Effects of Visual-Vestibular Interactions on Navigation Tasks in Virtual Environments

Date of Report: September 1st, 2016

Fellow: Heather Panic

Advisors: James R. Lackner and Paul DiZio

Institution: Brandeis University

Department: Neuroscience

Contents

1. Narrative

Introduction

Virtual environments (VEs) are increasingly used as a safe, cost-effective way to train first responders and military units to search buildings and urban environments. Trainees typically view the VE on a computer screen while seated, although some newer training systems allow the trainee limited mobility within the training room while viewing the VE through a head- mounted display (HMD). In either case, the trainee's physical movements do not fully match the simulated movements within the VE. The goal of the work during the Link Foundation Fellowship was to determine what effect this mismatch has on a trainee's ability to navigate through the virtual environment.

Two distinct forms of navigation have been identified: "waypoint navigation", which uses external cues such as visible landmarks to guide a person along a route, and "dead reckoning", which uses signals generated internally by the body such as vestibular cues. These cues are produced by the vestibular organs of the inner ear as a person moves, and include cues from the semicircular canals, which detect angular accelerations, as well as cues from the otolith organs, which detect tilts and linear accelerations. The brain integrates the vestibular cues to infer how far a person has walked or how far a person has turned at a corner, even in complete darkness. Both of these navigation forms are used in daily life, even though we usually are not consciously aware of dead reckoning navigation.

VEs that lack a motion base or that incorporate limited motion cues force a mismatch between these two forms of navigation. Movements between visual landmarks in the virtual world are not matched by corresponding vestibular movement cues from the dead reckoning system. This mismatch could potentially lead to navigational errors by the trainee within the VE that would not exist in a real-world equivalent. This experiment investigated whether visual or vestibular cues are given more weight when a mismatch occurs.

The visual-vestibular mismatch was created by presenting visual tasks with an HMD while simultaneously presenting conflicting vestibular cues by angularly accelerating the individual around the yaw axis. The expectation was that the vestibular cues (yaw rotation) would combine with the visual cues to increase the sensation of linear or angular distance traveled. For example, if the visual turn in the VE was 30°, then a physical yaw acceleration of 1.0 $°/s^2$ would cause the participant to feel that they were turning through a larger angle than if no physical yaw acceleration was given.

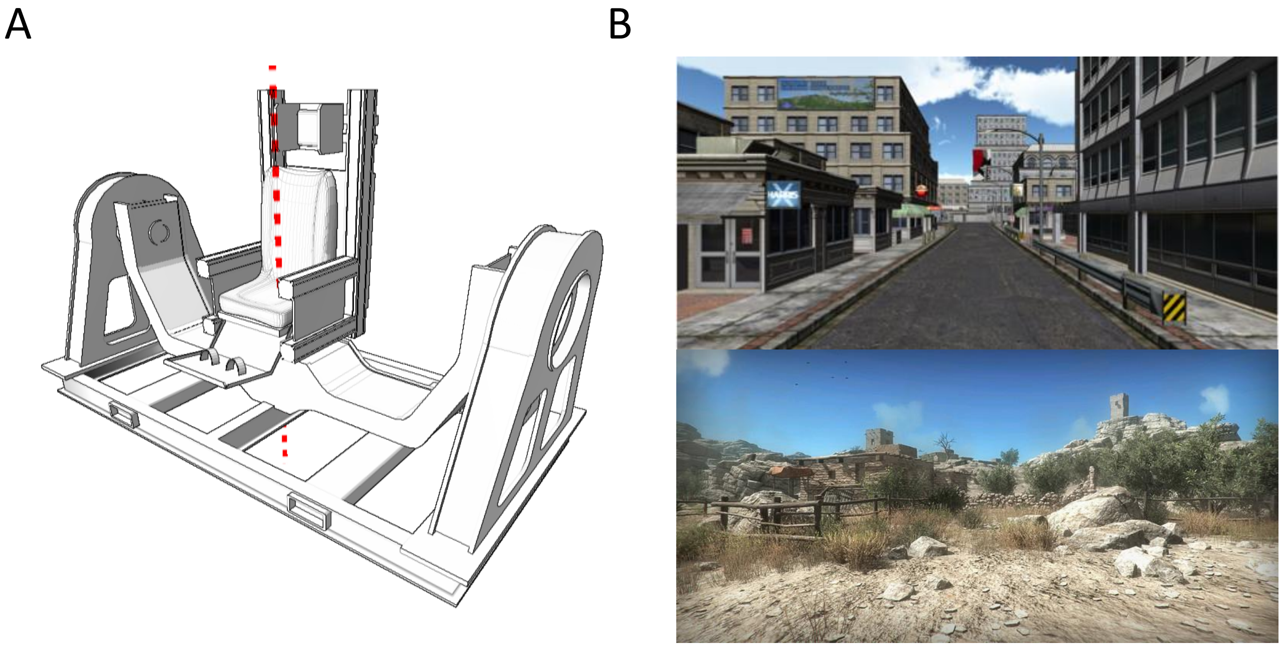

Figure 1. MARS device and virtual environments used. *Left: MARS device. The yaw axis (red dashed line) was aligned with the gravitational vertical. The reference yaw orientation of 0^o orients the chair facing forward, as shown. Positive angles in yaw rotate the chair clockwise. Right: Visual scenery used during training (top) and experiment (bottom). In both scenes, one unit in the virtual world equals one meter in the real world.*

Results

The primary apparatus was a NeuroKinetics Multi-Axis Rotation System (MARS) configured to rotate around the yaw axis (Figure 1a). An Oculus Rift HMD was used to present the VE for the navigation tasks (Figure 1b). The internal tracking system of the HMD was disabled to allow for a stable image while the individual was rotated. The HMD presented stereoscopic imagery at a resolution of 960x1080 pixels for each eye, with a refresh rate of 75Hz and a nominal field of view of 100^o. An isotonic joystick mounted on the right armrest of the MARS allowed the participant to control their movement through the VE.

The participants performed two different experimental tasks. In the first task, they were shown a linear forward displacement (5m or 8m) through a VE and instructed to remember the total distance traveled (demonstration phase). They were then placed at a new location within the VE and instructed to use forward-backward joystick inputs to move themselves through the VE by the same distance (replication phase). The movement speeds within the VE differed between the demonstration and replication phases so that timing alone could not be used to replicate the distance. In the second task, participants were instructed to note the angle through which they turned during the demonstration phase (30° or 50°), and then to use left-right joystick movements to turn through the same angle during the replication phase. The participant was physically rotated in yaw by the MARS during both the linear and angular tasks, at angular accelerations of 0 (none), 0.5 (medium), or 1.0 $°/s^2$ (high). Each combination of movement type, displacement, and yaw acceleration was repeated four times per participant.

Before the start of the experiment, all participants completed a familiarization session that included three trials at each distance and each displacement type, without yaw acceleration. Familiarization ended when the participant could complete all 12 familiarization trials without providing a response that was less than half or more than twice the correct value. Only one participant required an extra set of familiarization trials. An urban scene (Figure 1b, top) was used for familiarization, while an Afghanistan village scene (Figure 1b, bottom) was used for the experiment.

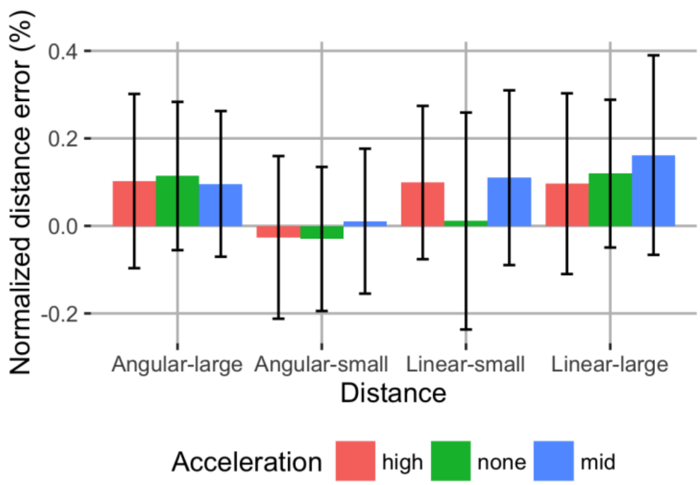

Figure 2. Normalized distance error across accelerations and displacements, N=6. The normalized distance error was calculated as the difference between the distance and the response, relative to the distance. Positive percentages correspond to underestimations of distance. Error bars represent one standard deviation.

A 2 (motion type: linear, angular) x 2 displacement (small, large) x 3 yaw acceleration (none, mid, high) ANOVA of normalized distance error showed main effects of motion type ($p<.025$) and distance ($p<.001$). Interestingly, there was no effect of the yaw accelerations ($p=0.36$). Tukey HSD showed that the normalized distance error was smaller when angular displacements were small ($p<.005$), while distance had no effect on linear displacements ($p=.415$).

Significance and impact

This experiment, in line with previous studies [1,2,3], found that observers underestimate distances in virtual environments and that the error increases as the distances increase.

Previous work has also shown [3] that proprioceptive cues from muscle movement do not improve linear distance estimations, suggesting that the cause of the underestimation is a mismatch of visual and vestibular cues. A recent study [4] that used linear accelerations instead of the angular accelerations used in this experiment found that visual and vestibular cues are optimally integrated: the visual and vestibular cues are given different weighting based on their presumed reliability. Results from the present study suggest that lateral semicircular canal signals do not contribute to the mismatch since yaw accelerations did not affect linear distance estimates. Surprisingly, angular distance estimates were also unaffected by the yaw accelerations. Since physical rotation in yaw is relevant to the task (estimating angular distance), one could expect that changing the yaw acceleration would affect the visual-vestibular cue integration, and thus the angular distance estimates. These findings suggest that visual-vestibular integration of lateral semicircular canal cues are not given the same sensory weighting as cues from the superior and posterior canals.

Where might this lead?

The novel finding that lateral semicircular canal cues do not affect visual perception of linear and angular distance opens up further avenues for investigation of visual-vestibular stimulation. With some changes to the experimental procedure, such as an increase in performance cutoff values during the familiarization phase, the experimental paradigm could be used to investigate the effects of superior and posterior canal stimulation on visual perception of linear and angular distance. A clearer understanding of visual-vestibular integration would allow training systems to be designed with sensory limitations in mind.

2. How did the fellowship make a difference?

The Link Foundation fellowship allowed me to work on a project of personal interest that was outside the scope of my thesis lab's other funding grants. Being awarded the fellowship increased my interest in conducting research as part of my future career, and I had many interesting and enlightening conversations with other researchers during the process of designing and conducting this experiment. I am thankful and honored to have been a Link Fellow.

3. Future Plans

I entered medical school after completing my PhD this summer. I intend to continue my research on visual-vestibular integration as an MD/PhD research physician. Specifically, I hope to investigate the use of head-mounted displays in the preparation of complex surgical procedures and for the treatment of vestibular deficits.

4. Publications, Presentations, and Other Outputs

This work has not yet been published or presented, but we plan to incorporate it into a paper on navigation within virtual environments.

5. References

[1] Wright RH. (1995) Virtual Reality Psychophysics: Forward and Lateral Distance, Height, and Speed Perceptions with a Wide-Angle Helmet Display (No. ARI-TR-1025). Army Research Institute for the Behavioral and Social Sciences, Alexandria, VA.

[2] Lampton DR, McDonald DP, Singer M, Bliss JP. (1995) Distance estimation in virtual environments. In: Proceedings of the human factors and ergonomics society annual meeting, 39(20), 1268-1272.

[3] Witmer BG, Kline PB. (1998) Judging perceived and traversed distance in virtual environments. Presence 7(2): 144-167.

[4] Ter Horst AC, Koppen M, Selen LPJ, Medendorp WP. (2015) Reliability-based weighting of visual and vestibular cues in displacement estimation. PLoS One 10(12): e0145015.