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Task Description:

Long duration spaceflight poses many physiological (e.g., cardiovascular, bone, muscle, visual and vestibular) and psychological (e.g., isolation, anxiety, depression) stressors on astronauts, making them more susceptible to spatial disorientation. The number of stressors and their potential impact are especially serious during gravitational transitions such as when landing on the surface of a planet or the Moon where astronauts will not have access to familiar gravitational cues and will have undergone prior sensorimotor adaptations to weightless conditions (Shelhamer, 2015; Clément et al., 2020). Spatial disorientation can occur under many circumstances including when there is an inaccurate or attenuated perception of position, motion or attitude (Lackner, 1992; Poisson and Miller, 2014). In addition to the unique stressors of spaceflight such as gravitational transitions and sensory reweighting, some common causes of spatial disorientation shared between spaceflight and aviation include inaccurate sensory information and mismatch between different sensory systems (e.g., the vestibular, visual and somatosensory) (Heinle and Ercoline, 2003). Between 1993 and 2013, spatial disorientation led to 101 deaths. Sixty-five aircraft were lost, resulting in $2.32 billion of damages (Poisson and Miller, 2014). One proposed countermeasure for spatial disorientation is vibrotactile feedback about body orientation provided by small vibrating devices on the skin (Cholewiak et al., 2004). Such feedback has been shown to improve performance (Wenzel and Godfroy-Cooper, 2021) in motion platform control (Bouak et al., 2011), flight simulators (Cardin et al., 2006; Ouyang et al., 2017), helicopter flight (Raj et al., 2000; Lawson and Rupert, 2014), and fixed wing aircraft flight (Rupert, 2000a; Rupert, 2000b). Additional vibrotactile uses include providing cockpit alerts (Salzer et al., 2011), cueing astronaut orientation in the International Space Station (van Erp and van Veen, 2006), performing a nulling task after being rotated in yaw to cause disorientation (van Erp et al., 2006), and a nulling task after returning from spaceflight (Clément et al., 2018).
In this project, we will answer the following research questions: - How does the magnitude of spatial disorientation change in relation to different magnitudes of gravitational cues provided through Earth, Martian, Lunar and 0g analogs? - Will vibrotactile feedback during our disorienting dynamic orientation task be useful? - How does the effectiveness of vibrotactile feedback change in relation to different magnitudes of gravitational cues? - When disoriented, a pilot’s own internal sensory feedback may be misleading. Will vibrotactile feedback be able to correct this misperception of orientation? - If vibrotactile feedback is unable to correct the misperception, will this create confusion? Will pilots be able to rely on and trust the vibrotactors during highly stressful and disorienting conditions? - Will participants learn to use the vibrotactile feedback better with greater exposure to the 0g analog condition? - What types of training can enhance the ability to use vibrotactile feedback to mitigate spatial disorientation? - Does vibrotactile feedback create dependence?

Rationale for HRP Directed Research:

Research Impact/Earth Benefits:

We found that vibrotactile feedback enhances stabilization performance, without creating a negative dependence, in Martian, Lunar and 0g analogs. This means that vibrotactile feedback will be an important countermeasure for spatial disorientation experienced during space exploration and even on Earth. One of the leading causes of fatal aircraft accidents on Earth is from spatial disorientation.
However, the vibrotactile feedback was unable to restore performance, in Martian, Lunar and 0g, to the Earth analog level. This was because participants experienced a feeling of conflict between their perception of orientation and their actual orientation indicated by the vibrotactors. Knowledge of being disoriented and high levels of trust in the vibrotactile feedback were not enough to allow continued learning in the spaceflight analog condition, suggesting that in stressful disorienting conditions that demand fast reactions, trust and knowledge are not enough to ensure reliance on vibrotactile feedback. Instead, a training program, in the Earth analog condition, where participants had to disengage from aligning with gravitational vertical while focusing on vibrotactile feedback was needed to acquire much better performance and sustained learning in the spaceflight analog condition. The training program did not reduce the feeling of conflict however it allowed participants to overcome it. This suggests that as we think about human and sensory augmentation through technology as a countermeasure for spatial disorientation and other problems, we must think about the nature of the training program. Our research shows that for space related tasks where there is a novel environment, the training program should teach astronauts how to disengage from their erroneous sensory system while focusing on the sensory augmentation device.

Our work contributes to a broad effort to enable space exploration with vibrotactile feedback. For example, it could be useful for recognizing alerts (Salzer, Oron-Gilad, Ronen and Parmet, 2011) such as during flight or egress. Vibrotactors could be used as a sensory augmentation device, enhancing performance of manual control tasks (Clément et al.,2018) such as during extravehicular activity (Bakke and Fairburn, 2019). After landing on the surface of a planet or the Moon or returning to Earth, vibrotactile feedback could likely help with postural instability (Sienko et al., 2013; Wall, 2010), and later on, with navigation while exploring the surface (Erp et al., 2005). During flight, vibrotactile feedback could be useful as an aid for maneuvers like sustained hovering (Raj et al., 2000; Lawson and Rupert, 2014). Our research shows that vibrotactile feedback will also be a useful countermeasure for spatial disorientation however will require specialized training. Finally, our work extends the sensory substitution literature (Bach-y-Rita and Kercel, 2003; Bertram and Stafford, 2016) where individuals are usually trained and tested to use a feedback device in the same environment. In our paradigm, individuals are trained to use vibrotactors in one environment (Earth analog) and then tested in a novel environment (spaceflight analog). We find that effective use of the vibrotactors requires not only free exploration (active sensing) but also specialized training that teaches individuals to disengage from one sense while focusing on the vibrotactile feedback. This could be relevant for other work where body systems or environment can change significantly, such as in rehabilitation (Alahakone and Senanayake, 2009; Wall, 2010; Sienko et al., 2013; De Angelis et al., 2021), sports (van Breda et al., 2017), virtual, augmented and mixed realities (Islam and Lim, 2022), human enhancement and augmentation (Raisamo et al., 2019).

1. How does performance in a dynamic orientation task change in relation to different magnitudes of gravitational cues provided through Earth, Martial, Lunar, and 0g analogs?
In our 2023 study, blindfolded participants were strapped into a Multi-Axis Rotation System (MARS) device that was programmed to behave like an inverted pendulum in the roll plane. Participants used an attached joystick to keep themselves stabilized around the balance point. The direction of balance, in this experiment, was always set to the center (0 deg in the roll plane). In the Earth analog condition (vertical roll plane), participants could use full gravitational cues to determine their angular position. In the Martial analog condition (pitched back by 68 deg) and Lunar analog condition (pitched back by 80 degrees), participants had partial gravitational cues to determine their angular position. In the 0g analog condition, participants could not use gravitational cues to determine their angular position from the balance point.

Task Progress:

In the experiment, participants first received 8 100-second long trials in the Earth analog condition to learn the task. Then, they received 3 blocks of 4 trials where they had a randomized order of Earth, Martial, Lunar, and 0g analogs. We found that as the magnitude of gravitational cues decreased, performance worsened across a variety of metrics (e.g., number of crashes, standard deviation of angular position, positional drifting, joystick magnitude). As the magnitude of gravitational cues decreased, we also found that participants' self-reported levels of confusion increased when sensing their angular position and, surprisingly, also their angular velocity.

2. Does the effectiveness of vibrotactile feedback change in relation to different magnitudes of gravitational cues?

In our 2023 study, along with the Control group (described above) we also had a Vibrotactile group who had 4 vibrotactors placed on each arm from the shoulder to the wrist. The first vibrotactor (near the shoulder) activated when the MARS deviated 1 deg from the direction of balance, the second at 7 deg, the third at 15 deg, and the fourth (near the wrist) at 31 deg. We found significant differences between the Control and Vibrotactile group for all conditions except the Earth condition. This suggests that the vibrotactile cues are not very useful when full (Earth analog) gravitational cues are provided in a non-disorienting condition; however, they are useful in partial gravity. However, similar to the Control group, the Vibrotactile group's performance worsened as the gravitational levels decreased from Earth to Martian to Lunar to 0g. These results suggest that, without extensive training, the vibrotacile feedback most likely won't be able to restore performance to Earth levels when exposed to partial-g. Additionally, we found significant increases in self-reported confusion for angular position and velocity in both groups; however, no difference between groups. This means that even at partial-g levels, with considerable gravitational cues (e.g., Martian), the vibrotacile feedback did not correct perception. Instead, participants still felt disoriented and confused; however, they were able to use vibrotactile feedback to perform better than the Control group. All of this suggests that astronauts will be much more susceptible to spatial disorientation in partial-g than in Earth conditions and this susceptibility will worsen as the gravitational level decreases.

3. Does a specialized training program lead to better usage of vibrotactile feedback in the 0g analog condition?

In our 2022 study, we examined learning and training and the findings have been published: Vimal, Vivekanand Pandey, et al. "Vibrotactile feedback as a countermeasure for spatial disorientation." Frontiers in physiology 14 (2023): 1249962. [Ed. Note: See Bibliography.]

All groups in this study did the stabilization task in the Earth analog condition on the first day, and the 0g condition on the second day. The Vibrotactile+Training group received a specialized training program that taught participants how to disengage from relying on gravitational cues while focusing on the vibrotactile feedback. The Vibrotactile group did not receive any training; however, did have exposure and practice on day 1 to become familiarized with the vibrotactors. The OnlyTraining group received the specialized training program; however, without any vibrotactile feedback.

Compared to the OnlyTraining group who received the same training, the Vibrotactile+Training group performed significantly better than the Vibrotactile group in the first block, across a greater number of metrics and with a greater magnitude of significance. They had better positional and velocity based control, fewer crashes, better joystick control, and less positional drifting, which is a characteristic feature of balancing in the spaceflight condition likely caused by poor angular path integration in the absence of gravitational cues. The Vibrotactile+Training group also performed statistically better when compared to the Vibrotactile group. These results show that the training program was effective for the Vibrotactile + Training group and resulted in significantly better performance in early exposure to the disorienting condition (Block 1). Nevertheless, in Block 1 of the spaceflight analog condition, the Vibrotactile + Training group did not perform as well as they had in the final block of the Earth analog condition on Day 1 and showed elevated levels of crashing. Importantly, 90% of both the Vibrotactile and Vibrotactile+Training groups reported confusion and a conflict in which they perceived their orientation to be different from what the vibrotactors were indicating. Therefore, the training did not reduce the feeling of conflict; but it did help the participants overcome this conflict.

4. Do participants learn to use the vibrotactile feedback better with greater exposure to the 0g analog condition?

While participants were informed that they would be in the 0g analog condition on the second day, they were not told that they may experience spatial disorientation. Would participants perform better, after Block 1, once they knew that they were disoriented and that their internal perception of orientation was incorrect? Surprisingly, the Vibrotactile group showed minimal learning on Day 2. By contrast, the Vibrotactile+Training group showed significant learning by improving positional, velocity, and joystick control and reducing the number of crashes. By the fourth block on Day 2, the difference between the Vibrotactile+Training and the Vibrotactile group significantly widened on most measures. Both vibrotactile groups by the end of trial 1 on Day 2 expressed awareness that they were disoriented and that a conflict existed between the perception of their orientation and what the vibrotactors were indicating. There was no statistical difference in their ratings of trust of the vibrotactile feedback between the Earth analog condition and the spaceflight analog condition (84%–92% trust). It is important to emphasize that the Vibrotactile group had both knowledge that they were disoriented and high levels of trust in the vibrotactile feedback, and yet they were unable to rely on the vibrotactile feedback. Why was the Vibrotactile group unable to continue learning even though they knew that they were disoriented and trusted the vibrotactile feedback? One possibility is that they were unable to build an association between their orientation and the vibrotactile feedback. In the sensory substitution literature, effective training often requires free exploration (active sensing) to build a strong association with the new sensory feedback device (Bach-y-Rita and Kercel, 2003; Bertram and Stafford, 2016). Our Day 1 exposure allowed the Vibrotactile group to have this free exploration with the vibrotactors; however, they most likely relied on the gravitational cues to complete the task and not the vibrotactile cues. This is reflected in their responses to the survey, where they did not report any increase in the usefulness of the vibrotactors across the trials; nor did they feel like the device became an extension of themselves on Day 1 or 2, whereas the Vibrotactile + Training group did show a significant increase in their report of usefulness by the end of Day 1, and an increase in the feeling that the device became an extension of themselves on Day 2. These results suggest that to build association between human and device, especially where one is trained and tested in different environments, one must give participants a training condition where the task demands that they exclusively use the device.

5. Does vibrotactile feedback create dependence?

In the final block of Day 2 in the spaceflight analog condition, we deactivated the vibrotactors to determine whether performance would become significantly worse than for the OnlyTraining group. If so, this would signify that the vibrotactors created a negative dependence. We found that in the final block, both the Vibrotactile and the Vibrotactile +

	Training groups did not perform worse than the OnlyTraining group, and instead showed a slight improvement by having lower mean squared displacements. These results indicate that the vibrotactors did not create a negative dependence, and instead helped the participants acquire a similar level of improvement and learning as the OnlyTraining group who showed significant learning, across blocks, as reflected in decreasing the frequency of crashes and the percentage of destabilizing joystick deflections.
Bibliography Type:	Description: (Last Updated: 06/09/2025)
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