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Motion perception during tilt and translation after space flight

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ABSTRACT

Preliminary results of an ongoing study examining the effects of space flight on astronauts' motion perception induced by independent tilt and translation motions are presented. This experiment used a sled and a variable radius centrifuge that translated the subjects forward-backward or laterally, and simultaneously tilted them in pitch or roll, respectively. Tests were performed on the ground prior to and immediately after landing. The astronauts were asked to report about their perceived motion in response to different combinations of body tilt and translation in darkness. Their ability to manually control their own orientation was also evaluated using a joystick with which they nulled out the perceived tilt while the sled and centrifuge were in motion. Preliminary results confirm that the magnitude of perceived tilt increased during static tilt in roll after space flight. A deterioration in the crewmember to control tilt using non-visual inertial cues was also observed post-flight. However, the use of a tactile prosthesis indicating the direction of down on the subject's trunk improved manual control performance both before and after space flight.
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1. Introduction

In darkness, the central nervous system must resolve the ambiguity of inertial motion sensory cues in order to derive an accurate representation of spatial orientation. The balance system in the inner ear (otoliths) senses both head translation and head tilt relative to gravity. During space flight, head tilt is not sensed; the brain must therefore learn new ways of orienting oneself in weightlessness, which can then lead to disturbances in perceived motion and balance control upon return to Earth's gravity [1,2]. Adaptive changes during space flight in how the brain integrates vestibular cues with other sensory information can lead to impaired movement coordination, vertigo, spatial disorientation and perceptual illusions following gravity level transitions [3].

This ongoing study was designed to examine both the physiological basis and operational implications for disorientation and tilt-translation disturbances following short-duration space flights. Specifically, this study addressed three questions: (1) What adaptive changes occur in motion perception in response to different combinations of tilt and translation motion? (2) Do adaptive changes in tilt-translation responses impair the ability to manually control vehicle orientation? (3) Can sensory substitution aids, such as tactile cues, mitigate the risks associated with manual control of vehicle orientation?

The primary objective of this study was to evaluate how the brain adapts to conflicting motion cues by measuring changes in awareness of position. Before and after space flight, subjects were exposed to a combination of body tilt and translation on a sled or a centrifuge. Based on the results from previous post-flight studies [4–6] we

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hypothesized that perceived tilt will increase post-flight during static tilt, as a result of the in-flight decrease in the amplitude of the internal model of gravity. During dynamic tilt and translation, it was expected that motion perception will have specific frequency characteristics, with adaptive changes being greatest in the mid-frequency range where there is a crossover of tilt and translation [7].

The secondary objective of this experiment was to evaluate how a tactile prosthesis can be used to improve control performance. The tactile prosthesis is a simple four vibrotactile system that provide feedback when tilt position exceeds predetermined levels in either pitch or roll [8]. Subjects were tasked to use a joystick to null out tilt and translation motion disturbances with or without the help of the tactile prosthesis. We predicted that performance in the closed-loop tilt control task would be compromised following tilt-translation adaptation after space flight, with increased control errors corresponding to changes in self-motion perception [9]. Furthermore, that performance would improve with tactile feedback of tilt control errors.

In this paper we describe the equipment and experimental protocol used for this study and report the preliminary results obtained with astronaut-subjects.

2. Methods

2.1. Equipment

Our sled protocol was based on an elegant set of experiments performed by Angelaki and colleagues [10] in monkeys to demonstrate the importance of multisensory integration for discriminating tilt from translations. Angelaki's experimental protocols consisted of either lateral translations, roll tilts, or combined translation-tilt paradigms. With intact animals, horizontal eye movements that compensate for translation were present during translation but were negligible during pure roll tilt. However, when the semicircular canals were inactivated (plugged), horizontal eye movements at 0.5 Hz could no longer be correlated with head translation, but were present regardless of whether the resultant linear acceleration resulted from translation or tilt. Golding et al. [11] performed a similar paradigm in humans during pitch tilt and fore-aft translations. During oscillation at about 0.2 Hz, subjects perceived that "they were not moving fore and aft along the track but were being swung on a giant swing". Similar to the Angelaki and Golding protocols, we utilized the NASA Tilt-Translation Sled (TTS) that synchronizes chair tilt within an enclosure that simultaneously translates along a sled. The tilt and translation profiles were restricted to the pitch tilt with fore-aft translation on the TTS.

A second method to examine tilt-translation ambiguity has been variable radius centrifugation (VRC). In this device a chair is mounted on a sled that translates sideways on top of a base rotating at a constant velocity in yaw. The displacement of the sled results in a radial-directed linear acceleration (sum of centripetal and sled acceleration). This radial linear acceleration combines with gravity so that the resultant force vector is tilted with respect to vertical; hence stimulating directly the otolith organs without the normal canal cues. During one study by Merfeld et al. [12], repeated measures were obtained from the same subjects during Earth-horizontal axis (EHA) rotation involving both canal and otolith cues, and VRC involving primarily otolith cues (± 3.3 m/s^2 generating resultant vector tilted 20° relative to vertical; 0.005–0.7 Hz). During EHA rotation, the perception of roll-tilt and the modulation of eye torsion were present at all frequencies. However, during VRC stimulation the perception of roll-tilt and modulation of eye torsion declined with increasing stimulus frequency. Differences between EHA and VRC responses at higher frequencies (>0.1 Hz) suggest that canal cues are important in resolving ambiguous linear acceleration information. In the present experiment, we therefore utilized a VRC to examine adaptive changes after space flight in tilt and translational motion perception in response to linear acceleration in the absence of canal cues across frequencies ranging from 0.15 to 0.6 Hz.

2.2. Experimental protocol

Roll VRC Session: Subjects were restrained on a chair that was mounted on a small translation stage fixed to a rotating chair. Before getting in the chair, subjects donned an elastic belt with two vibrotactile stimulators (e.g., small pager motors) located on the right and left sides. These tactors are used to provide orientation cues by vibrating when the subject has exceeded pre-set threshold levels of tilt in the roll-plane. This was essentially a small laboratory version of the Tactile Stimulation and Awareness System (TSAS) developed by Rupert and colleagues [8] for rotatory and fixed wing aircraft. This system includes control electronics that can drive multiple electro-mechanical tactors. A tight-fitting elastic belt with thermoplastic inserts was used to position and hold the tactors relative to body coordinates. Custom software transferred chair eccentric position based on predetermined thresholds, and displayed this information to the subjects using the tactor belt.

Subjects were restrained in the chair with straps and padding around the shoulders, mid-torso, waist, legs and feet. A head restraint with adjustable pads was used to secure the subject's head in an upright orientation. The head was carefully centered over the axis of rotation in both fore-aft and lateral directions. Noise-canceling headphones were used to mask auditory cues, and a microphone allowed constant communication with the test operator. A joystick was mounted directly in front of the subject to allow both motion perception and manual control tasks (nulling chair translation). The rotator room was darkened so the subjects were in complete darkness.

Subjects were accelerated at $<5°/s^2$ to a constant velocity of 400°/s. After 1–2 minutes when the subjects no longer sensed the rotation and the per-rotatory nystagmus decayed, the chair was positioned off-center 3.5 cm so that the resulting GIF at the center of the head was tilted by 10° to the right or to the left. Subjects then reported their perception of roll tilt and lateral translation

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