Geography and the Brain's Spatial System

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Abstract

Extensive research in spatial cognition and mobility has advanced our knowledge about the effects of geographic settings on human behaviors. This study, however, takes an alternative perspective to examine how the brain's spatial system may mediate the geographic effects on spatial behaviors. Our previous research using data from OpenStreetMap, SafeGraph POIs, and human participants from the National Alzheimer's Coordinating Center (NACC) resulted in a model with 83.33% prediction accuracy from geographic settings to the zonal categorization of the cognitive state based on NACC participants. A follow-up study showed that the complexity of a geographic setting has a direct effect on cortical thickness in the brain's spatial cell system. In this study, we leverage findings from the two studies and interrogate the geographic settings to discern environmental correlates to zonal cognitive categorization. We conclude with thoughts on the implications of brain-inspired GIScience.

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1 Introduction

Tolman's [13] concept of cognitive maps, as an essential mental representation of space, prevails in GIScience literature. The discoveries of place cells [8] and grid cells [7] in the hippocampal formation in mammalian brains gave new insights into cognitive maps with neural connections and activities. Yet recent advances in neuroscience unveiled the brain's spatial system much different from the conventional GIS. Although what works in the brain may not be the most effective strategy for computer systems, understanding the brain's spatial system may provoke new ideas for spatial encoding or algorithms that are more flexible and perhaps more powerful than what the prevalent GIScience research can offer.

This study is part of a larger project that investigates the correlative effects of environmental complexity on Mild Cognitive Impairment (MCI) and Alzheimer's Disease (AD). The project is based on the premise that people living in a geographically more complex environment are more often able to retrieve information on spatial relations among landmarks and places when navigating the environment. Traffic dynamics further motivate them to build cognitive maps and recall route options. MCI and AD diseases weaken such cognitive mapping abilities as four out of 10 early warning signs of dementia relate to spatial functions (Figure 1).

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Figure 1 Four out of 10 early warning signs of dementia are related to spatial cognition: 4, 6, 7, and 9.

Moreover, neural research showed early neuropathology of AD in the brain's spatial system [11], leading to spatial navigation impairments which differentiated MCI and AD patients from healthy aging adults [9, 1]. We hypothesize that regularly navigating a complex environment can strengthen the brain's spatial system responsible for cognitive map building and lead to non-pharmaceutical mitigation of MCI and AD.

The next section highlights key ideas and findings from the two previous studies as background information. We will then report findings from this study on environmental measures that correlate to zonal cognitive categorization. From the findings and recent advances in the brain's spatial system, we contrast the brain's spatial system with GIScience approaches to spatial representation and computing for potential new ideas moving forward in GIScience.

2 Our recent studies

Lynch's seminal work: *The Image of the City*, defined the concept of city legibility by the pattern of interrelations among five elements: paths, edges, districts, nodes, and landmarks [6]. Our previous study followed Lynch's ideas to compute network measures and points of interest (POI) to represent the complexity of an environment, with which we developed a neural network model to predict zonal cognitive status based on NACC participants' cognitive tests and diagnoses across the US [14]. Both environmental and cognitive measures were summarized into 3-digit zipcode zones, the finest spatial resolution available to researchers. We categorized the cognitive status (normal or AD-inclined) for 154 individual zipcode zones based on cognitive diagnoses (normal, MCI, or AD) of 22,553 NACC participants. Taking the approach of categorical prediction commonly used in medical science, we developed a neural network model that used environmental measures (discussed in Section 3) to predict the cognitive status of each zipcode zone. The input data inherited high spatial heterogeneity and spatial uncertainty. These 3-digit zipcode zones varied from less than 2 to more than 35,000 km^2. More often than not, environmental measures and cognitive diagnoses were unevenly distributed within individual zones. Participants might travel across zipcode zones or relocate across zones. Other researchers showed PM2.5, ozone, nitrogen dioxide and nanoparticles and other environmental factors might increase the risk of MCI and AD [5, 4, 10]. Despite the massively noisy data, the model was able to make predictions at 83.87% accuracy, 95.23% precision, 83.33% recall, and 0.89 F1-score. The model suggested AD-inclined zones likely associated with longer street segments, higher circuity, and fewer points of interest (i.e., lower environmental complexity).

Following the initial study, Shin (2023) explored the associations among environmental complexity, regional brain volumes and cortical thicknesses, against diagnoses of 660 NACC participants with structural brain MRI images[12]. The study compared two sets of brain regions (Figure 2): (1) the hippocampus and the parahippocampal cortex, and posterior cingulate cortex responsible for the allocentric frame of reference in which locations of entities and their relations are external to and independent of the agent who interacts with the environment; (2) the posterior parietal cortex, responsible for the egocentric frame of reference in which all entities, their locations, and relations are based on the agent's location and perspective. ANOVA analyses suggested no interactions between environmental complexity and age on MCI/AD diagnoses, while both showed significant associations. Shin then applied structural equation modeling (SEM) to test the effects of environmental complexity and age on AD diagnoses and the brain's egocentric and allocentric regions and spatial cognition. His SEM suggested a significant effect of higher environmental complexity on a greater volume in the brain's allocentric regions, but not in the egocentric regions. The SEM also suggested a significant pathway with higher environmental complexity to higher allocentric volume then to lower MCI/AD diagnosis. However, the direct effect of environmental complexity on MCI/AD was insignificant. Shin concluded that the relationship between environmental complexity and spatial cognitive deficits in MCI/AD was indirect and was mediated by the brain's allocentric regions. Compared to other social and economic determinants (like gender, income, and education), the direct association of environmental complexity and the allocentric brain implied possibilities of geographically induced neural plasticity and a new role for geography in non-pharmaceutical interventions to MCI and AD.

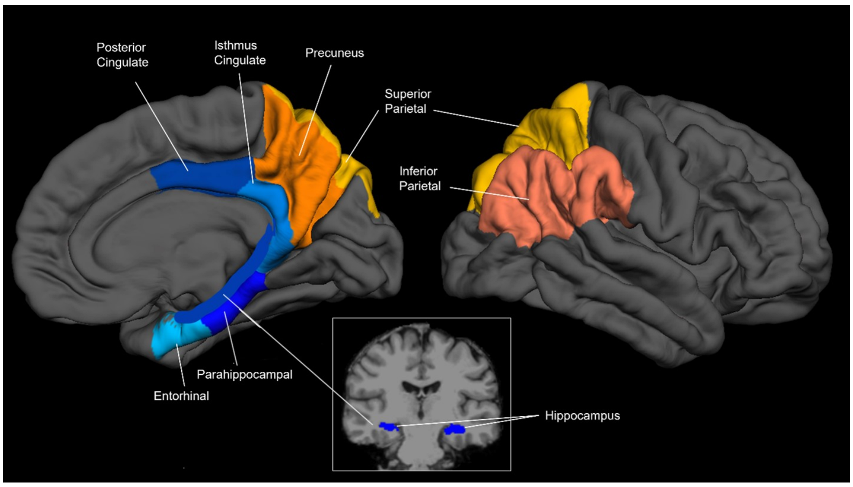
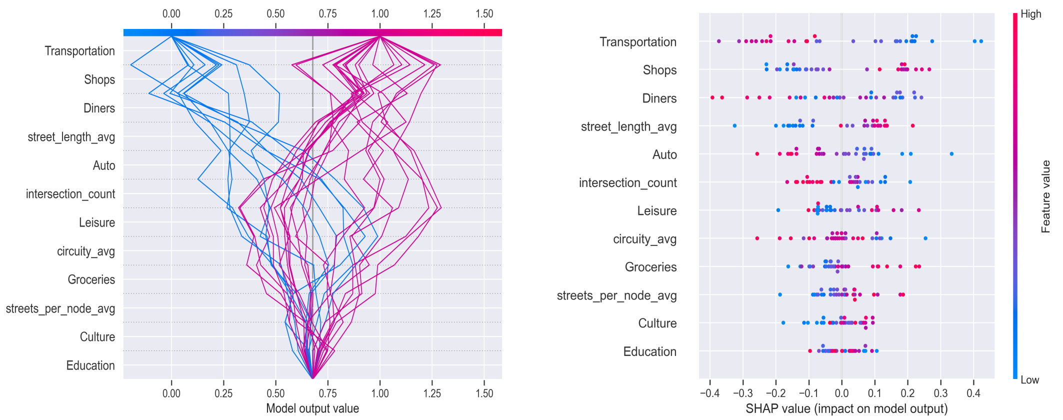


Figure 2 Distinct brain regions responsible for allocentric (blue shades) and egocentric (orange shade) frames of reference. Adapted from [12].

3 Environmental measures, zonal cognitive prediction, and the brain's allocentric system

Initially, we considered 40 environmental measures from street networks, POI types, and POI distributions. We reduced the number of environmental measures to 12 by removing highly correlated measures and those with extremely skewed distributions across zipcode zones. We applied Shapley additive explanations (SHAP) tools to evaluate the contributions of these environmental measures to model prediction on the test data (Figure 3). The model predicted binary zonal categories: 0 for cognitively-normal zones and 1 for AD-inclined zones. All POI measures (transportation, shops, dining, auto, leisure, groceries, culture, and education) and intersection counts were linear density measures (i.e., frequency over total street length in a zone). Education institutions, cultural landmarks, and averaged number of streets per node (streets_per_node_avg) contributed minimally to the model prediction, while intersection counts, auto services, averaged street length, diners, shops, and transportation stations appeared as major discriminators to differentiate normal from AD-inclined zones. Moreover, more transportation stations, diners, auto services, and intersection counts as well as shorter averaged street lengths appeared as the primary push for "normal" predictions (Figure 3b). The other environmental measures showed large overlaps between measures and model prediction and gave mixed signals on their effects on model prediction.



(a) Contributions of environmental measures to model prediction.

(b) Correlations of model prediction with environmental measures.

Figure 3 Twelve environmental correlates for zonal categorical predictions.

The measure of shop density over street length was counter-intuitive as higher shop density was more correlated to "AD-inclined" prediction (Figure 3b). We consider two possible explanations. First, zoning regulations restrict shops clustered in malls or plazas in the US. Therefore, shops are seldom evenly distributed along a street, so the shop density over unit street length is unlikely meaningful in many US places. Second, except for major stores, such as the Home Depot, Macy's, or Barnes & Noble, shop signage is often invisible from the street. Therefore, most shops likely provide little help for spatial cognition but may create complications in learning the environment.

The primary environmental measures (transportation, diners, average street length, auto services, and intersection counts) relate well with the brain's spatial system for allocentric navigation: grid cells, place cells, head orientation cells, boundary cells, object vector cells, and goal direction cells (Figure 4). Grid cells reside primarily in the entorhinal cortex. Each grid cell is responsive to locations in a hexagonal configuration. Grid cells located towards the dorsal end of the entorhinal cortex are responsive to finer hexagonal grids. Head direction cells, boundary vector cells (a.k.a border cells), object vector cells, reward cells, goal direction cells, place cells, and social place cells in the hippocampal formation have specialized firing fields when the agent (i.e., animals or humans) faces a particular direction, nears a boundary, observes objects, seeks a goal, and recognizes a reward location, one's own location, or locations of one's own kind. Grid cells provide the allocentric reference frame necessary to position objects, boundaries, destinations, one's own location, and others' locations in a common framework and create a cognitive map. The major environmental measures contributed to our prediction model correspond to edges, connections, and nodes in creating navigation routes. Nodes likely correspond to object vector cells, connections to head direction cells, and edges to boundary cells. As one navigates in a geographic environment (i.e., the entire environment is not visible from a single vantage point, and learning the environment requires one to traverse through the environment and mentally integrate spatial observations and experiences from location to location), the sequential firings of place cells and head direction cells, as well as other spatial cells, in the common framework provided by the grid cells allow the hippocampus to construct a cognitive map and perform path integration. Degradation in the entorhinal cortex and hippocampus leads to spatial dysfunctions commonly observed in early MCI and AD patients [1, 3].

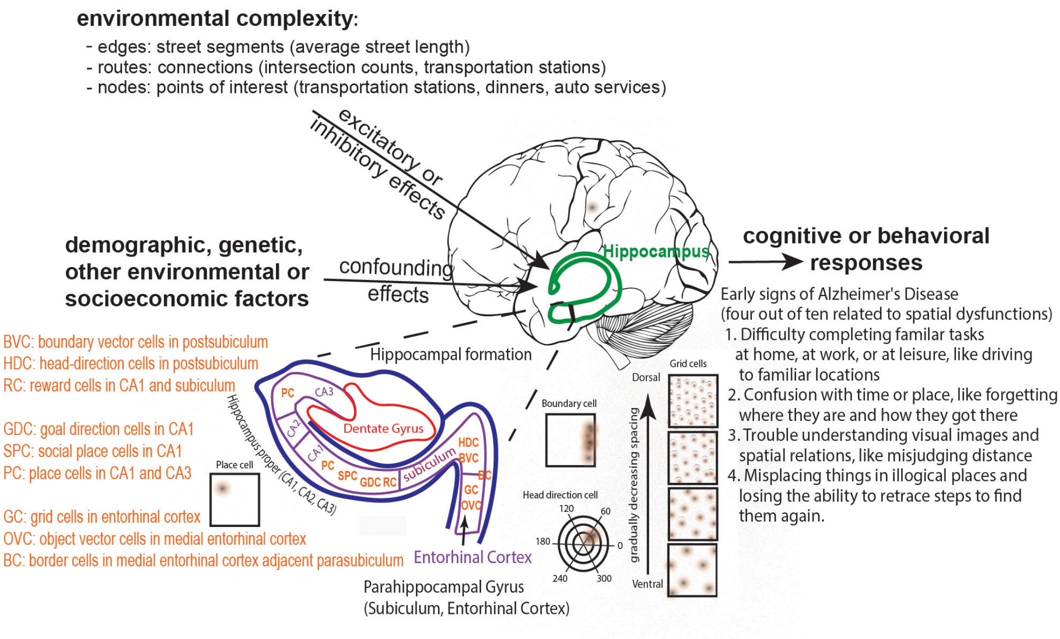


Figure 4 Environmental complexity, the brain's spatial system, and spatial cognitive degradation.

There are many neural implications for GIScience. We highlight three points here. First, the multiple resolutions of grid cells collectively fire to transmit signals to downstream spatial cells. Simultaneously imposing hexagon configurations of varying resolutions allows for capturing the bigger picture and fine details for everything, everywhere, all at once. On the contrary, GIS data or functions commonly stay in one scale or resolution. A common practice is to separate data at different resolutions into separate layers or sets. Vertical integration of data representing different themes at different resolutions remains underdeveloped.

Secondly, a place cell's firing field is context-dependent. As one moves from one environment to another, place cells remap firing fields accordingly. Only sparse place cells fire in a given environment. Among the place cells that fire, some place cells fire immediately, but others fire late. The fast-firing place cells are generalists, rapidly recognizing the general spatial configuration of one's location; for example, I am in a school. The late firing place cells refine location recognition to, say, my daughter's high school. By doing so, the brain's allocentric system allows one to recognize the kind of environment quickly and then the specifics of the environment. On the other hand, grid cells have no remap functions, hence providing persistent references to different environments and facilitating spatial integration across environments. Research on geospatial ontology and semantic knowledge graphs has been building hierarchical structures of geographic kinds. Multiple place cells with different responses may give rise to algorithms for ontological or semantic computing.

Thirdly, the current GPS design gives users turn-by-turn instructions or has users follow a blue dot in close view without any geographic context. Even when we safely arrive at a destination on time, we have no idea about where we are and what we have passed by. Like people losing arithmetic skills due to over-reliance on calculators, the popularity of GPS navigation systems likely deskills people's spatial cognition and wayfinding, or worse yet, increases the risk of MCI and AD. Redesigning GPS navigation systems should attend to means that can encourage cognitive map building and attend to geographic contexts. New auditory GPS, for example, promises a viable alternative [2]

The brain encodes and processes spatial information differently from conventional GIS technologies. Many AI researchers seek inspiration from neuroscience to develop new algorithm architectures or learning pipelines. GIScience researchers should also explore the brain's spatial functions, not only for GeoAI but for Brain-inspired GIScience.

References

1. Jiri Cerman, Andel Ross, Jan Laczo, Vyhnalek Martin, Nedelska Zuzana, Mokrisova Ivana, Sheardova Katerina, and Hort Jakub. Subjective spatial navigation complaints-a frequent symptom reported by patients with subjective cognitive decline, mild cognitive impairment and alzheimer's disease. *Current Alzheimer Research*, 15(3):219–228, 2018.
2. Gregory D Clemenson, Antonella Maselli, Alexander J Fiannaca, Amos Miller, and Mar Gonzalez-Franco. Rethinking gps navigation: creating cognitive maps through auditory clues. *Scientific reports*, 11(1):1–10, 2021.
3. DP Devanand, G Pradhaban, X Liu, A Khandji, S De Santi, S Segal, H Rusinek, GH Pelton, LS Honig, R Mayeux, et al. Hippocampal and entorhinal atrophy in mild cognitive impairment: prediction of alzheimer disease. *Neurology*, 68(11):828–836, 2007.
4. Carles Falcón, Mireia Gascon, José Luis Molinuevo, Grégory Operto, Marta Cirach, Xavier Gotsens, Karine Fauria, Eider M Arenaza-Urquijo, Jesús Pujol, Jordi Sunyer, et al. Brain correlates of urban environmental exposures in cognitively unimpaired individuals at increased risk for alzheimer's disease: A study on barcelona's population. *Alzheimer's & Dementia: Diagnosis, Assessment & Disease Monitoring*, 13(1):e12205, 2021.
5. Caleb E Finch and Alexander M Kulminski. The alzheimer's disease exposome. *Alzheimer's & Dementia*, 15(9):1123–1132, 2019.
6. Kevin Lynch. *The image of the city.* MIT press, 1964.
7. Edvard I Moser, Emilio Kropff, and May-Britt Moser. Place cells, grid cells, and the brain's spatial representation system. *Annu. Rev. Neurosci.*, 31:69–89, 2008.
8. John O'Keefe and Jonathan Dostrovsky. The hippocampus as a spatial map: preliminary evidence from unit activity in the freely-moving rat. *Brain research*, 1971.

9 Martina Parizkova, Ondrej Lerch, Scott Douglas Moffat, Ross Andel, Adela Fendrych Mazancova, Zuzana Nedelska, Martin Vyhnalek, Jakub Hort, and Jan Laczó. The effect of alzheimer's disease on spatial navigation strategies. *Neurobiology of Aging*, 64:107–115, 2018.

10 Ruth Peters, Nicole Ee, Jean Peters, Andrew Booth, Ian Mudway, and Kaarin J Anstey. Air pollution and dementia: a systematic review. *Journal of Alzheimer's Disease*, 70(s1):S145–S163, 2019.

11 Alberto Serrano-Pozo, Matthew P Frosch, Eliezer Masliah, and Bradley T Hyman. Neuropathological alterations in alzheimer disease. *Cold Spring Harbor perspectives in medicine*, 1(1):a006189, 2011.

12 Naewoo Shin. Investigating associations among geospatial environmental complexity, brain morphometry, and cognition across the alzheimer's disease spectrum. Master's thesis, Department of Cognition and Neuroscience, The University of Texas at Dallas, Richardson, Texas, USA, 2023.

13 Edward C Tolman. Cognitive maps in rats and men. *Psychological review*, 55(4):189, 1948.

14 May Yuan and Kristen M Kennedy. Utility of environmental complexity as a predictor of alzheimer's disease diagnosis: A big-data machine learning approach. *The Journal of Prevention of Alzheimer's Disease*, 10(2):223–235, 2023.