Assessing Large-Scale Spatial Abilities in Real and Virtual Environments

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Significance of the Topic and Method

Large-scale spatial abilities have long been recognized as a central component of human cognition, underlying navigation, wayfinding, and the integration of spatial information across extended environments. They not only play an important role in everyday life such as in personal mobility or in various job settings, but are also an essential part of research in cognitive science. This particularly concerns areas such as cognitive development (e.g., in children), medical research on age-related diseases (such as dementia), sports and physical activity, architecture, and other fields that depend on the understanding and use of space at the environmental scale. Despite their importance for everyday functioning and learning (Wai et al., 2009; Newcombe, 2016; Hawes et al., 2022), these abilities have remained comparatively underrepresented in standardized assessment research. Widely used instruments such as mental rotation or spatial visualization tests target situations in which spatial information can be apprehended from a single viewpoint and manipulated without bodily movement (small-scale spatial abilities). Research has repeatedly shown that performance on such tasks overlaps only partially with performance in navigation and wayfinding, suggesting that large-scale spatial abilities involve additional cognitive processes related to embodiment, sequential decision-making, and the integration of spatial information over time (Hegarty et al., 2006; Montello, 2005; Li et al., 2019; Lasc et al., 2023). While small-scale spatial abilities are routinely measured using well-established psychometric instruments, large-scale spatial abilities are most commonly investigated using navigation tasks that are tailored to specific experimental settings. As a consequence, studies often rely on highly heterogeneous environments, task designs, and outcome measures, which substantially limits comparability and standardization across studies.

Navigation tasks constitute the dominant empirical approach to studying large-scale spatial abilities, but their methodological implementation varies widely. Experimental setups differ in environmental layout, realism, interaction techniques, and navigational affordances, both in real-world and virtual settings. Even when virtual reality is used as a supposedly standardized medium, psychological studies differ considerably in how environments are designed, how movement is realized, and which aspects of spatial behavior are emphasized. As a result, findings across studies are difficult to integrate into a coherent picture of large-scale spatial cognition.

At the same time, measurement practices in spatial cognition research often rely on highly reduced outcome variables. Common measures include task completion time, path length, or the number of errors, which capture only coarse summaries of spatial behavior. Such measures largely ignore the rich temporal and spatial structure of navigation, including how individuals orient themselves, how they explore environments, how strategies unfold over time, and how spatial decisions are adapted in response to environmental cues. In real-world navigation studies, this reduction is often unavoidable, as continuous observation of movement, orientation, and interaction is difficult to achieve without substantial technical support. However, focusing on a small set of aggregate measures provides only a limited window into the cognitive processes underlying large-scale spatial behavior.

Recent technological advances fundamentally change this situation. Digital and immersive technologies enable researchers to continuously record spatial behavior with high temporal and spatial resolution. Navigation trajectories, orientation changes, rotations, speed, pauses, and interactions with spatial representations can be captured automatically and synchronously (Pastel et al., 2022; Dong et al., 2021). Empirical work has demonstrated that navigation behavior in virtual environments captures meaningful individual differences and relates to real-world wayfinding performance, supporting the use of VR as a valid assessment context for large-scale spatial abilities (Coutrot et al., 2019; Shimada et al., 2016). Rather than inferring spatial cognition from a single endpoint or summary statistic, researchers can observe how spatial behavior unfolds moment by moment within its spatial context. This opens the door to a more comprehensive and process-oriented understanding of large-scale spatial cognition, but it also requires tools that systematically integrate task design, data collection, and analysis.

This tutorial addresses these challenges by introducing the app **GeoGami**, a tool designed specifically to support the standardized assessment of large-scale spatial abilities in real-world and virtual environments. GeoGami provides a unified framework for designing navigation and map-based tasks, deploying them across contexts, and collecting rich behavioral data in a consistent format. By combining maps with embodied navigation in real space, head-mounted virtual reality, and on-screen virtual environments, GeoGami enables researchers to study large-scale spatial cognition under controlled yet ecologically meaningful conditions.

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Crucially, GeoGami moves beyond traditional outcome measures by automatically recording continuous spatial behavior. Navigation trajectories, orientation and rotation data, interaction events, and performance outcomes are logged in a structured format, allowing researchers to analyze not only whether a task was solved, but how it was solved. This makes it possible to link established theoretical constructs in spatial cognition to detailed behavioral signatures and to compare spatial behavior across tasks, environments, and participant groups.

By integrating standardized task design with fine-grained behavioral measurement, GeoGami responds directly to long-standing methodological limitations in spatial cognition research. The tutorial builds on this approach to demonstrate how contemporary technology can be used to move beyond isolated navigation tasks and coarse self-report or performance measures toward a more comprehensive, comparable, and theory-driven assessment of large-scale spatial abilities.

Structure and Activities of the Tutorial

The tutorial is organized as a half-day session of approximately four hours and follows an interactive, methods-oriented format that alternates between conceptual input, tool demonstrations, and hands-on activities.

The tutorial begins with a focused discussion of the challenges associated with assessing large-scale spatial abilities. This part situates large-scale spatial cognition within established frameworks that distinguish spatial abilities by scale and highlights why common psychometric instruments capture only a subset of spatial cognition relevant to navigation and map use (Montello, 1993; Hegarty et al., 2006). The discussion emphasizes the trade-off between experimental control and ecological validity that characterizes existing assessment approaches and motivates the need for digital and immersive methods.

The second part introduces GeoGami as an assessment tool. Participants are familiarized with the conceptual design of GeoGami and its relevance for measurement rather than with technical implementation details. The tutorial explains how GeoGami integrates maps with real-world and virtual environments, including both head-mounted VR and on-screen VR. Participants are shown how tasks are structured, how spatial interaction is logged, and what types of data are generated during task execution. These include performance measures as well as detailed process data such as navigation trajectories, orientation changes, and interactions with spatial representations, stored in a standardized GeoJSON format.

Building on this introduction, the core methodological part of the tutorial focuses on translating established spatial cognition tasks into GeoGami-based assessments. Rather than introducing new task taxonomies, this section explicitly connects GeoGami to familiar paradigms from spatial cognition research. Examples include landmark-based tasks, self-location and target-location judgments, direction and orientation tasks, and route-following or route-reconstruction tasks. For each example, the tutorial discusses which cognitive processes are targeted, how task difficulty can be manipulated, and how tasks can be implemented consistently across real-world and virtual environments. Particular attention is given to tasks that require transformations between maps and environments, as these transformations are central to navigational map use and large-scale spatial cognition (Liben & Downs, 1989; Thorndyke & Hayes-Roth, 1982; Lobben, 2007).

Following a short break, participants engage in a hands-on session in which they design and implement their own GeoGami tasks. Working in small groups, participants define the target spatial ability, select a real-world or virtual environment, and create a corresponding task within GeoGami. Tasks are then run within the group, allowing participants to experience GeoGami both as designers and as participants. Head-mounted VR devices as well as laptops or tablets with on-screen VR are provided, enabling comparison between different modes of spatial interaction.

In the subsequent data analysis session, participants receive the player data generated during the hands-on activities. Using GeoGami's integrated analysis tools, they explore performance outcomes alongside process data such as navigation trajectories and interaction patterns. This session illustrates how rich behavioral data can inform the assessment of large-scale spatial abilities and how process-oriented analyses can complement traditional outcome measures.

The tutorial concludes with a discussion of applications and open challenges. Topics include scalability, comparability across environments and age groups, and the role of digital tools in advancing the assessment of large-scale spatial cognition in cognitive science research.

Credentials of the Tutorial Organizers

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