Spatial Thinking and GIS

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Abstract. The practice of spatial thinking involves applying multiple spatial concepts during processes of reasoning, and it is a constant component of our daily professional and personal lives. Certain concepts such as location, scale, representation, and distance play particularly important roles in the teaching and learning of geographic information systems (GIS). As GIS is increasingly used by people without a geographic foundation of thinking spatially, identifying why and how to make spatial thinking more explicit can have positive learning outcomes.

1 Introduction

Thinking spatially integrates spatial concepts with processes of reasoning, often relying on internal or external representations to enable or facilitate and support the experience [10]. A single act of spatial thinking also involves visualizing and interpreting location, position, distance, direction, patterns, relationships, movement, and change through space and time [13], [15]. Because these processes are such fundamental parts of our everyday cognition, they are rarely thought of explicitly or deliberately. Yet with evidence growing for the links between spatial thinking and professional success in the STEM disciplines, not to mention the daily practices of navigation and information visualization, the need for increased and focused attention on spatial thinking is paramount.

1.1 Visual and Spatial Thinking

Significant and substantial overlap exists between *visual* and *spatial* thinking, yet they also differ on cognitive, and experiential levels. Frequently, people describe a preference for visual thinking when they are describing their preference to *see* information versus *hear* it. Just as frequently, though, the preference is instead for information to be conveyed via images, charts, graphs, or figures, versus through the use of words. These are all visually dependent forms of communication, since it is through one's sense of vision that the information is perceived. But in this case, to opt for an image or a chart over words or text derives in part from the benefit that *spatial* thinking provides. That is, the meaning from the image or chart is being extracted via the spatial arrangement or other spatial characteristics of items or data in the image or chart. As a simple example, familial relationships between generations of grandparents, parents, siblings, cousins, and grandchildren are possible to be described through a lengthy paragraph of text. Those same relationships can be intuited much more efficiently and succinctly through the conventional arrangement of a family tree, with subsequent generations arranged vertically and same generations aligned horizontally. There is also a directional component to interpreting relative ages.

1.2 Spatial Thinking, Geography, and Maps

The skills used to extract meaning based on the spatial arrangement of individuals in a family tree are analogous to those applied to the arrangement of objects or phenomena represented on a map. Geographers have long practiced spatial thinking in terms of a disciplinary focus on location, distance, arrangements, patterns, and other space-based phenomena. In practice, geographers are likely to first make note of arrangement or patterns and then deduce the natural or social processes that would have resulted in such a pattern being observable. Thus, “Why is it like this, here?” is a quintessential question for geographers. Historically, this was consistent with direct observations, and this was one reason why field work has always been an essential component of geography.

To study and review areas beyond what could be seen via direct observation, maps have always been the obvious geographical tool. Historically maps would have been derived from direct experience, but since the use of aerial photography and satellite imagery became widely available, geographers are more likely to use these as sources of data. What has changed more recently in the last few decades is not so much the use of remotely-sensed data but the practice of using geographic information systems (GIS) to manipulate the data and generate maps. The ability to interact with and visualize geographic space via digital technologies has dramatically expanded our ability to conceptualize space in novel ways. This has opened up new avenues for both knowledge and research, invoking multiple and distinctive notions of scale [7].

2 Location, Scale, and Representation

Through the use of digital technologies such as GIS, spaces become manipulable (able to be grasped, rotated, scaled through zooming, moved), and one can insert oneself into the space and recreate the perspective of direct observation (locomotion) [2]. Depending on the purpose of the interaction and the nature and overall size of the space being explored, the experience that occurs during manipulation or locomotion would vary greatly. Appreciating these distinctions has significant implications for the design and use of GIS, such as how to implement data editing functionality or add functionality to modify perspectives [8]. How research questions are framed and how research is designed are affected by these experiential differences. For example, the study of navigation in real-world spaces may or may not mimic the augmented reality experience of locomotion in virtual spaces [9]. The differences further extend to other domains of science learning [4], [17], [19].

Concepts of location, representation, and scale are central to the connections between spatial thinking, GIS, and GIScience. Most people are unlikely to know the capabilities and technological constraints of how a computer is able to represent the features and the characteristics of the natural and social world, much less the differences among spatial data models themselves. Smith and Mark [16] found that people were more comfortable identifying "geographic features" such as mountains and rivers as things that "can be portrayed on a map," but were much less likely to be able to envision ta cartographic representation of a geographic "object" or "concept." This lack of familiarity with the digital representation of geographic phenomena that exist beyond one's direct level of observation, regardless of scale, affects how people understand the nature of GIS data sets [14]. For example, it can be particularly challenging to appreciate how we represent 3-dimensional phenomena, such as geologic bedrock, ground water, or air temperature, with 0-, 1-, or 2-dimensional digital data structures.

Making decisions about data models and aggregation affect not only representation but analysis and interpretation as well. For example, the classic example of John Snow's 1854 map of cholera deaths around a certain water pump on Broad Street in London generated a pattern that suggested the correlation between deaths and that water source. This is an example of spatial thinking that considers how two different 0-dimensional "point" patterns may be related to one another. However, if the pattern of points (the individual deaths) had instead only been available in an aggregated form, such as at a neighborhood or a census tract as a two-dimensional polygon, the formation of those polygons could either support or refute a correlation with the Broad Street pump. For an illustration if this particular example, see Mark Monmonier's mapped version [6].

The London cholera example illustrates the risks inherent with undertaking spatial analysis without a clear understanding of the spatial scale at which the different variables naturally operate and interact. Related to this is the modifiable areal unit problem (MAUP), often invoked in GIS-based spatial analysis when one is analyzing the relationships between data sets aggregated at different scales and across different administrative units, such ZIP code areas and Census tract areas.

Another area in which scale and representation conflict with regards to spatial thinking involves spatial reference and coordinate systems, map projections, and the art and science of cartography. Technically, a GIS can accommodate virtually an unlimited number of coordinate systems associated with an equally large number of map projections, assuming the software provides the functionality to change key parameters. However, by design the system does not expect and cannot easily permit these to be manipulated or distorted across map scales or map extents. That is, a single map that is "not drawn to scale," that simultaneously depicts multiple, geographically-coincident data sets, or a single but multi-part data set, each at a different scale, cannot be generated. So, a data set of the fifty United States cannot, in one single frame, have Alaska appear to be the size of Texas, unless it has it as an inset map with its own different scale than the other contiguous states. Again, this is by design because a GIS is expected to maintain the georeferencing of its digital data sets with absolute consistency and reliability.

In contrast, our minds do not maintain our knowledge of geographic space either "to scale" or in correct georeferenced alignment. This has significant implications for the ways in which we learn to navigate in new locations [3] or interpret You-Are-Here maps [5]. However, it can be to our educational benefit to deliberately distort and manipulate fixed and deterministic spatial reference systems to design alternative representations of geographic features. The 1856 map titled "Mountains and Rivers" (Figure 1) designed by G. W. Colton depicts both the world's longest rivers and its tallest mountains, arranged side-by-side respectfully to allow comparison between these geographic features. Such a map could be produced via a GIS only with extensive manipulation of the software and data structures, to trick the system into ignoring scale and location.

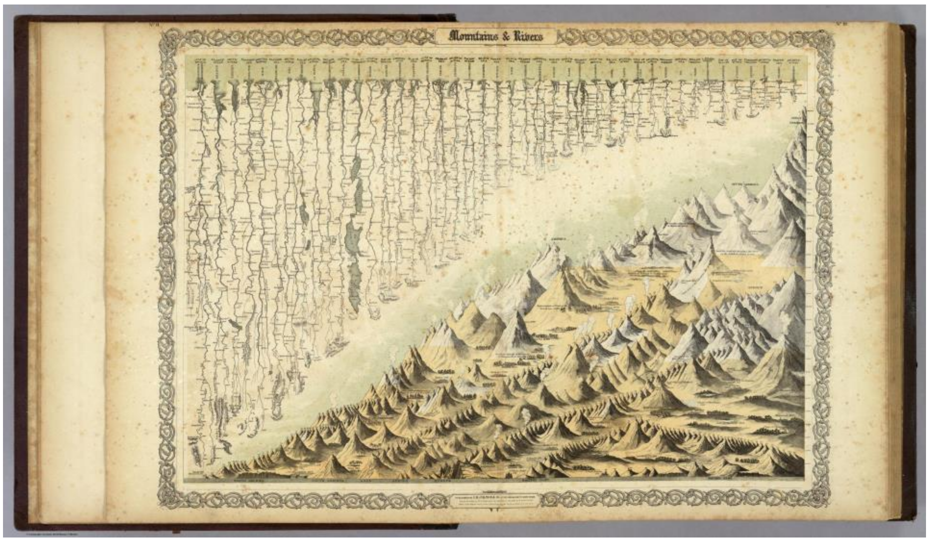

Fig. 1. Mountains & Rivers, a map by G. W. Colton. Published by J.H. Colton & Co.(1865). Map courtesy of the David Rumsey Map Collection.

3 Distance and Directionality

The spatial concept of distance may be the most important one connecting spatial thinking and geographic information science. The role of distance in interpreting and predicting patterns of natural and social phenomena is so essential that it forms the basis of the so-called First Law of Geography: that everything is related to everything else, but near things are more likely to be related than far things. This observation, first made by geographer and computer scientist Waldo Tobler in 1970 [18], holds for many phenomena and at many scales, yet because it is not a universal truth and has exceptions, it therefore becomes a factor to be considered and addressed during analysis before it can be dismissed.

Evaluating it, however, is in itself problematic. How "near" and "far" are interpreted makes all the difference. GIS operations rely on the distance measurements calculated within and between data sets. Distances form the basis of how buffers and all other tools of proximity and adjacency are implemented. Appreciating distance as a spatial concept seems deceptively obvious, but to *correctly* apply distance-based tools during a spatial analysis requires an understanding of the scale at which the data's patterns and processes exist and operate. Moreover, "near" and "far" will always vary by context, application, scale, and setting. Programming a computer to be sensitive to those variables is not yet easily done.

Another challenge being introduced are the inconsistent and idiosyncratic methods that are applied to analyze patterns based on distance. Conceptually the role of distance may be a simple concept to understand, but there are numerous computational approaches to its analysis and little communication between researchers from different fields. For instance, a Generalized Spatial Association Rule (GSAR) is being used in business and logistics [1], but it is identical to existing methods for detecting spatial autocorrelation that are already well-known and implemented in GIS. This exemplifies the significant gaps that exist between tool developers and researchers across different fields and industries, all of whom are grappling with how best to analyze distance.

An understanding of directionality is also relevant, as spatial processes are non-uniform [11]. Water flows downhill, wind blows things down-wind rather than up-wind, and people tend to move back-and-forth along roads, trails, and other corridors, rather than randomly across the landscape. Thus there is prior knowledge about both space and geography that ought to be considered when one is making choices about analysis via a GIS. Unfortunately, the science behind geographic information does not systematically or consistently result in ideal tool or system development.

4 Curricular Instruction around Spatial Thinking and GIS

Given the important connections between spatial thinking, spatial concepts, and GIS, it makes sense to leverage the knowledge to enhance and improve learning. Knowledge about location, scale, representation and distance serves as "pre-GIS" background to make their GIS learning as efficient and effective as possible. This is particularly important for students who lack formal education in geography, and for whom the practices of spatial thinking are not familiar.

Curricula like these have been developed in several different educational settings [13]. Typical introductory GIS classes cover numerous topics that can be explained with their spatial context explicitly provided. For example, when students are learning about digital elevation models (DEMs) used to represent topography, have students first venture outdoors and sketch any nearby vista containing topographical relief, from both frontal and planar perspectives (as contour lines). As a second indoors step, have students create a physical model of the topography with clay, and once the model is complete and placed within a clear plastic or glass container, they can view it from its side and sketch what would be its contour lines (with a marker on the outside of the container itself). Lastly, have the students place different small pieces of mesh netting (like an assortment of 5” by 5” pieces of window screens, with different mesh sizes, available for purchase at hardware stores) over the top of the containers and view their topographical model through the mesh. This mimics the experience of having elevation represented in a GIS as pixels of different sizes or resolutions. Together, these steps contribute important prior knowledge about scale and digital constraints for how natural features are represented in a GIS, and they can be completed during a class session prior to beginning work with DEMs themselves. In these ways, a DEM will not be such an unfamiliar abstraction of reality and students gain confidence in the analyses they conduct with them.

A GIS class is one particular type of course which benefits immensely from explicit instruction on spatial concepts and spatial thinking, but there are many others as well. Spatial thinking can also be the topic of its own class. Because it is such a multi-faceted and varied topic, it fits well into a learning situation designed for flexibility and creativity, such as a First-Year Seminar for undergraduate students or a professional development workshop for teachers or faculty, for example. Ideas and suggestions for specific curricular ideas can be found at teachspatial.org.

5 Conclusion

The role of spatial thinking in, with, and about GIS and GIScience is necessarily important but inevitably complex. There are substantial needs and opportunities for educational research in these areas but significant progress has been hindered by the lack of robust and reliable assessment instruments and the absence of funding available for lines of inquiry that must necessary be multi-disciplinary. Even twenty years ago, when the digital technologies were first being used more widely by researchers and academics, it was clear that the relationships needed to be better understood.

> *What are the fundamental spatial concepts humans use and understand'? We believe this question has wide significance for many aspects of GIS design, education, social effects, etc. An important question yet to be answered, however, is whether we should concentrate more on modifying GIS for humans, or on training users to understand and use GIS effectively. Should GIS be developed to mirror human capabilities or to compensate for human limitations? The answer to these questions undoubtedly lies somewhere between these choices.* [8:175]

References

1. Dong, W., Li, L., Zhou, C., Yu Wang; Li, M.; Tian, C., Sun. W.: Discovery of generalized spatial association rules. Service Operations and Logistics, and Informatics (SOLI), 2012 IEEE International Conference Proceedings. (2012) 60-65
2. Freundschuh, S., Egenhofer, M.: Human Conceptions of Spaces: Implications for Geographic Information Systems. Transactions in GIS 2(4) (1997): 361-375
3. Golledge, R.: The Nature of Geographic Knowledge. Annals of the Association of American Geographers 92(1) (2002) 1–14
4. Jones, M. G., Gardner, G., Taylor, A., Wiebe E., Forrester, J.: Conceptualizing Magnification and Scale: The Roles of Spatial Visualization and Logical Thinking. Research in Science Education 41(3) (2011) 357-368
5. Lobben, A.: Tasks and Cognitive Processes Associated with Navigational Map Reading. The Professional Geographer 56(2) (2004) 270–281
6. Monmonier, M.: How to Lie with Maps. 2nd edition. University of Chicago Press (1996)
7. Montello, D.R.: Scale in Geography. In: Smelser, N. J., Baltes, P. B. (eds.), International Encyclopedia of the Social and Behavioral Sciences Oxford: Pergamon Press (2001) 13501-13504
8. Montello, D. R., Freundschuh, S. M.: Sources of spatial knowledge and their implications for GIS: An introduction. Geographical Systems (2) (1995) 169-176
9. Montello, D. R., Waller, D., Hegarty, M., Richardson, A. E.: Spatial memory of real environments, virtual environments, and maps. In: Allen, G. L. (ed.), Human spatial memory: Remembering where. Lawrence Erlbaum Associates, Mahway, New Jersey (2004) 251-285
10. National Research Council: Learning to Think Spatially. National Academies Press, Washington, DC (2006)
11. O'Sullivan, D., Unwin, D.: Geographic Information Analysis, 2nd Edition. Wiley Hoboken New Jersey (2010)
12. Sinton, D. S.: Spatial Thinking. In: Stoltman, J. (ed.), 21st Century Geography: A Reference Handbook. SAGE Publications, Thousand Oaks, California (2011) 734-744.
13. Sinton, D. S.: Spatial Learning in Higher Education. In: Montello, D. R., Grossner, K., Janelle, D. G. (eds.), Space in mind: Concepts for spatial learning and education. MIT Press, Cambridge, Massachusetts (2014) 219-238
14. Sinton, D. S., Bednarz, S. W.: About that G in GIS. In: Sinton, D., Lund, J. (eds.): Understanding Place: GIS and Mapping across the Curriculum. Redlands, CA: ESRI Press, Redlands, California (2007) 19-34
15. Sinton, D. S., Kolvoord, B., Gersmehl, P., Bednarz, S., Uttal, D.: The People's Guide to Spatial Thinking. National Council for Geographic Education, Washington, DC (2013)
16. Smith, B., Mark, D.: Geographical categories: an ontological investigation. Int. J. Geographical Information Science 15(7) (2001) 591-612
17. Taylor, A., Jones, M. G.: Proportional reasoning ability and concepts of scale: surface area to volume relationships in science. International Journal of Science Education 31(9) (2009) 1231–1247
18. Tobler, W.: A computer movie simulating urban growth in the Detroit region. Economic Geography 46(2) (1970) 234-240
19. Tretter, T., Jones, M. G., Andre, T., Negishi, A., Minogue, J.: Conceptual boundaries and distances: students' and experts' concepts of the scale of scientific phenomena. Journal of Research in Science Teaching 43 (2006) 282–319