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<b>Project Title:</b>	Vibrotactile Feedback as a Countermeasure for Spatial Disorientation During a Stabilization Task in a Spaceflight Analog Condition		
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**Task Description:**

Spaceflights can cause many sensorimotor-related difficulties that could jeopardize a mission. For example, if astronauts are forced to land manually onto the surface of Mars or the Moon, they will experience a rapid gravitational transition while dynamically stabilizing the spacecraft. In low-g and 0 g environments, gravitationally dependent vestibular and somatosensory cues are minimized and astronauts can easily become spatially disoriented. Vibrotactile feedback has been shown to improve performance of a variety of tasks such as navigation, driving, providing alerts, postural stabilization, rehabilitation, and sports. Additionally, it has been shown that vibrotactile cueing is useful in enhancing control of a motion platform, performance in helicopter flight, control of acrobatic flight in an aircraft, orientation of an astronaut in the International Space Station (ISS), and performance in a nulling task after returning from space. However, there are few controlled studies that have examined the effectiveness of vibrotactile feedback during a manual control task in a disorienting spaceflight analog condition that simulates gravitational transitions. Little is known about what types of training will ensure immediate and successful use of vibrotactile feedback during spatial disorientation felt during a gravitational transition. In Aim 1, we study whether specialized, context-specific training with vibrotactors is required to avoid loss of control when immediately transitioning to a condition without relevant gravitational cues. In Aim 2, we examine whether vibrotactile feedback given at points of stability is better than at points of danger.

**Rationale for HRP Directed Research:****Research Impact/Earth Benefits:**

Our work reveals that vibrotactile feedback is a useful countermeasure for spatial disorientation, however much more research is needed to understand how to prevent or overcome the conflict that arises between a person's erroneous perception of self-orientation and the correct indication of orientation from the vibrotactile feedback when disoriented. We found that a specialized training program that required participants to rely on the vibrotactile feedback while disengaging from their normal sense of aligning with gravitational vertical was important. We also found that this did not cause a negative dependence on vibrotactile feedback.

Our work has relevance to other research on vibrotactile feedback where the system or environment can change significantly, such as in rehabilitation (Alahakone and Senanayake, 2009; Wall III, 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). Our work also has relevance to the larger fields of sensory substitution (Bach-y-Rita and Kercel, 2003; Bertram and Stafford, 2016) and human enhancement and augmentation (Raisamo et al., 2019) and provides insights into how to make stronger connections between feedback devices and the human, especially in novel environments that have not been experienced before.

Long-duration spaceflight will place many simultaneous physiological (e.g., changes to the cardiovascular, bone, muscle, visual, and vestibular systems) and psychological stressors (e.g., isolation, anxiety, and depression) on astronauts making them more susceptible to spatial disorientation, especially during gravitational transitions such as when landing on the surface of a planet or the Moon where they will not have access to familiar gravitational cues and will have undergone prior sensorimotor adaptations to weightlessness (Shelhamer, 2015; Clément et al., 2020). Spatial disorientation occurs when there is an inaccurate perception of position, motion or attitude (Poisson and Miller, 2014) and may contribute to up to 33% of aircraft accidents with a fatality rate of almost 100% (Gibb et al., 2011). One proposed countermeasure is vibrotactile feedback which consists of putting small vibrating devices on the skin (Wenzel and Godfroy-Cooper, 2021). Vibrotactile feedback has been shown to be useful in aerospace applications such as improving performance 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), airplane flight (Rupert, 2000a;b), providing alerts in the cockpit (Salzer et al., 2011), orienting an astronaut in the International Space Station (van Erp and van Veen, 2006), a nulling task after rotating in yaw that caused disorientation (van Erp et al., 2006), and a nulling task after returning from space (Clément et al., 2018). It is unknown whether pilots will be able to rely on external vibrotactile feedback during highly stressful and disorienting conditions where they may not be able to rely upon their own internal sensory feedback, and it is unknown whether the added vibrotactile feedback will help or cause confusion. It is also unknown what types of training can enhance the ability to use vibrotactile feedback while disoriented. We create a disorienting spaceflight analog task by placing blindfolded participants into our Multi-axis Rotation System Device (MARS) that is programmed with inverted pendulum dynamics (Figure 1) (Panic et al., 2015). Participants use an attached joystick to stabilize themselves around the direction of balance. When the MARS is oriented in the vertical roll plane (Earth analog condition), participants can use gravitational cues detected by their otolith organs and somatosensory shear forces detected by their skin to determine their angular position relative to the balance point (Vimal et al., 2016). By contrast, when the MARS is oriented in the horizontal roll plane (spaceflight analog condition), they do not tilt relative to the gravitational vertical, and as a result, they cannot use gravity-dependent otolith and somatosensory shear forces to provide a sense of angular position in relation to the direction of balance (Panic et al., 2017; Vimal et al., 2017). They can only use motion cues detected by the semicircular canals and somatosensory receptors. In this condition, as a group, participants show minimal learning, poor performance, and a very high rate of losing control (Vimal et al., 2017; Vimal et al., 2018). Ninety percent of participants report feeling disoriented, and all participants show a characteristic pattern of positional drifting.

In our present study, participants in the Vibrotactile group 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. On the first day of experimentation, participants balanced in the vertical roll plane with the vibrotactors (i.e., they trained with natural terrestrial gravitational cues augmented by vibrotactors), and on the second day they were placed in the horizontal roll plane with the vibrotactors (i.e., they were tested in the spaceflight analog condition with vibrotactile cue replacement of missing gravitational cues). We hypothesize that the Vibrotactile group will perform better and show greater learning than the Control+Training group (who received training (see below) but have no vibrotactors) in the spaceflight analog task. However, we hypothesize that the Vibrotactile group will not perform as well in the spaceflight analog condition as they did in the Earth analog condition because the exposure in the Earth analog condition would not be sufficient to teach participants how to rely on the vibrotactors. This is because, in the Earth analog condition, participants primarily rely on gravitational-based cues (Vimal et al., 2017) and would most likely not pay attention to the redundant vibrotactile cues.

In the sensory substitution literature, effective training often includes free exploration (active sensing) with the device to build the appropriate associations between the new sensory feedback and the task (Bach-y-Rita and Kercel, 2003; Bertram and Stafford, 2016). We propose that in addition to free exploration, one also needs to create conditions during training where participants have to rely on the new sensory feedback. The Vibrotactile+Training group received a

## Task Progress:

specialized training program based on our prior work (Vimal et al., 2019), where on Day 1, participants balanced in the Earth analog condition using vibrotactors. Unlike the Vibrotactile group, participants in the Vibrotactile+Training group did not know the location of the balance point, which was randomized and never at the gravitational vertical. Therefore, to complete the task successfully, participants had to disengage from aligning with gravitational vertical and instead had to rely on vibrotactile feedback and motion cues. We hypothesize that the Vibrotactile+Training group will perform better than the Control+Training and Vibrotactile groups in the spaceflight analog condition on Day 2. Finally, to determine whether a negative dependence on the vibrotactors would form, we disengaged the vibrotactors in the last block of the experiment in the spaceflight analog condition, and we hypothesize that performance will worsen however, will not be worse than the Control+Training group.

We found that the Vibrotactile group performed significantly better than the Control+Training group. These findings show that vibrotactile feedback can enhance stabilization performance in a spaceflight analog condition where participants cannot rely on gravitational cues and where they become spatially disoriented. When comparing the final block on Day 1 in the Earth analog condition (vertical roll plane), where participants could use gravitational cues, to the first block on Day 2 of the spaceflight analog condition (horizontal roll plane), we found that all groups performed significantly worse across the majority of the metrics. Why were both vibrotactile groups in the spaceflight analog condition unable to completely recover performance? When asked to report their magnitude of confusion about their self-orientation, all groups reported an average of 300-370% increase in their confusion between Day 1 (Earth analog) and Day 2 (spaceflight analog). When questioned at the end of Block 1 on Day 2, 90% of vibrotactile users from both groups reported that their perception of self-orientation did not match what the vibrotactors were indicating. In another words, when the participants were in the spaceflight analog condition (horizontal roll plane) and experienced disorientation, the vibrotactors led to a feeling of confusion and conflict where participants had to determine whether to follow their inner sense of orientation or use the vibrotactors. These new findings show, for the first time, that during disorienting and high-stress conditions where each participant's perception of their orientation can be vastly different (Vimal et al., 2022) and where very large errors in perception occur, vibrotactile feedback may not be intuitively and immediately useful.

Perhaps one reason why the Vibrotactile group did not show as significant of an improvement in the spaceflight analog condition was that their exposure to vibrotactors on Day 1 was not enough. Our prior work (Vimal et al., 2017) shows that there are two dissociable components to balance control (i.e., alignment to gravitational vertical and dynamic stabilization), and in the Earth analog condition (vertical roll plane), participants primarily rely on using gravitational cues to align to gravitational vertical. Therefore, it is likely that participants in the Vibrotactile group primarily focused on gravitational cues sensed by their otoliths and touch receptors on their skin and did not pay significant attention to the vibrotactors on Day 1 since they provided a redundant cue. Using as motivation the training program from Vimal et al. (2019), on Day 1 the Vibrotactile+Training group's task required them to disengage from aligning to gravitational vertical while relying on vibrotactile and motion cues to successfully perform the task. We did this by randomizing the location of non-vertical balance points in the Earth analog condition. Participants did not know the location of the balance point and had to search for them and then stabilize around them. For example, if the balance point was set at 10 degrees from the gravitational vertical, a greater number of vibrotactors would activate as one deviated from an angular position of 10 degrees. In this way, participants had to disengage from their sense of gravitational vertical and focus on the vibrotactors to find the balance point.

Compared to the Control+Training group (who also received the same training), the Vibrotactile+Training performed significantly better in the first block. The Vibrotactile+Training group also performed significantly better in the first block when compared to the Control+Training group on measures that the Vibrotactile group did not. These results show that the training program was effective and resulted in significantly better performance in early exposure to the disorienting condition. Nevertheless, in Block 1 of the spaceflight analog condition, the Vibrotactile+Training group did not perform as well as they did in the Earth analog condition and still showed elevated levels of crashing. Similar to the Vibrotactile group, 90% of the Vibrotactile+Training group reported confusion and conflict where they perceived their orientation differently than what the vibrotactors were indicating. Therefore, the training did not reduce the feeling of conflict, but it did help the participants overcome this conflict.

While participants were informed that they would be in the horizontal roll plane on the second day, they were not told that they might experience spatial disorientation. Would participants perform better 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, only learning to reduce the frequency of Crashes with a marginal significance. By contrast, the Vibrotactile+Training group showed significant learning across the majority of the metrics. By the fourth block, the difference between the Vibrotactile+Training and the Vibrotactile group widened.

By the end of trial 1 on Day 2, both groups expressed awareness that they were disoriented and that a conflict existed between the perception of their orientation and what the vibrotactors were indicating. At the end of trial 1, there was no statistical difference in their rating of trust in the reliability of the vibrotactors between the Earth analog condition and the spaceflight analog condition (84% - 92% trust). Why was the Vibrotactile group unable to continue learning even though they knew that they were disoriented and that the vibrotactors were provided reliable information? 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 needs 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 only used their gravitational cues to complete the task and disregarded 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 an 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.

In the final block of Day 2 in the spaceflight analog condition, we deactivated the vibrotactors to determine whether the performance would become significantly worse than the Control+Training group, which 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 Control+Training group and instead showed a slight improvement by having less mean-squared displacement. These results signify that the vibrotactors did not create a negative dependence and instead helped the participants acquire a similar level of improvement and learning as the

Control+Training group who showed significant learning, across blocks, in decreasing the frequency of crashes and the percentage of destabilizing joystick deflections.	
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