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SHARED CORTICAL ARCHITECTURE OF SPATIAL NAVIGATION AND PLANNING: A COMPREHENSIVE META-ANALYSIS

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Abstract

Planning is a crucial aspect of spatial navigation and visuospatial tasks, relying on both shared and distinct neural mechanisms, which are not yet fully understood. We conducted an Activation Likelihood Estimation (ALE) meta-analysis on fMRI studies examining active, goal-directed navigation and visuospatial planning tasks (i.e., the Tower of London paradigm). Conjunction and contrast analyses revealed a shared network encompassing bilateral frontal regions, including the superior frontal gyrus (SFG), middle frontal gyrus (MFG), anterior insula (INS), and clusters in the left supplementary motor area (SMA) and right inferior frontal gyrus (IFGtriang). Contrast analyses highlighted greater involvement of the hippocampus (HIP) and parahippocampal gyrus (PHG) in navigation, and posterior parietal and dorsolateral prefrontal regions in visuospatial planning. These findings elucidate the neural mechanisms involved in these processes, highlighting the common amodal regions that play a role in both visuo-spatial planning and spatial navigation. This study offers a deeper understanding of the fundamental deficits linked to neurodevelopmental disorders and brain injuries.

Keywords: *Human navigation, visuo-spatial planning, travel planning, ALE meta-analysis, fMRI.*

1. Introduction

Spatial navigation and visuo-spatial planning are intricate cognitive functions governed by interconnected yet distinct neural systems. Spatial navigation focused on mapping out routes to a destination, relying on the medial temporal and prefrontal regions of the brain for support (Spiers & Gilbert, 2015; Bonner & Epstein, 2017). Visuo-spatial planning, evaluated through tasks such as the Tower of London, engages the prefrontal cortex to orchestrate multi-step actions (Shallice, 1982). Despite differing domains, both processes involve goal representation and strategic decision-making, suggesting possible shared neural substrates (Nitschke et al., 2017).

2. Objectives

This study sought to uncover the shared and distinct neural substrates involved in spatial navigation and visuo-spatial planning through an ALE meta-analysis. By examining fMRI studies of goal-directed, first-person navigation alongside ToL-based planning, we aimed to identify areas of common activation and functional specialization. We hypothesized that there would be overlapping activity in the prefrontal regions, as well as distinct contributions from the medial temporal lobe specifically related to navigation (Kaplan et al., 2017).

3. Methods

In accordance with PRISMA guidelines, we carefully selected fMRI studies focused on active, goal-directed navigation and ToL planning. Only studies that used whole-brain analyses and reported MNI/Talairach coordinates in healthy adults were selected for inclusion. The ALE analyses were performed using Ginger ALE software with Family-Wise Error (FWE) correction (Eickhoff et al., 2012). Additionally, conjunction and contrast analyses were employed to compare patterns across the two domains.

4. Results

Spatial navigation analysis revealed bilateral activation in key brain regions, including the hippocampus, parahippocampal gyrus, fusiform gyrus, and prefrontal areas. In contrast, visuo-spatial planning analysis highlighted bilateral activation of the dorsolateral prefrontal and parietal cortices, alongside additional clusters in the anterior insula and caudate. A conjunction analysis revealed overlapping activity in the bilateral superior and middle frontal gyri, anterior insula, and left supplementary motor area (SMA; Figure 1). Navigation > Planning contrast highlighted medial temporal areas, while Planning > Navigation showed greater parietal and basal ganglia involvement (Figure 2).

Figure 1. Conjunction results showing shared activations between spatial navigation and visuo-spatial planning.

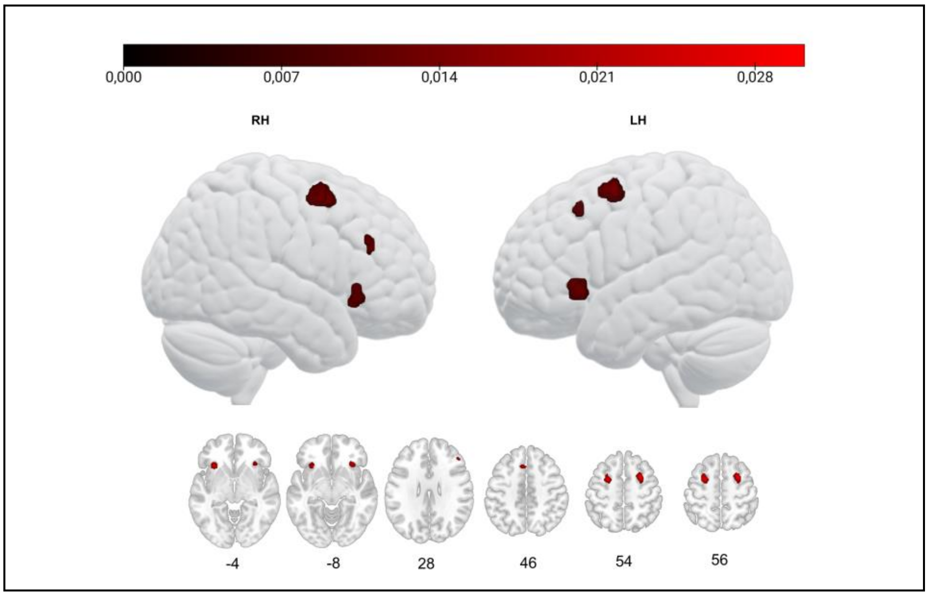
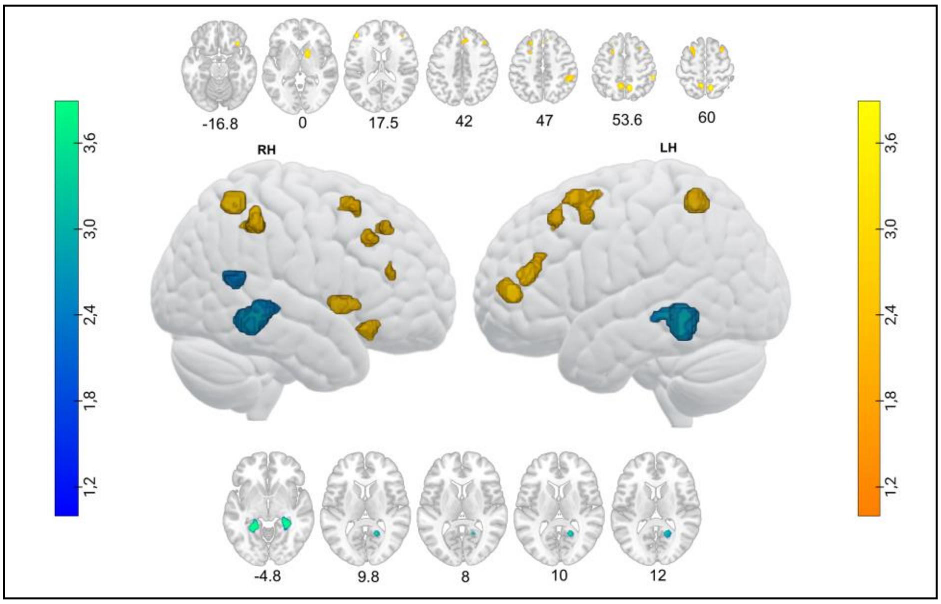


Figure 2. Contrast results showing spatial navigation > planning (blue) and planning > spatial navigation (yellow).



5. Discussion

Our findings indicate that spatial navigation and visuospatial planning activate a common neural network that includes the prefrontal cortex (PFC) and anterior insula (INS), which are critical for high-level cognitive regulation (Milner, 1982; Shallice, 1982; Spiers & Gilbert, 2015). Specifically, the dorsomedial (SFG/MFG) and right lateral PFC (MFG) support strategic planning and decision-making, aligning with models that connect the PFC to goal-directed behaviour and adaptive control (Ito, 2018). Additionally, the anterior INS, recognized for its role in processing sensory cues and directing goal-oriented actions, enhances a flexible and context-sensitive network (Craig, 2002).

Despite these shared areas, distinct activations emerged: spatial navigation mainly involved the medial temporal structures (HIP/PHG), crucial for visuo-spatial memory and spatial orientation (Burgess, 2000; Ito, 2018). In contrast, visuospatial planning engaged on fronto-parietal regions and the caudate, which aid in sequential reasoning and action selection (Nitschke et al., 2017; Kaplan et al., 2017). These findings underscore the hierarchical structure of the PFC, demonstrating its adaptability to a range of different cognitive tasks—from navigation to abstract planning—through a functional division of labor among its subregions (Patai & Spiers, 2021).

6. Conclusion and future directions

Our findings show that spatial navigation and visuospatial planning rely on a shared prefrontal-insular network, with the medial temporal lobe aiding navigation and fronto-parietal regions supporting planning. The prefrontal cortex plays a crucial role in goal-directed tasks, highlighting its significance in cognitive control. These results provide insights into the neural mechanisms that drive cognitive processes, revealing significant implications for disorders that impact spatial behavior and planning abilities. Clinical applications may involve personalized interventions for individuals with difficulties in navigation and planning deficits. Future research should focus on real-world tasks, the complexity of these tasks, and the influence of working memory, deepen our understanding of how these brain regions interact.

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