Distributed Cognition: A Conceptual Framework for Understanding Map-based Reasoning

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Abstract. *GeoVisual Analytics* (GVA) focuses on visual interfaces to analytical methods that support reasoning with and about (big, heterogeneous, messy) geo-information–to enable insights and decisions about something for which place matters. Maps are, of course, central to the reasoning that GVA interfaces attempt to support. Although "reasoning" has been a purported focus of visual analytics generally (and GVA specifically) since the field was initiated in 2004, progress on understanding how to enable map-based reasoning (or any visual-display based reasoning) has been slow. One impediment to progress on reasoning as a core focus of GVA is lack of an accepted conceptual framework through which to investigate and understand map-based reasoning. Here, I make a case for the theory of *distributed cognition*, as a strong candidate for filling that conceptual framework gap.

1. Introduction

This short paper outlines a potential conceptual framework for research to study the processes through which map-based display can enable analytical reasoning about geographic patterns, relationships, and processes and to fold insights derived from that study into design and implementation of Geo-visual Analytics (GVA) tools in a range of contexts. The conceptual framework is grounded in the theory of *distributed cognition*. Below, I introduce briefly distributed cognition and selected prior work related to how visual artifacts support expert reasoning; outline the roles maps can play as cognitive artifacts that support reasoning; and then sketch the rough outline of a distributed cognition framework for GVA.

2. Distributed Cognition

Distributed cognition (henceforth: DCog) provides an attractive framework for considering how map-based visual interfaces can support an extended process of reasoning (whether through dedicated GVA tools or as a component of GISystems). The core contention of DCog is that cognition is neither completely individual nor in the head, instead it is "distributed" among actors and artifacts (Hollan et al. 2000). Colleagues and I have drawn upon DCog in past work directed to developing a theoretical basis for geocollaboration (MacEachren & Brewer 2004, MacEachren & Cai 2006) as well as work to apply the theory to development of web-based interfaces for coordinated crisis teams (Tomaszewski & MacEachren 2006). DCog (and the related concept of external cognition) has also been applied as a framework through which to consider the role of visual artifacts in thinking (e.g., Zhang & Norman 1994, Scaife & Rogers 1996, Zhang 1997, Rogers et al. 2002). In spatially-focused research Keehner, et al (2008) found that performance on spatial reasoning tasks with an interactive external visual spatial display was not necessarily better than with static views, but that task relevant views (whether static or selected interactively) had a consistently positive impact.

In a series of ethnographic studies, Nersessian and colleagues (2003, , 2009 #17470) used a DCog framework to study science work in multiple biomedical engineering labs where physical models and their visual representation are central cognitive artifacts. The most recent study identified two important roles for visualization: (a) "visualizing counterfactuals"—the representation of what a process might look like if it could be seen and (b) "visualization as a generator"—for generating possible solutions (Nersessian & Chandrasekharan 2009). Recent non-geographical research in visual analytics by Liu, et al (2008) draws upon the empirical work in cognitive science to ground development of a conceptual framework for understanding the role of interaction used to coordinate external representations in problem solving. Subsequent research by Liu and Stasko (2010) proposes three roles for external visual display: "external anchoring, information foraging, and cognitive offloading".

3. Maps as Cognitive Artifacts

In the studies cited above, whether geographical in focus or not, there has been limited attention to maps, specifically, as devices that structure cognition. Particularly absent has been any attention to the roles of map symbolization and design as integral to the externalization of cognition and the mechanisms through which this externalization enables reasoning. While prior research provides a starting point, there is a knowledge gap between experiments with narrowly focused tasks in a controlled laboratory setting and analytical reasoning in complex science or professional domains. Filling this gap is exactly what Fisher, et al (2011) argue is necessary in their call for approaching visual analytics as a translational cognitive science.

With place-related reasoning, maps can act as cognitive artifacts to enable reasoning in many ways. The table below (next page) identifies several possible roles (mentioned in relevant prior research) for visual artifacts in cognitive processes (not limited to maps). The table begins with three core roles for "graphical representations" identified in early work by Scaife and Rogers (1996) on "external cognition". They conceptualized external cognition as the interface between external and internal (mental) representations, in which external artifacts enable cognition via: computational offloading—reducing cognitive effort by providing direct perceptual representation of geometric (or other) relationships, thus turning (some) cognitive work into perceptual judgments, providing re-representation—essentially re-framing the problem so it can be conceptualized from a new perspective, and providing graphical constraining—limiting the kinds of inferences that are possible; e.g., visual grouping in a display constrains search for information. This is followed in the table by five roles (introduced above) from Nersessian, et al (2009) and from Liu and Stasko (2010).

Finally, the concept of "boundary object" focuses on the role of visual artifacts in mediating cognition among actors (see: Arias & Fischer 2000, MacEachren & Brewer 2004). Boundary objects are artifacts (or concepts) that provide a common context that can serve to enable the actors to share at least partial knowledge and reasoning with their collaborators. The other roles identified for maps/visual artifacts focus on supporting the external-internal mental representation interactions of external cognition, as outlined by Scaife and Rogers (1996). In contrast, boundary objects address explicitly the role of maps (and other artifacts or concepts) in supporting the broader conceptualization of DCog as being distributed among actors as well as between individual actors and artifacts. Considerably more attention has been given to the external cognition perspective on the role of visual artifacts in support of individual reasoning than on their role in a broader distributed cognition process involving multiple actors. Thus, the table of roles is probably incomplete and implications of the first eight roles for multi-actor cognitive systems needs research attention.

The roles identified for visual artifacts in enabling cognition are typically considered in a positive way within discussions of DCog (and external cognition). But, there is also potential that externalizing cognition through visual artifacts can change cognitive processes in less positive ways. Anchoring, for example (whether through visual or other means) has been addressed in a wide range of research related to reasoning and decision-making as a factor that generates bias in judgements toward an "anchor" (Mussweiler & Strack 2000).

Role of Visual Artifacts in Cognition	Source
1. ***computational offloading***—reducing load on reasoning	Scaife & Rogers, 1996
2. ***re-representation***—re-framing the problem {overlaps with restructuring of 'information foraging'}	Scaife & Rogers, 1996
3. ***graphical constraining***—limiting kinds of possible inferences	Scaife & Rogers, 1996
4. ***signifying counterfactuals***—simulating possible situations; representing 'what-if'	Nersessian, et al 2009
5. ***generators of solutions***—mechanism that suggests patterns, structures, processes	Nersessian, et al 2009
6. ***external anchoring***—enabling projection of mental structures onto visual forms	Liu & Stasko, 2010
7. ***information foraging***—support for information exportation and information restructuring in the search for patterns and relationships	Liu & Stasko, 2010
8. ***cognitive offloading***—reducing load on memory	Liu & Stasko, 2010
9. ***boundary objects***—mediating cognitive understanding/processes among actors	Arias & Fischer, 2000

4. Sketching a DCog Framework for Geo-Visual Analytics

A DCog framework for GVA needs to support an integrated perspective on human analytical reasoning as a distributed cognitive process with an understanding of maps as cognitive artifacts that enable place-focused reasoning. One component of a DCog framework for understanding and enabling maps as reasoning devices in GVA tools is to consider relations between (a) the entities among which cognition is distributed and (b) the roles of maps as cognitive artifacts (as outlined above). The entities involved in distributed cognition can be any agent with which collaboration is possible; this (potentially) includes both human and virtual agents. Broadly, the roles of maps as cognitive artifacts for GVA (the nine identified above and others that may be uncovered) are to: increase cognitive efficiency (e.g., supporting reasoning in time critical situations), extend reasoning beyond typical human limitations (e.g., supporting an ability to cope with big and messy data), and mediate reasoning across agents (e.g., to support tasks such as interdisciplinary research, negotiation about place-based activities, and place-based decision-making).

In relation to analytical reasoning and the role of maps as artifacts to enable it, there has been a start on development of methods to study visually-enabled reasoning in a Visual Analytics (VA) context (e.g., Costello et al. 2009, Dou et al. 2009, Plaisant et al. 2009, Dou et al. 2010, Fisher et al. 2011). A recent innovation for the study of reasoning within VA is Pair-Analytics (P-A), a method that pairs a domain expert and VA expert who work together on domain tasks (Arias-Hernandez et al. 2011). The approach draws on both in-vivo studies of cognition (e.g., Dunbar 1996, Nersessian & Chandrasekharan 2009) and pair programming from software development (Williams et al. 2000) and extends some traditional social science approaches for field data collection and analysis (e.g., ethnographic methods, grounded theory). In P-A, joint work is captured using audio and/or video recording and automated screen captures and/or interaction logging. Then, the data are systematically coded to uncover key components of the reasoning process. In P-A, a stated objective of pairing two experts for joint, visually enabled analysis is to generate a dialog that makes the mental models and cognitive processes of the two individuals explicit and enables analysis features critical to success to be extracted from the complexities of real work processes. Arias-Hernandez, et al (2011) claim two advantages for P-A (over think-aloud and other methods for study of real-world work): (1) a more natural way of making explicit and capturing reasoning processes and (2) an approach to capture social and cognitive processes used to conduct collaborative analysis in real-life settings.

P-A is well suited as a method for exploring the role of maps as cognitive artifacts in a DCog (Arias-Hernandez et al. 2011). Specifically, DCog as a theory is compatible with the P-A emphasis on an approach to understanding reasoning with visual representations/interfaces that relies on externalization of cognitive process through the dialog of joint work (Arias-Hernandez et al. 2012).

5. Conclusions

This short paper only scratches the surface of the potential of distributed/external cognition theory as a framework for developing and understanding use of map-based GVA methods to support place-based reasoning. If GVA is to be successful in moving beyond past cartographic and geovisualization research to provide more than a means to communicate and/or explore data, thus to achieve the visual analytics challenge of facilitating analytical reasoning, we must ground our approaches more firmly in what is known about human cognition and reasoning. While DCog is certainly not the only useful framework, it is one that is directly applicable. Evaluating its potential will require a broad program of empirical research (comparable to that carried out by cartographers in the past to understand the perceptual characteristics of map interpretation). A key objective of this paper is to stimulate such a research program. I conclude by suggesting a few foci for a research program in DCog for GVA:

- Develop a more comprehensive DCog framework to support the targeting of key research questions and the integration of diverse research results;
- Investigate the roles of maps in reasoning about place, spatial relationships, and space-time processes, starting with the list above and develop a more complete typology;
- For each role, carry out empirical research (both in the field and lab / both qualitative and quantitative) to understand the process through which maps act effectively as cognitive artifacts (or do not) and use results as input to design of maps and their interaction within GVA;
- Apply the P-A methodology to develop a deep understanding of map-enabled, place-based reasoning;
- Apply the DCog framework to the challenge of understanding and enhancing use of maps as cognitive artifacts in reasoning under uncertainty (for complementary ideas on visual analytics and reasoning under uncertainty, see: MacEachren 2015).

Pursuing the research foci above can address the challenge and potential offered by geo-visual analytics: to move beyond support for exploration and hypothesis formulation to a deeper level of support for reasoning about questions or problems for which place matters.

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