be true during periods of hypergravity as well. Human performance under long-duration microgravity is less well understood, primarily due to the small subject pool of astronauts who have experienced long duration periods of microgravity [22]. The Bodies in the Space Environment (BISE) project, sponsored by the Canadian Space Agency, currently underway on the International Space Station is studying the long terms effects of exposure to microgravity on the perception of up. Although the BISE project will answer critical questions about the adaptation of self-orientation perception to microgravity conditions, the question of human performance under other gravity states is not as well studied.

Our preliminary experiments using parabolic flights to simulate other gravity conditions suggest that lunar gravity conditions are more similar to Earth gravity conditions. Given that zero gravity conditions (and hypergravity conditions) are significantly different from earth gravity, what is the minimum gravity state that is necessary to provide Earth-like performance?

**Perceptual measurements will help us live and work in space.**

As we move from our constant one gravity environment to the harsh realities of outer space, the moon and mars, we leave behind our normal gravity conditions. We will also leave behind a range of perceptual cues that underlie much of human perception. We must expect that these differences will have both short-term and long-term perceptual consequences. Ground-based and short-duration microgravity experiments have demonstrated a range of systemic and reproducible effects on our perception of self-orientation.

Many of the experiments needed to investigate perceptual phenomena can be carried out using a laptop with controlled viewing conditions, currently available on the International Space Station in the form of Neurospat, with appropriate software to control the display.

For humans to function properly in space it is critical that the effects of operating in that environment be properly quantified. Such knowledge can be used to train space travelers to understand the effects of the unnatural environment on their perception of self-orientation and to aid in their training. The information may also be of value in terms of designing appropriate countermeasures for these effects and in the design of habitats and equipment that reduces or minimizes the severity of the effects.
References