Mapping neural representations of heading direction and environmental context during imagined navigation of learned virtual environments

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Introduction

- Navigating about one's environment is a multi-faceted effort requiring a faithful representation of the visuospatial layout and one's position and orientation within a space.
- Mental imagery is known to play a key role in successful navigation; whether planning out one's own route or providing directions to others, we must mentally simulate a trajectory through space and conjure up representations of pertinent contextual details. Males and females are evidenced to employ different mental navigation strategies[1].
- In this fMRI study, subjects first learned their way around three unique virtual reality environments, and later were scanned while viewing or imagining specific navigational routes through each of these worlds.
- We used a searchlight-based multi-voxel pattern analysis approach to examine how the neural representations of one's environment and navigational trajectory change as a function of whether the navigation is perceived or imagined.

fMRI Methods

Acquisition & Preprocessing: Siemens 3T Tim Trio; CMRR Multiband EPI parameters: TR = 1.5s; TE = 33ms; Flip Angle = 90º; # slices = 60; Voxel Size = 2.25 x 2.25 x 2.5 mm^3; Multiband acceleration factor = 3; B0 Unwarping; HPF = 0.01 Hz.

Registration: For each subject, the middle volume of each run was used to create a subject-specific BOLD template to which all volumes were aligned using the ANTS diffeomorphic image registration software. Each subject's MPRAGE was aligned to both the BOLD template and MNI space using FLIRT. All analyses were conducted in this subject-specific BOLD template space, and the resulting stat-maps were warped to MNI space to facilitate group-level analyses.

Classification: We employed a multi-class SVM (polynomial kernel; penalty=1) within a whole-brain searchlight (5-voxel radius) mapping procedure. Single trial brain activity patterns were defined by averaging the middle third of the TRs acquired during that trial. We used a leave-one-run-out cross validation scheme to predict "Which World" the subject was viewing or imagining on each trial of the held-out run. Separate analyses decoded "Which Direction" (clockwise vs. counterclockwise) the subject was viewing or imagining.

Significance testing: Voxel-wise one-sample *t*-tests were used to determine if the distribution of classification accuracies across subjects differed from chance (33% for Which World classifications; 50% for Which Direction). We report voxels at $p<.005$ with a cluster extent ≥ 46 voxels, which yields a corrected threshold of $p<.05$. Results were also analyzed as a function of gender to showcase a divergence in the cortical areas that facilitated classification in males (N=13) and females (N=10). Direct across-gender contrasts were not performed due to low sample size. We are currently recruiting additional subjects to facilitate a sufficiently powered comparison.

Design & Stimuli

Day 1 (Lab)

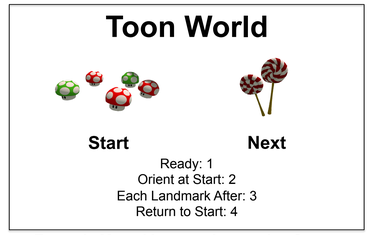
- After a VR "orientation session" subjects were teleported, in a random order, to one of three virtual environments, each populated with 8 distinctive landmarks at the cardinal locations along the periphery:

Lagoon World ***Toon World*** ***Ruin World***

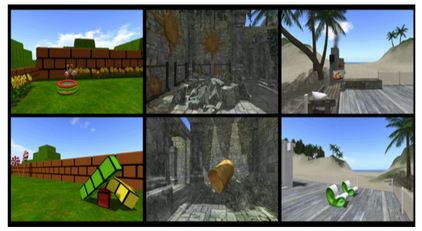
- Subjects (N=23; 13 Males) were given five minutes to collect 20 tokens scattered throughout the environment, using any remaining time to freely explore. Subjects were explicitly instructed to take note of each environment and relevant landmarks. Subjects were then cycled back through each environment and given three minutes to collect the same tokens as quickly as possible.
- Subjects also participated in "guided-navigation tasks" where they were instructed to move about each environment so as to pass by a designated sequence of major landmarks located at cardinal directions around the periphery.

Day 2 (Lab & Scanner)

- After more "guided-navigation" in the lab, subjects watched a series of 24 videos (8 from each world) in the scanner. The videos started at a landmark and circumnavigated the environment in either a Clockwise or Counter-Clockwise fashion. Videos were enforced to be 30s long.
- Subject were then instructed to close their eyes and mentally position themselves at a specified landmark in each environment. Their task was to navigate about the perimeter of the environment, making sure a particular landmark was the first they passed. This ensured 12 CW and 12 CCW mental navigation efforts that mirrored the trajectories seen in the videos.

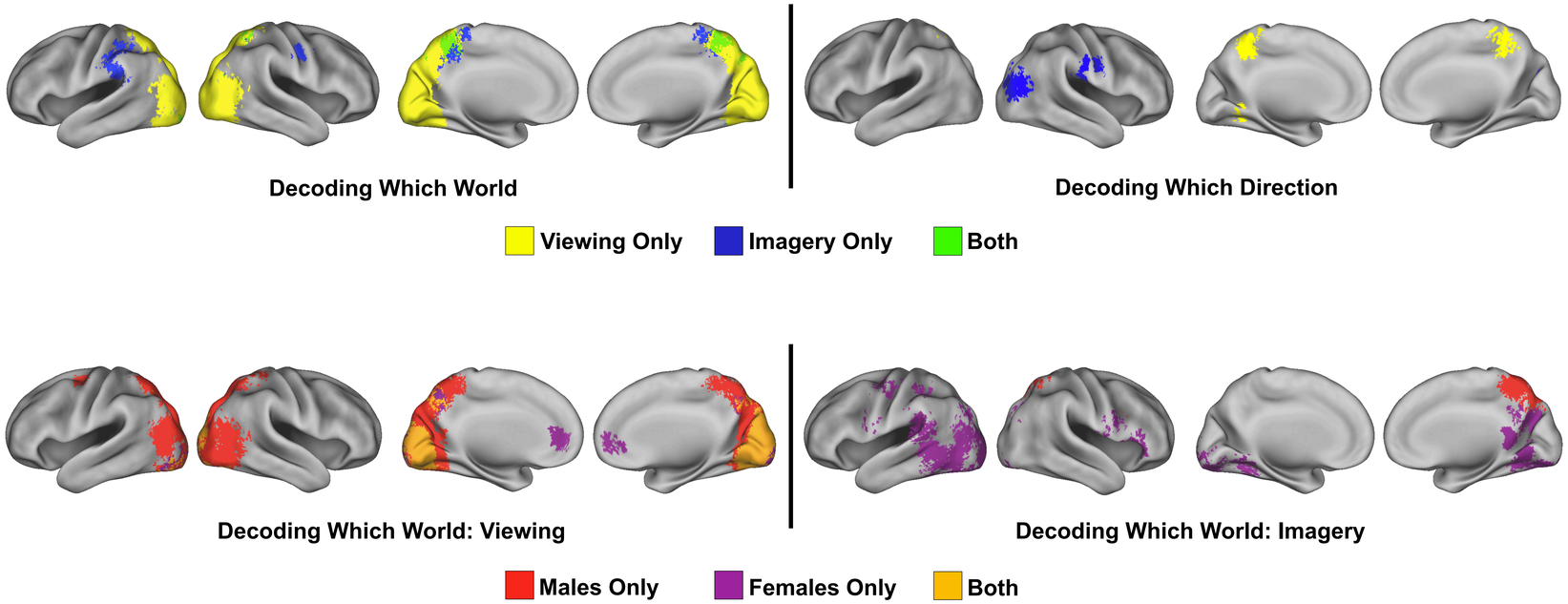


Example Mental Imagery Instruction Screen



Screenshots of Clockwise and Counter-Clockwise Videos

Searchlight Classification Results



Conclusions

- Unsurprisingly, the classifier was able to use patterns of BOLD data from early visual areas, the lingual gyrus, and visual association areas extending along the dorsal visual stream to decode which world a subject was actively viewing. Males and females showed a great degree of overlap in regions that could successfully decode which world a subject was viewing, such as early visual areas and the precuneus. However, males drove the visual association and lingual gyrus effects. Furthermore, a medial prefrontal region was exclusive to females. This could reflect that females were more actively *planning* the route they were viewing, whereas males merely allowed the visual scene to unfold[2].
- The classifier relied on similar visual areas to decode which world the subject was imagining, but only along the more abstract portions of the dorsal stream. Regions such as the supramarginal gyrus, a region known to play a role in mental imagery[3], exclusively contributed to decoding which world a subject was imagining. Males selectively showed significant decoding accuracy in the precuneus, which may indicate they took a more egocentric approach to completing their navigation[4]. Females, conversely, may have focused on visualizing the arrangement of the landmarks in a more allocentric fashion, indicated by succesful classification in visual association and retrosplenial regions.
- The classifier was also able to decode which direction subjects were viewing and imagining, but relied on entirely non-overlapping regions for each. During viewing, the classifier was most successful when pooling information from the precuneus and lingual gyrus. During mental imagery, it relied on information from visual association and SMA areas to reliably decode directional content.

References

1) Dabbs, J. M., Chang, E. L., Strong, R. A., & Milun, R. (1998). Spatial ability, navigation strategy, and geographic knowledge among men and women. *Evolution and Human Behavior*
2) Granon, Sylvie, and Bruno Poucet. (1995) "Medial prefrontal lesions in the rat and spatial navigation: evidence for impaired planning." *Behavioral neuroscience*
3) Kosslyn, S. M., Ganis, G., & Thompson, W. L. (2001). Neural foundations of imagery. *Nature Reviews Neuroscience*
4) Spiers, Hugo J., and Caswell Barry. "Neural systems supporting navigation."*Current opinion in behavioral sciences* 1 (2015): 47-55

This study was funded by:

1) Defense Advanced Research Projects Agency award (D13AP00057) to Dr. Jesse Rissman
2) National Science Foundation Graduate Research Fellowships awarded to both Nicco Reggente and Joey Essoe