The human mind/brain is capable of many important cognitive functions. Some are uniquely human, such as language, tool use, and analogical thinking. Others are shared with a wide array of species. Among the latter functions, navigation is notable for its universality: it is an essential challenge not just for humans and primates, but for all mobile organisms. **The goal of my work is to understand how human cognition and its neural underpinnings support effective navigation**. To achieve this goal, I study navigation using a multidisciplinary approach, incorporating insights and tools from cognitive psychology, neuroscience, and education. I apply this approach in three themes: how cognitive systems vary (**theme 1**); how they are neurally instantiated (**theme 2**); and how they can be assisted and improved (**theme 3**).

Theme 1: Understanding individual variability in navigation. There are enormous individual differences in people's ability to navigate. One reason is that navigation tasks vary drastically in the information they require. Uncovering the cognitive and neural correlates of distinct spatial navigation tasks can reveal why navigation is difficult for some, and how to improve it.

To this end, I created Virtual Silcton (Weisberg et al., 2014, *JEP:LMC*), a replica of a real-world college campus (Fig. 1A-B). In Virtual Silcton, participants learn the locations of multiple buildings along two main routes, then learn two routes that connect the main routes. At test, participants stand next to each building, and point to every other building. Results showed that individuals could not simply be defined as either good or bad navigators, but rather fell into three groups: one group was accurate in their pointing judgments; a second group was inaccurate; and a third group was accurate within main routes, but inaccurate between main routes (Fig. 1C). These results support the hypothesis that **navigation is not monolithic.**

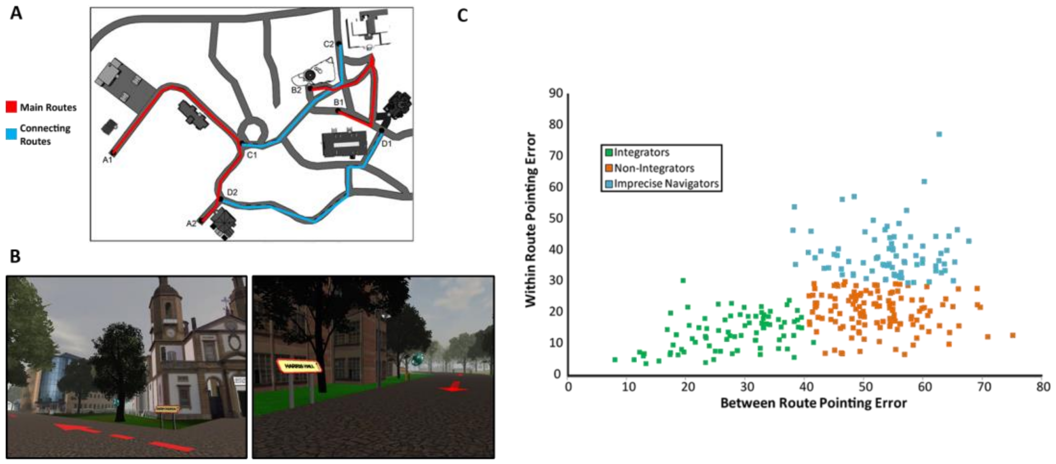

Figure 1. (A) The Virtual Silcton environment map view, which was never seen by participants. (B) Screenshots of Virtual Silcton environment displaying to-be-remembered buildings. (C) Performance on Virtual Silcton reveals individual differences on both within-route and between-route pointing.

This hypothesis yields new predictions about how cognitive processes relate to aspects of navigation behavior. Consider a navigator who must recall a series of turns at specific landmarks. Even if they can construct an accurate map, they may get lost if they cannot remember the turns and landmarks. Accordingly, I found that Virtual Silcton participants who pointed inaccurately to within-route locations performed significantly worse on measures of working memory, regardless of their performance between-route (Weisberg & Newcombe, 2016; *JEP:LMC*; Blacker, Weisberg, Newcombe, & Courtney, 2017, *Visual Cognition*).

Distinct navigation strategies, on the other hand, may afford similar spatial behavior. Consistent with this idea, accurate navigators in Virtual Silcton showed no preference for a place strategy, in which directions to landmarks are remembered (as opposed to a *response strategy*, in which specific turns along routes are remembered). Moreover, structural MRI data shows no relation between hippocampal volume (a brain region thought to underlie the place strategy) and accuracy on Virtual Silcton (Weisberg, Newcombe, & Chatterjee, *bioRxiv*). Integrating behavioral and neuroanatomical data, these findings challenge previous research that suggests a tight coupling between navigation strategy and ability.

Future work: Modeling spatial representations. A new hypothesis challenges the notion of a cognitive map (in which distances and directions are represented by Euclidean coordinates), proposing instead a cognitive graph (a network-like representation where landmarks are nodes and paths between them are edges). I am developing a novel analysis to test whether a cognitive map or graph better captures variability in Virtual Silcton. Preliminary results reveal that the cognitive map model better fits participant pointing judgments.

Future work: Navigation ability and outcomes in science, technology, engineering, and mathematics (STEM) disciplines? Success in STEM fields may require large-scale spatial thinking to better reason about landforms, countries, and solar systems. I previously conducted studies on how spatial information is communicated in a STEM context through maps (Atit, Weisberg, Newcombe, & Shipley, 2016, *CR:PI*), and diagrams (Cromley et al., 2016, *Science Education*). In the future, I will apply my work on individual differences in navigation ability to predict STEM achievement, mapping specific aspects of spatial navigation ability to aptitudes in STEM.

Theme 2: The neural basis of transforming spatial representations. As humans navigate, we follow maps, look at signs, and listen to directions. We must then associate this information to the real-world scenes in front of us. How are these different formats (maps, arrows, words, visual scenes) used to compute spatial directions? At the core of this question is the broader issue of whether representations are modality-specific (i.e., varied based on properties of the stimulus) or domain-general (i.e., abstracted to the conceptual level). Under the modality-specific hypothesis, neural representations of spatial directions are likely to be encoded in different brain regions depending on the format of the sensory information. Under the domain-general hypothesis, neural representations of spatial directions should be encoded using the same neuroanatomical substrate, irrespective of format.

I received an NRSA from the NIH to investigate this idea by using multivariate fMRI to identify the neural correlates of spatial directions across different representational formats (Weisberg, Marchette, & Chatterjee, 2018, *J. Neuro.*). I scanned participants with fMRI while they viewed spatial directions presented in one of three formats: words, schemas, or images (Fig. 2A). I used multi-voxel pattern analysis to determine which areas of the brain could decode spatial

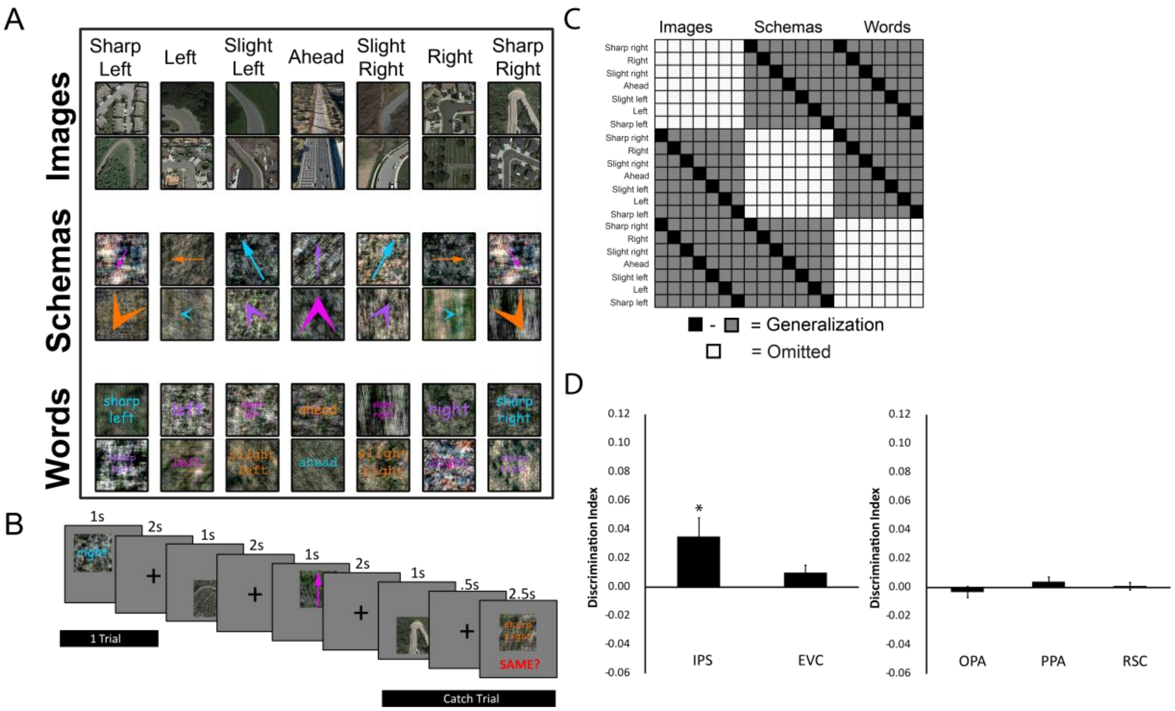

Figure 2. (A) Stimuli used in Weisberg, Marchette, & Chatterjee (2018, *J. Neuro.*). (B) Time course of the task participants performed in the scanner. (C) Theoretical correlation matrix. Black boxes are correlations between the same spatial direction across formats; gray boxes are different spatial directions across formats. Subtracting correlations in gray boxes from those in black boxes yields a Discrimination Index for spatial directions across formats. (D) Results show discrimination of spatial directions across-format in IPS. IPS = intraparietal sulcus. EVC = early visual cortex. OPA = occipital place area. PPA = parahippocampal place area. RSC = retrosplenial complex. *$p < .05$. Error bars = ± 1SEM.

directions across formats (Fig. 2B). ROI analyses revealed significant across-format decoding of spatial directions in intraparietal sulcus (IPS; Fig. 2C-D). In other words, despite distinct visual information, IPS contained a representation of spatial direction such that a ‘slight left’ image was more similar to a ‘slight left’ word or arrow than a different spatial direction. Combined with research on the IPS' role in processing body-centered spatial directions for action, **these results suggest a modality-independent code for spatial directions**.

Future work: Network properties of the brain in spatial direction processing. My neuroimaging work establishes IPS as a potential seat of spatial direction processing in the brain. Yet, format-specific processing still occurs in domain-specific regions (see Weisberg, Marchette, & Chatterjee, 2018, *J. Neuro.*). Using network neuroscience methods, I will model functional connectivity to test the hypothesis that the IPS functions as a hub, receiving domain-specific input (e.g., scenes or words) and transmitting spatial directions in a common code.

Future work: Applying real-time neurofeedback to improving spatial navigation. Promoting the engagement of IPS during spatial tasks may enhance spatial processing and recall, which may ultimately help navigators who require additional support. I am currently developing a real-time neurofeedback paradigm in which fMRI data are processed while the subject is in the scanner. In future work, I will measure activity in the IPS while participants complete spatial navigation tasks. I will then present average IPS activity back to participants in the form of an auditory tone that gets louder as their IPS is more active. Encouraging participants to engage their IPS more should result in improved spatial processing speed and possibly spatial memory.

Theme 3: Exploring technologies to improve and support navigation. Spatial navigation can be profoundly difficult, particularly for aging populations, and people with Alzheimer's disease. Tools like GPS, maps, and compasses could support navigation behavior, but my behavioral work reveals that we should pay attention to which navigational tasks to support. In one example of this approach, I investigated the effectiveness of a compass in two tasks: orienting to familiar landmarks and learning new ones. In a labyrinthine hospital, I taught participants landmarks along two different routes (Weisberg, Badgio, & Chatterjee, 2017, *JEP:LMC*). While navigating one route, participants wore a vibrotactile compass, which vibrated continuously toward north. Along the other route, participants navigated without the vibrotactile compass. Wearing the vibrotactile compass helped participants point toward familiar landmarks (around Philadelphia), but did not have any effect on pointing to newly-learned landmarks.

Why did the compass improve performance for familiar but not newly-learned landmarks? I modeled pointing responses as a function of where each participant thought north was. Without the compass, errors pointing to familiar landmarks were correlated with error for north. In other words, if a participant thought north was east, familiar landmark judgments rotated 90°. However, newly-learned landmark judgments rotated randomly, suggesting the compass was not helpful for learning new landmarks. These findings emphasize the multifarious nature of navigation: **a tool that helps with one process may not help with another**.

Future work: Applying basic science on spatial navigation to improve and support navigation behavior. GPS and sensory substitution devices offer an opportunity to promote easier and safer navigation, but how are they used? For example, GPS may ease the dual-task of driving and navigating by allowing the driver's attention to focus on the road, rather than on the next turn. But this may mean that the navigator develops a more impoverished representation of their environment. In this line of research, I will train and test users to learn environments with various forms of technology and seek to understand what specific information is conveyed and used during different navigation tasks.

Conclusion. My research program applies multiple disciplines, using tools from cognitive and developmental psychology, neuroscience, and education, to triangulate the variegated nature of spatial navigation. Importantly, this broad approach will make my research fundable through the NSF and NIH. As a faculty member, I plan on writing an NSF CAREER award focused on Themes 1 and 3 – improving spatial skills using technology with the goal of boosting enrollment and performance in STEM disciplines. I also plan on writing an R01, building off my F32 to NIDCD, focusing on Theme 2 – elucidating the network properties of the brain to enhance spatial communication in impaired populations. In sum, through human behavioral and neuroimaging research, I hope to gain insights into the mechanisms underlying navigation, which will ultimately allow us to support and improve it.