Auditory and Vestibular Control of Inverted Pendulum Dynamics in Spatial Orientation

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Fellow: Lila Naheed Fakharzadeh

Advisors: James R. Lackner and Paul DiZio

Institution: Brandeis University

Department: Neuroscience

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1. <u>Narrative</u>

Introduction

Human standing balance requires continuously nulling the tendency to fall like an inverted pendulum, and this process relies on the convergence of information from multiple sensory modalities including vestibular, vision, audition, proprioception and somatosensation. Dynamic control of unstable balance is also a critical and difficult task in aviation and spaceflight. Pilots may lose orientation and vehicle control during unstable maneuvers like helicopter hovering in a degraded visual environment or during ambiguous vestibular signaling. It is therefore imperative to determine whether training with combinations of sensory modalities can aid the ability to balance in operational environments where some sensory signals can be insufficient or distorted. The goal of this work during the Link Foundation Fellowship was to determine whether training protocols using auditory environments that provide location, velocity, and acceleration information about self-motion can enhance alignment with the direction of balance (DOB) and the direction of gravity (DOG).

Studies here at the Graybiel Laboratory have shown that when the static DOG and dynamic pendulum DOB are experimentally uncoupled, self-balancing involves synergistic, dissociable vestibular/somatosensory mechanisms for orienting to each direction (Panic et al., 2015). The Graybiel Laboratory Multi-Axis Rotation System (MARS) was programmed with parameters that simulated inverted pendulum dynamics about the roll axis. Subjects used a manual joystick to control the MARS during supine (90°pitch) roll balancing where semicircular canal cues about the dynamic DOB were present and otolith cues about the DOG were absent. Orientation to the DOG could involve determining and regulating the angular error between the body's angular position and the gravitational upright; dynamic stabilization without any reference to the DOG could be accomplished using angular acceleration signals contingent on the direction and magnitude of deviation from the DOB. Experimentally it has been observed that without a reference to gravity, subjects tend to have more difficulty orienting to the DOB in the supine orientation, which is termed as positional drifting (Panic et al., 2015)

We used the supine roll condition to assess the efficacy of auditory cues to suppress positional drifting without a gravity reference. Auditory cues were created in the form of gated white noise busts with interaural time differences proportional to angular deviation from DOB. The experimental group received auditory cues while balancing, while the control group was not provided with any auditory cues. The direction of balance was set to 0°.

It was expected that with auditory training without relevant gravitational cues, that subjects would use the inter-aural time and level differences to determine the direction of balance and demonstrate better performance and less positional drifting than the control group. The results of this study could potentially be used to enhance the design of multi-sensory training simulators.

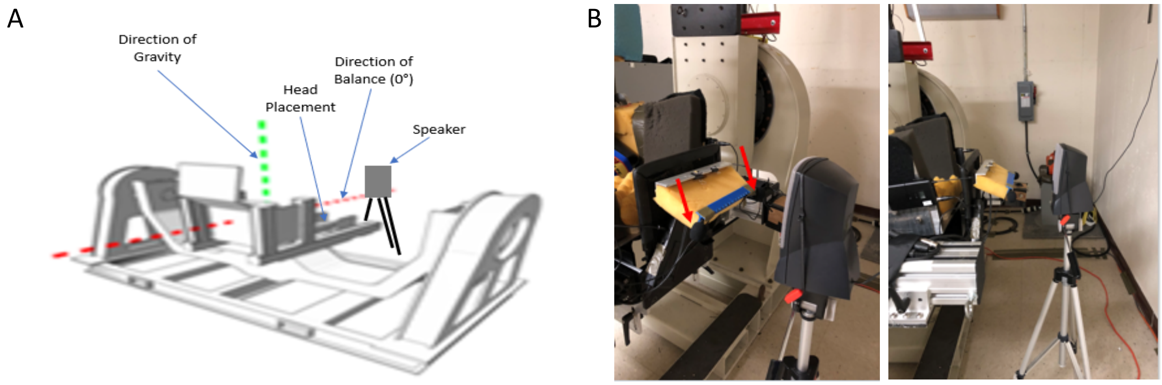

Figure 1. **Multi-Axis Rotation System (MARS) device and auditory setup.** A. The MARS in the Supine roll position (90° from vertical) where subjects make movements about the roll axis on their backs. The MARS is an apparatus that simulates inverted pendulum dynamics which means it is inherently unstable. The direction of balance was set to 0° and subjects were instructed to move their joysticks left and right to keep the MARS stable. The auditory cues, in the experimental condition, were projected from the speaker from behind the MARS; B. A pair of microphones mounted on either side of the MARS head holder (indicated by the read arrows), like “artificial ears”, sent signals from a single earth-fixed speaker emitting white noise to headphones worn by the blindfolded subject. This created the binaural perception of a structured sound field rolling in synchrony with the MARS.

A refined Neuro Kinetics Multi-Axis Rotation System (MARS) was programmed with parameters that simulated inverted pendulum dynamics about the roll axis corresponding to the equation $\ddot{\phi} = k_P \sin \phi$, where ϕ represents the degrees of angular deviation from the direction of balance, and k_P represents the pendulum constant. Subjects used a Logitech Freedom 2.4 joystick with a light spring loaded towards the central position. The MARS rotated in roll about a vertical axis in the mid-sagittal plane through their center of mass. A speaker was placed behind the MARS at the direction of balance. The speaker produced a range of frequencies (white noise) with a burst length of 1 ms, and a 30 ms latency between bursts. Microphones were placed on the left and right side of the MARS 18 cm apart with a distance of 13.5 cm between each microphone and the speaker. This setup allowed participants to gain polarity and dynamic cues with interaural time differences (ITD) and interaural level differences (ILD). For example, if the participant moved to the left of the sound source, the magnitude of the sound wave would have been greater and arrived more quickly to the right ear compared to the left.

Prior to experimentation, subjects were informed that the MARS was programmed to exhibit inverted pendulum dynamics. They were instructed to move the joystick in the opposite direction of MARS movement to remain at the center of balance. Subjects were also informed that there were 30-degree boundaries programmed. After instructions, subjects put on noise-cancelling headphones and blindfolds and were secured in the MARS. Subjects were not given practice trials prior to experimentation. Subjects in both the control and experimental groups balanced in the supine orientation on first and second days. The first and second day of experimentation each included of five blocks with each block consisting of four trials. The trial continued until subjects balanced for a cumulative 100 seconds of balance time or the trial period reached 120 seconds. After every 4 trials, subjects were given a 1-minute break and asked about their degree of nausea on a scale of 0 to 10. Control participants were not provided with auditory or visual cues throughout experimentation. Participants in the experimental group were provided with auditory white noise clicks without visual cues. On the first day, subjects balanced the MARS at a pendulum constant that was incrementally increased from 60 $°/s^2$ to 600 $°/s^2$ in increments of 60 $°/s^2$. On the second day of experimentation, subjects were tested at 600 $°/s^2$ in all trials. The direction of balance was set to 0°. If a subject's position in the MARS deviated more than 30° from the direction of balance, the subject received an auditory message indicating that control was lost and that the machine was resetting.

Results

To determine whether the addition of auditory position and velocity cues enhances balance performance in conditions lacking gravitational cues, we compared the performance of subjects balancing in supine roll on days 1 and 2 without auditory cues to subjects who balanced in supine roll on days 1 and 2 with continuous auditory cueing. On the first day, the standard deviation of MARS angle was already significantly lower in the experimental group during block 1 (p=0.0141). After five blocks of exposure, we found that the experimental group had significantly lower mean MARS angle (p=0.0014), standard deviation of MARS angle (p=2.63*10^-4), joystick magnitude (p=0.0153) and joystick standard deviation of position (p=0.0228). Group comparisons of performance on day 2 demonstrated that the experimental group had significantly lower standard deviation of mean MARS angle in blocks 1 (p=0.0033) and 5 (p=0.0046), significantly lower joystick magnitude(p=0.0155), significantly less anticipatory joystick movements (p=0.0415) and lower joystick standard deviation of position in block 1.

An important performance measure is the degree of positional drifting. Positional drifting was quantified by first identifying loops in the MARS position versus velocity phase plots using information about the acceleration of each datapoint in addition to position and velocity. Loop "quadrants" were defined as points in each loop with unique velocity and acceleration attributes, that could be visualized by drawing two orthogonal lines intersecting at the loop center. The horizontal position of the point in the hemi-loop with maximum velocity was used to identify the "center" of the hemi-loop. Drift measures that were derived using information about the hemi-loops included the mean absolute value of the hemi-loop center positions, and the mean absolute value of the hemi-loop center velocity. The drift velocity was calculated by fitting a regression line to the hemi-loop center positions versus time in each individual crash segments and taking the absolute value of the slopes. The rate of drifting was found to be significantly lower in the experimental group during both the first (p= 3.19*10^-10) and second (p=7.26*10^-17) days of experimentation. The overall magnitude of positional drifting was found to be significantly larger in the control group than the experimental group on both the first (p=1.26*10^-9) and second (p=6.13*10^-12) days.

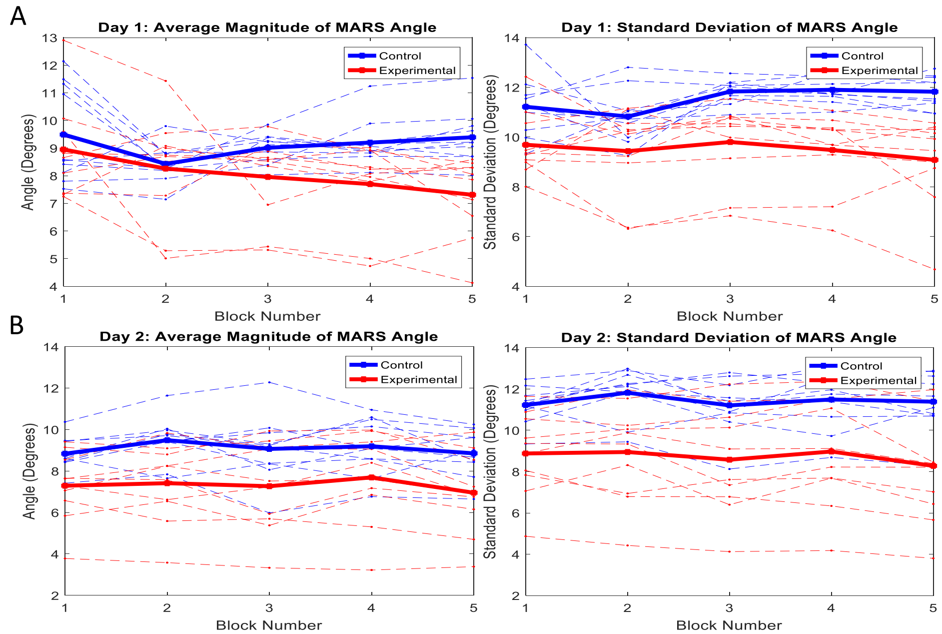

Figure 2. Average magnitude and standard deviation of MARS angular position on day 1 and day 2 of experimentation, N=10. X-axis shows block number and y-axis shows the angle in degrees. Dashed lines represent data from individual subjects, and thick lines represent the mean across subjects for each block. Blue lines represent control subjects and red lines represent experimental subjects. A. Left: MARS angular magnitude collected on day 1 of experimentation from control and experimental subjects; Right: variability of MARS angular position on day 1. B. Left: MARS angular magnitude collected on day 2; Right: variability of position collected on day 2.

Significance and Impact

This study demonstrates that continuous natural auditory cueing on the degree of angular deflection from the direction of balance significantly enhances balance performance in environments lacking gravitational cues.

This finding is in agreement with a previous study conducted by Dozza et al. (2005) which had demonstrated that auditory cueing can be used for upright balancing in patients lacking vestibular function. The auditory cues involved *artificial* pitch and volume changes of medial-lateral and anterior-posterior accelerations. The results from this present study demonstrate that natural cueing utilizing emphasized ITD and ILD information under optimal conditions from the auditory system can be utilized to balance sufficiently without information about the direction of gravity, and peripheral mechanisms such as leg reflexes and muscle stiffness. Further research, however, is needed to understand which aspects of the auditory cueing are most critical (position, velocity, or acceleration) to optimize auditory cues.

Where might this lead?

This finding could potentially be utilized for developing more advanced pilot training methods. It can also be used to improve rehabilitation techniques for those with impaired sensory systems. Vestibular disorders affect approximately 20% of the population (University of Iowa Healthcare, 2002) which is mainly a result of disease and aging. In patients with impaired vestibular organs, it is critical to determine how training with other sensory modalities can aid their ability to balance.

2. How did the fellowship make a difference?

The Link Foundation Fellowship gave me the opportunity to work on a project that was of interest to me that was not funded by the grants in my research lab. When I initially reviewed the literature on auditory spatial coding, I had found a lot of information on static spatial coding, but very little on the importance of dynamic auditory information. It was an honor being awarded this fellowship grant as it greatly allowed me to increase the level of creativity in my research as a PhD student. This grant also led to some invaluable collaborations with researchers in the field of auditory research.

3. Future Plans

My career plans are to make a transition from academia to industry as a data scientist. I intend to continue research to improve the quality of life in patients suffering from vestibular-related illnesses as well as other medical illnesses.

4. Publications, Presentations, and Other Outputs

The results of this study have not yet been presented at conferences; however, the findings will be presented in a paper that will be submitted within this year.

5. References

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