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Formally grounding spatio-temporal thinking

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Abstract: To navigate through daily life, humans use their ability to conceptualize spatio-temporal information, which ultimately leads to a system of categories. Likewise, the spatial sciences rely heavily on conceptualization and categorization as means to create knowledge when they process spatio-temporal data. In the spatial sciences and in related branches of artificial intelligence, an approach has been developed for processing spatio-temporal data on the level of coarse categories: qualitative spatio-temporal representation and reasoning (QSTR). Calculi developed in QSTR allow for the meaningful processing of and reasoning with spatio-temporal information. While qualitative calculi are widely acknowledged in the cognitive sciences, there is little behavioral assessment whether these calculi are indeed cognitively adequate. This is an astonishing conundrum given that these calculi are ubiquitous and are often intended to improve processes at the human-machine interface and are on several occasions claimed to be cognitively adequate. We have systematically evaluated several approaches to formally characterize spatial relations from a cognitive-behavioral perspective for both, static as well as dynamically changing spatial relations. This contribution will detail our framework, which is addressing the question how formal characterization of space can help us understand how people think with, in, and about space.

Keywords: Qualitative Spatial Reasoning, Formalized Cognition, Similarity Measures

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1 Introduction

This paper provides an overview of a research framework that seeks to establish the cognitive foundations of using qualitative spatio-temporal representation and reasoning (henceforth referred to as QSTR) at the human-machine interface. QSTR calculi, such as the topological 9-Intersection Model (Egenhofer & Franzosa, 1991) and RCC-8 (Randell, Cui, & Cohn, 1992), are essential in many application areas that require the formalization of spatial and/or temporal knowledge such as natural language interpretation (Kordjamshidi, von Otterlo, & Moens, 2010), cognitive robotics (Moratz & Tenbrink, 2006), spatial query languages (Camara & Jungert, 2007), or video annotations (Sridhar, Cohn, & Hogg, 2011). For the purpose of furthering the value of QSTR, for example to facilitate processes at the human-machine interface, we have established a research framework that allows for making significant contributions to cognitively grounding QSTR calculi. Key elements of this research framework are:

- a flexible experimental approach based on a grouping paradigm to assess how humans conceptualize spatio-temporal information;
- an extensive collection of analysis methods for evaluating human conceptualizations to assess the similarity of relations and events and their relation to natural language;
- methods for evaluating and improving the adequacy of existing QSTR calculi, comparing different calculi, and designing new QSTR approaches based on behavioral data.

In the following, we will briefly discuss why QSTR is essential for bridging the gap between artificial and natural cognitive processing of spatio-temporal information. We will then lay out our research methodology and provide a prospect on future research.

2 Preliminaries

One of the most important assumptions in the area of QSTR can be summarized by quoting Galton (2000):

"The divisions of qualitative space correspond to salient discontinuities in our apprehension of quantitative space."

This statement is critical for understanding and modeling cognitive processes as it links the formal identification of salient information to cognitive research with the same goal, that is, the identification of invariant information that a cognitive system is able to use to conceptualize both spatial and temporal information. Without going into too much detail here, prominent approaches in both perception and cognition have been built around invariants such as Gibson's (1979) theory of perception or Lakoff's and Johnson's theory of image schemata (Lakoff, 1990). QSTR has the potential to contribute to the formal grounding of core theories in the cognitive sciences as salient discontinuities are identified through formally specified equivalence classes, which function as invariants.

However, it has been shown that qualitative in a formal sense does not directly correspond to invariant in a cognitive sense. In other words, just because a calculus proposes a qualitative division of space, it does not follow that a natural cognitive agent would make the same distinctions. It is evident that the potential of QSTR to model natural cognitive processes only fully unfolds through behavioral validation, that is, qualitative formalisms require some cognitive adjustment. This has been demonstrated in the research by Mark and Egenhofer (1995) in which metric details modified topologically identified discontinuities, as well as in Klippel (in print) where it is shown that domain semantics has an influence on how salient individual topological equivalence classes are.

3 Research methodology

An efficient research methodology is needed to assess (cognitively) the ever growing number of calculi proposed in the area of QSTR. To this end, we have been working on a flexible experimental design and analysis framework. It is important to note that the components of this framework are either built on software that is freely available or is based on our own software developments which are freely accessible, as well[2]. We call this framework the Cognitive QSTR Evaluation PipeCircle (see Figure 1).

[2] For details visit: www.cognitiveGIScience.psu.edu

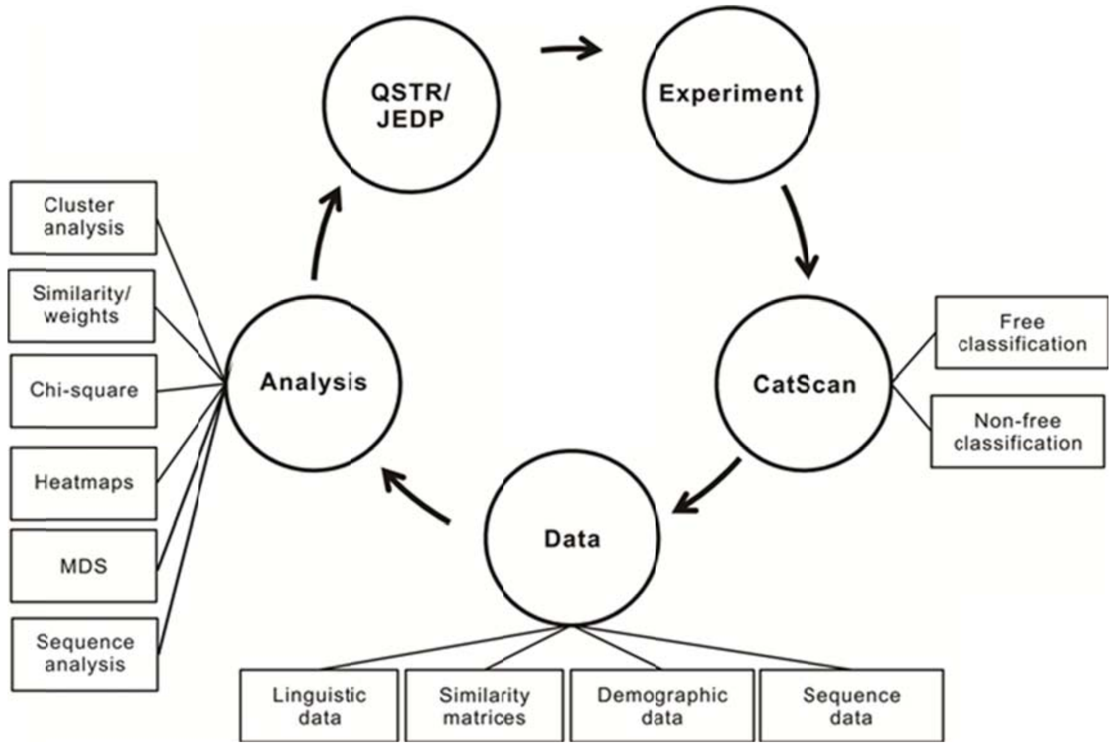

Figure 1. The Cognitive QSTR Evaluation PipeCircle is designed to evaluate existing and future QSTR approaches.

Each circle starts with the identification of a QSTR approach that is intended to improve processes at the human-machine interface. The lack of guidance for choosing an appropriate formalism has been identified as a major drawback to the value of QSTR approaches (Schultz, Amor, & Guesgen, 2011). As an example we will use here topological calculi. It is important to note though, that our framework is applicable to a large number of calculi. This includes calculi based on the concept of jointly exhaustive and pairwise disjoint (JEPD) (spatio-temporal) relations (Cohn & Renz, 2008) but also the assessment of vague qualitative distinctions (e.g., tall versus small).

QSTR identifies spatio-temporal categories (i.e., equivalence classes) which, from the perspective of a particular calculus, treat certain information as being indistinguishable or invariant. It is, therefore, straightforward to use a research methodology that is essentially built around such a calculus, incorporating maybe the most fundamental cognitive processes: conceptualization and categorization. While there are many methods potentially suitable for addressing conceptualization and categorization, we settled on using a grouping paradigm which has been successfully applied in previous research endeavors across several disciplines (Knauff, Rauh, & Renz, 1997). A distinction is made between grouping entities into existing groups (non-free classification) or creating groups from scratch (free classification / category construction, Medin, Wattenmaker, & Hampson, 1987). To efficiently administer grouping experiments we designed the software CatScan. CatScan allows for the presentation of both static as well as dynamic stimuli (see Figure 2).

CatScan automatically collects several types of data:

- background and demographic data of participants;
- data on the category construction behavior in form of proximity (similarity) matrices;
- linguistic labels for the groups that participants created (and provided);
- a detailed log file of each experimental setting which allows for analyzing participants decisions on which icons to use for seeds in the category construction task, how long it takes them to make decisions, whether they revise their decisions, how many groups they create, number of icons in each groups, total time spent on completing the category construction task, etc.

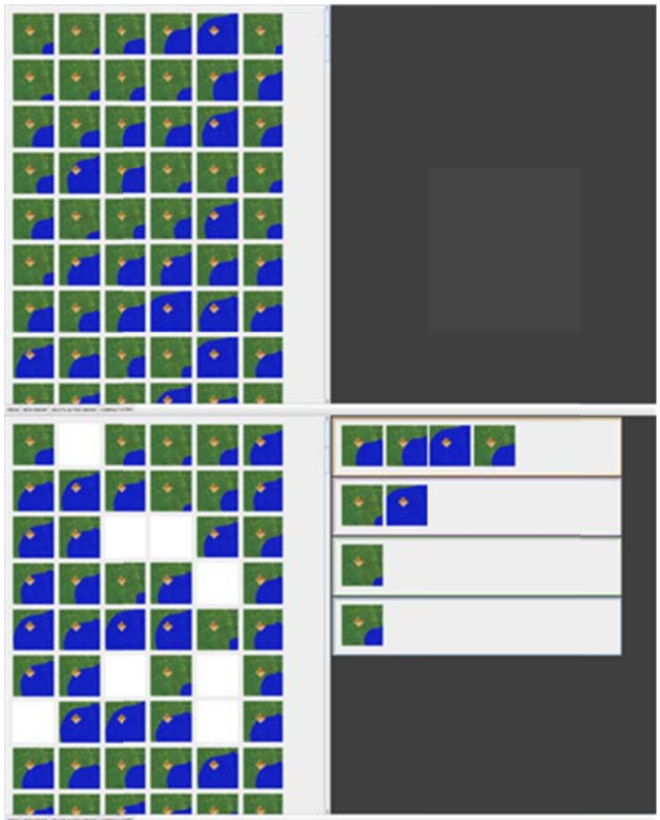

Figure 2. Ongoing free classification/category construction experiment using CatScan. Stimuli are presented on the left side. Initially no groups are present on the right. Participants create groups and sort stimuli into them.

We are continuously extending available (automated) analysis methods. To this end, we are in the process of designing an interface that allows for incorporating both standard analysis methods applicable to the behavioral data CatScan is collecting, as well as custom made analyses allowing for a deeper understanding of the underlying cognitive processes. The analysis tool (see Figure 3) is written in Java and has interfaces to R and web-based tools such as wordle (http://www.wordle.net), and allows for automatically generating the following analyses:

- Basic statistics: Based on the log files, general statistics, for instance regarding the number of groups created or the duration of the experiment, can be calculated.
- Raw similarity matrices and heat maps: An overall similarity matrix (OSM) summarizes the grouping of all participants into a single matrix. Once computed, the OSM forms the basis for other analyses (see below). Heat maps such as the one shown in the top right corner of Figure 3 can be generated to provide intuitive visualizations of similarity matrices.
- Cluster analyses and dendrograms: We incorporated frequently used cluster analysis methods into the interface (e.g., average linkage and Ward's method). The fusion coefficients computed by these methods taking an OSM matrix as input are stored in a cophenetic matrix and can be illustrated as dendrograms (see bottom left corner of Figure 3).
- Cluster validation indices: Cluster validation indices such as Rand Statistics, Jaccard Coefficient, and the Folkes and Mallows index allow for comparing the grouping behavior of the participants with a theoretical partition of the stimuli used in experiments for instance given by the conceptual neighborhood graph of a qualitative calculus.

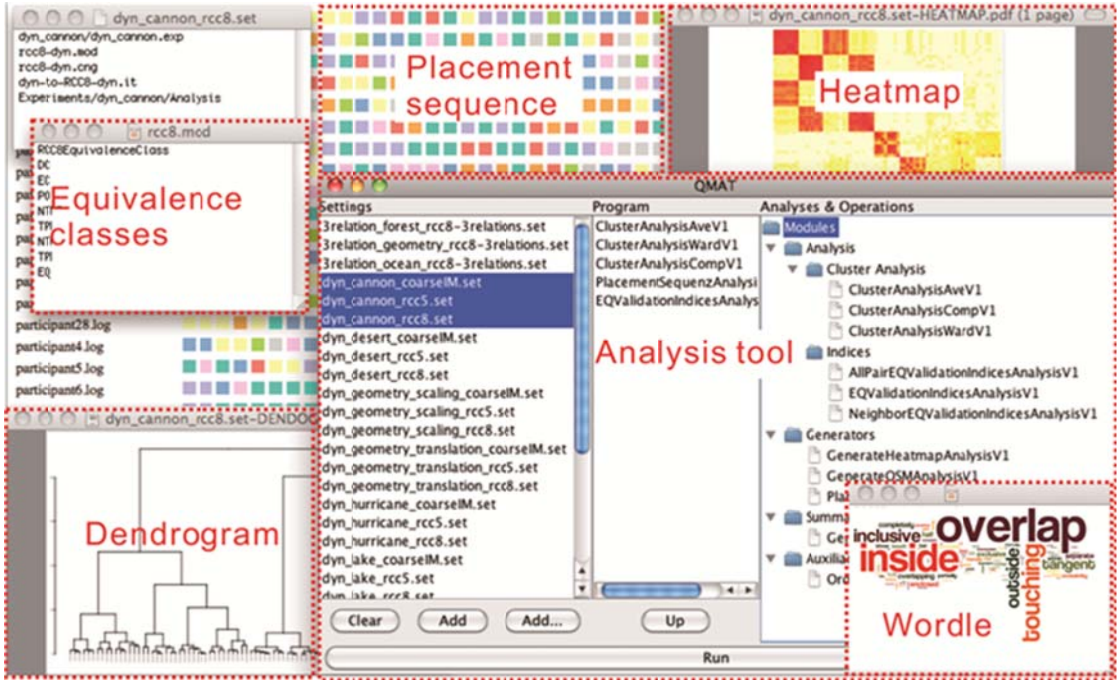

Figure 3. Analysis tool with different outputs.

The analyzed grouping behavior of humans in different scenarios and semantic domains allows for assessing existing QSTR calculi with respect to how well they reflect human spatial categorization and similarity assessment. When multiple calculi exist for the same aspect of space but making different distinctions (identify different invariants), cluster validation indices, for instance, can be used to identify which calculus or which variant is best suited to model human conceptualizations. In addition, the experimental results can be utilized to refine QSTR approaches by deriving weights for the edges in the corresponding conceptual neighborhood graph (Freksa, 1991) with the goal of improving their application in, for instance, spatial querying or matching scenarios. Raw similarities, fusion coefficients, and cluster validation indices all offer different alternatives for deriving neighborhood weights. For instance, using raw similarities, the similarity of two conceptual neighbors (CN) is the sum of all paired instances of CNs potentially normalized to adjust for the specifics of the experimental setup. While these different methods in principle also can be combined, it is still an open question under which conditions which method is the most suitable one.

4 Future work

Existing work on evaluating QSTR so far has been mostly concentrated on studying human conceptualization and similarity assessment for static spatial relations holding between two objects. We have recently started to extend this work into two new directions: (1) the conceptualization of geographic events in terms of spatial relations changing over time and (2) similarity assessment of larger spatial configurations, starting with three objects. Conceptualizations of geographic events on a qualitative level can be characterized as paths within a conceptual neighborhood graph. When more than two objects are present in a spatial scene, the traditional conceptual neighborhood graph needs to be replaced by a more complex graph structure in which the nodes stand for qualitative configurations specified by three or more spatial relations. A general research goal of our work in this context is to understand whether and how similarity assessment of complex scenes can be modeled based on the elementary similarity assessment of individual relations between two objects.

On the analysis side, we have recently started to focus more on the linguistic descriptions generated by the participants to shed light on conceptualization strategies. One simple but effective way to analyze the descriptions is the mentioned wordle tool which illustrates often occurring words based on their frequency (see bottom right corner of Figure 3). Another source which promises to provide new insights on human spatial conceptualizations is sequential data representing the order in which stimuli are sorted into groups. In addition to basic statistics about which stimuli and groups tend to be processed first or last, we plan to use sequence analysis approaches to discover recurring patterns or identify varying strategies used by different participants.

Both our experimental and analytical software are freely available. We invite other researchers to use them for their own purposes, in particular the cognitive assessment of newly designed calculi at an early stage.

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