Klippel, A., Yang, J., Li, R., & Wallgrün, J. O. (in print, 2012). Evaluating the cognitive adequacy of the DLine-Region Calculus. In SDH 2012 .

Evaluating the Cognitive Adequacy of the DLine-Region Calculus[1]

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Abstract. Qualitative spatio-temporal calculi play a crucial role in modeling, representing, and reasoning about geospatial dynamics such as the movement of agents or geographic entities. They are ubiquitous in ontological modeling, information retrieval, they play a central part at the human-machine interface, and are critical to process data collected from geosensor networks. What is common to all these application areas is the search for a mechanism to transform data into knowledge borrowing heavily from strategies of (human) cognitive information processing. Astonishingly, there is paucity in actual behavioral evaluations on whether the suggested calculi are indeed cognitively adequate. While the assumption seems to be made that qualitative equals cognitive, a more differentiated view is needed. This paper is filling the void by the first (to the best of our knowledge) behavioral assessment of the DLine-Region calculus using actual dynamic stimuli. These assessments are crucial as the few experiments that exist have clearly demonstrated that topological relations form conceptual groups (clusters), a fact that seems to be highly likely for the 26 DLine-Region relations as well. Our results show which topological relations form (cognitive) conceptual clusters.

1 Introduction

The meaningful processing of spatio-temporal data is a challenging and recent research topic. The tremendous amount of data that is becoming increasingly available has spurred multidisciplinary efforts to process and analyze data telling various stories of the dynamic earth (e.g., Adrienko, Adrienko, Dykes, Fabrikant, & Wachowicz, 2008; Yuan & Hornsby, 2008). One important development are qualitative spatio-temporal representation and reasoning (short: QSTR) approaches (e.g., Kurata & Egenhofer, 2009; Muller, 2002; Sridhar, Cohn, & Hogg, 2011; van de Weghe, Billen, Kuijpers, & Bogaert, 2008). The reason for the popularity of qualitative formalisms can be summarized by a quote from Galton's (2000) seminal book on qualitative change:

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

[1] This research is funded through the National Science Foundations (#0924534).

adfa, p. 1, 2011.

The importance of this statement is difficult to overestimate. If this statement is true, then we have found—by using QSTR—a way to bridge the gap between cognitive (semantic) information processing and requirements of formal systems fundamental to modern information technologies. From our usage of the word "if" the reader may derive that it is, unfortunately, not that easy. There are numerous suggestions for QSTR that all identify—sometimes contradictory—divisions of quantitative space. Additionally, while often a claim is made that qualitative approaches bear some inherent cognitive/commonsense aspects of how spatio-temporal information is processed, there is a paucity of actual behavioral evaluations that would back up the claim of capturing cognitive aspects of spatio-temporal information processing using QSTR. Hence, we do need an experimental framework that allows for effectively and efficiently assessing QSTR approaches cognitively. This article details an experiment assessing the DLine-Region calculus (Kurata, 2008) while at the same time showing general ways of assessing the cognitive adequacy of QSTR approaches that are built on jointly exhaustive and mutually exclusive relations.

The remainder of this article is structured as follows: First, we provide some background information on existing behavioral studies as well as the DLine-Region calculus. Second, we report on the conducted experiment evaluating the divisions (topological equivalence classes) that are inherent to the DLine-Region calculus. The results show that we need to superimpose a hierarchy onto the 26 primitive relations to reflect human conceptualizations of movement patterns captured by this calculus. We discuss in the outlook some strategies how behavioral results can be transformed into weights for conceptual neighborhood graphs (CNGs) that will cognitively adjust their use in areas such as information retrieval, ontology engineering, or the geo-spatial semantic web.

2 Background

Given the space limitations we will focus on some essential behavioral studies and a brief introduction to the DLine-Region calculus. Of particular importance to the topic of this article are the experiments by Mark and Egenhofer (e.g., Mark & Egenhofer, 1995; Mark & Egenhofer, 1994a; Shariff, Egenhofer, & Mark, 1998) on topologically characterized relations between a line and a region. In their experiments, the line had no direction and they used static images (rather than animations, see Section 3). They focused on both cognitive conceptualization processes as well as the spatial semantics of linguistic expressions. In some of their experiments they employed a grouping paradigm (Mark & Egenhofer, 1994b), similar to the approach taken in the experiment we will present later on. Their findings crystalized in the famous statement that *topology matters and metric refines* (Egenhofer and Mark, 1995). Not as widely discussed but equally important is their finding that the 19 relations between a line and a region are cognitively not primitive relations. In other words, the 19 relations form conceptual groups (clusters) with larger within group similarity as well as larger between group dissimilarity. This aspect has also been addressed in formal research papers and we will come back to this aspect throughout the paper.

Behavioral research on topology and qualitative calculi addressing actual movement patterns is rare. There are only a few studies that use dynamic stimuli in their experiments. Noteworthy is the research by Lu and collaborators (2009) in which the authors evaluate Allen's (1983) temporal interval calculus. The results, in a nutshell, indicate that certain relations can be considered forming clusters, mimicking the findings of Mark and Egenhofer (1994b). Specifically, *before* and *meet* form one cluster and all other relations of Allen's calculus form a second one. Our own research (see Klippel et al. in press, for an overview) so far has addressed topological movement patterns that can be modeled as changing relations between two spatially extended entities. Evaluating RCC-8 (Randell, Cui, & Cohn, 1992) and Egenhofer's intersection models (Egenhofer & Franzosa, 1991) that can be used to characterize these movement patterns, we found that topological relations form conceptual groups (clusters) and that domain semantics is an important contextual factor (Klippel, in press). To the best of our knowledge, there are no other published behavioral evaluations of dynamic movement patterns characterized by qualitative calculi[2].

Back to the DLine-Region calculus; Kurata and Egenhofer (2007) extended the original 9-intersection models proposed by Egenhofer and collaborators (Egenhofer & Franzosa, 1991) such that the direction of a line (in relation to a region) can be captured, too. The original 9-intersection model details the relation between two spatial objects A and B by creating a 3 x 3 matrix that details, from a point-set topological perspective, the relation (intersection) between three topological parts of A and B: interior, boundary, and exterior. For the case of a directed line, Kurata and Egenhofer introduced a finer distinction of the boundary of the line separately representing the start and the end of a line. This finer distinction results in an extra row in the 9-intersection matrix which then, consequently, is referred to as the 9+-Intersection Model (Kurata, 2008). In 2D, 19 relations are possible between a line and a region but there are 26 topologically equivalent relations possible in case the line is directed. Visually these relations can be organized into a conceptual neighborhood graph (see Figure 1, see also Egenhofer & Al-Taha, 1992; Freksa, 1992; Randell & Cohn, 1989). Two relations, R_1 and R_2, are conceptual neighbors if it is possible for R_1 to hold over a tuple of objects at a certain point in time, and for R_2 to hold over the tuple at a later time, with no other (third) mutually exclusive relation holding in between (Cohn, 2008; Freksa, 1992). A neighborhood graph has one node for each relation $R \in \boldsymbol{R}$, and an edge between two nodes if the corresponding relations are neighbors. The important aspect to keep in mind, which will tremendously add to the transformative nature of this paper, is that virtually every calculus with jointly exhaustive and pairwise disjoint (JEPD) relations (such as RCC and the intersection models) has a conceptual neighborhood graph (Cohn & Renz, 2008), and that the methods applied here will be universally applicable amongst these calculi to improve their cognitive adequacy.

[2] There are numerous proposals on general cognitive aspects of spatial dynamics (e.g., Mennis, Peuquet, & Qian, 2000), cognitive studies on events and movement (Shipley & Zacks, 2008) and there are also some unpublished studies.

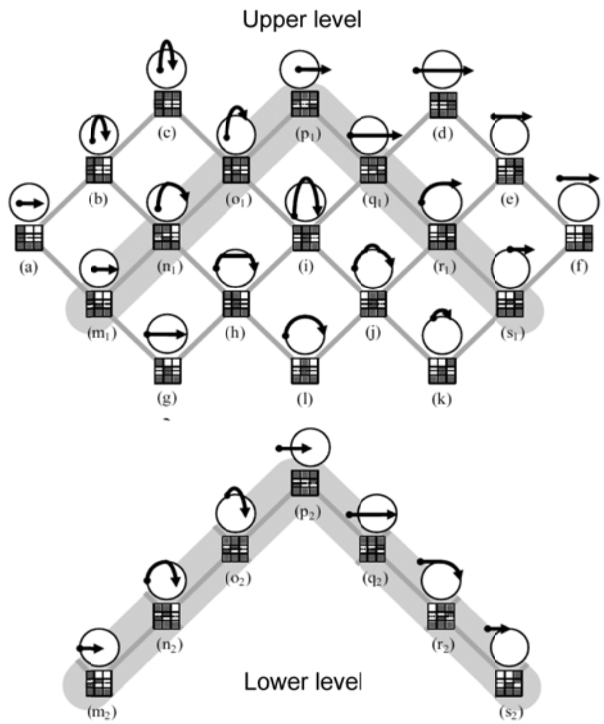

Fig. 1. Conceptual neighborhood graph for the 26 DLine-Region relations (see Kurata & Egenhofer, 2009)

3 Experiment

We have extended an experimental framework (Knauff, Rauh, & Renz, 1997; Mark & Egenhofer, 1994b) that is tailored to requirements in the spatial sciences in that it allows for evaluating qualitative spatial calculi built on JEPD relations. We are using a grouping paradigm, which is classically employed to reveal cognitive conceptualizations, and combining it with animations based on topological equivalence classes. The equivalence classes for the purpose of this article are the ones specified in the DLine-Region calculus, which we briefly introduced in the previous section. The critical questions that this experiment is answering are:

- Are the equivalence classes identified by the DLine-Region calculus salient discontinuities in our apprehension of (qualitative) space?

- On the basis of previous research it is fair to assume that not all 26 relations are equally salient but that they will form groups. If so, which relations are considered more similar to each other than others?

Participants. 26 Penn State undergraduate students participated for course credit. Average age was 22 (9 female).

Design and materials. 78 randomized animated icons depicting 26 DLine-Region relations (three per equivalence class) were constructed in Adobe Flash CS4. Each icon was 120 by 120 pixels in size. Given that participants see actual animations, we restricted the movement in that it, generally speaking, only went from left to right. Figure 2 shows an example of one DLine-Region relation (d, see Figure 1). A random start point was selected in the exterior of the start region. The movement of the black dot starts from the left exterior, fully crosses the interior, and then ends at a randomly selected point in the right exterior (the end region). To give another example, for relation (m_1) the dot starts from a randomized location in the interior of the start region, moves in the interior, and ends somewhere on the boundary in the end region.

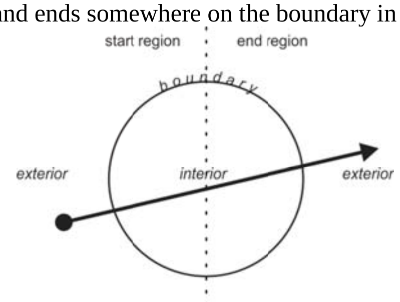

Fig. 2. Icon shows the case of DLine-Region relation (d), where the dot starts from a randomized location in the exterior (left), fully crosses the interior, and then ends at a randomized location in the exterior (right).

In the construction of all icons, particular attention was paid to two specific aspects: 1) that the starting and ending relations were perceptually clear; and 2) that the speed of the dot was constant in and among all icons. The speed of the dot movement was kept constant by maintaining the same ratio between the path length and the number of frames. At the end of each dot movement, the dot paused to represent the ending relation before the movement was repeated. The construction of icons involved manual inspection by experts to remove and replace icons that were ambiguous due to the randomized locations of start- and end-points. The final 78 icons did not convey DLine-Region relations that are ambiguous.

Procedure. The experiment took place in a GIS lab and was set up as a group experiment. The lab seats up to 16 participants at the same time at Dell workstations (Optiplex 755, 24’’ widescreen LCD monitors). View blocks ensured that participants performed this task individually. Participants performed a free classification (category construction) task as well as a linguistic labeling task.

Our custom-made grouping software, CatScan, allows for presenting dynamic stimuli and administers the complete experiment (see Figure 3). All 78 animations showing the 26 DLine-Region relations were initially displayed on the left side of the screen in random order. The right side was empty and participants were required to create all groups. Animated icons can be placed into groups by simple drag-and-drop operations; they can be placed into groups, out of groups, or moved between groups. In case a group is deleted, all icons are placed back on the left side. The main grouping task was preceded by a warm up grouping task (sorting animals) to acquaint participants with the interface, the grouping environment, and general idea of a free classification task. After finishing the task (no time limit was given), participants were presented with the groups they created and provided linguistic labels for these groups: a short label of no more than 5 words (e.g., *inside out in*) and a longer description (e.g., *found the dots that started inside the circle then went out then back in*).

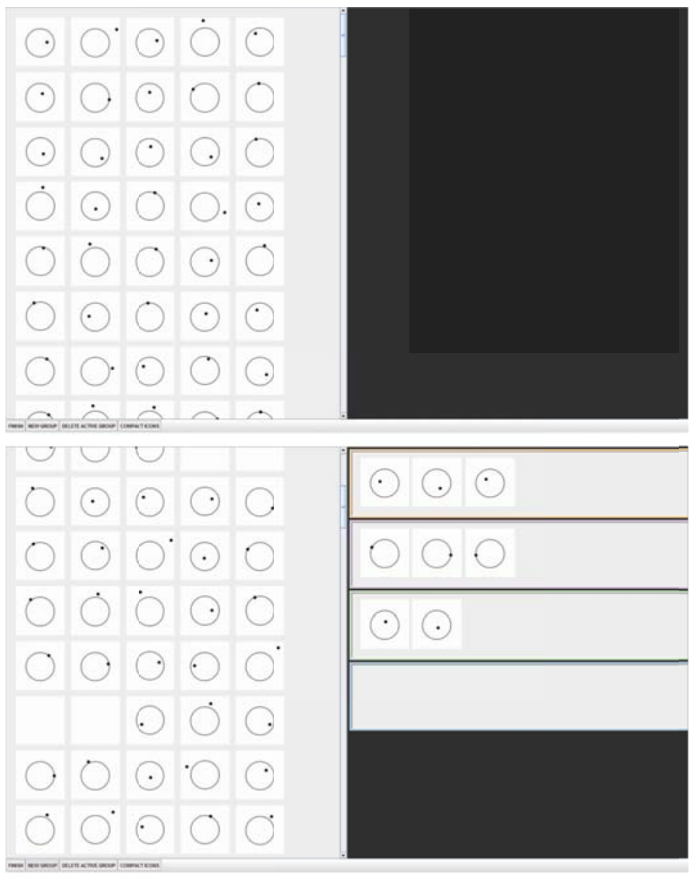

Fig. 3. The screenshots of the experiment interface. The top screenshot shows the initial screen before participants started to group. The bottom screenshot shows an ongoing experiment with groups created by the participant.

4 Results

On average, participants created 11.3 groups (min: 3; max 39, statistically an outlier) and it took them 22 min on average to finish the grouping task. The average number of groups is, as expected, below the 26 formally defined topological equivalence classes. This result is in accordance with several findings (Klippel et al. in press; Mark & Egenhofer, 1994b) that topological equivalence classes defined by a number of calculi are forming conceptual clusters, whose formally defined granularity is often not the granularity identified by human participants.

The grouping behavior of participants itself is captured in individual similarity matrices which encode two icons being placed into the same group as 1 and two icons not being placed into the same group as 0. By summing over all individual similarity matrices, an overall similarity matrix (OSM) can be created. Thereby maximum similarity is assigned to those pairs of animations that are always placed together into the same group and minimum similarity is assigned to those pairs of animations that are never placed into the same group. The maximum similarity corresponds to the number of participants (here: N = 26), the minimum similarity is 0. This data can be analyzed using a number of techniques such as cluster analysis, multidimensional scaling, or simple heat maps that allow for visualizing raw similarities.

Figure 4 shows a combination of a cluster analysis (Ward's method) and a heat map. Additional annotations in Figure 4 (dashed boxes) show a synthesis of comparing different cluster methods as a means to validate clustering results (Kos & Psenicka, 2000). The two dendrograms (top and left part) are identical and show the result of the cluster analysis; icon names are placed on the bottom and right part of the heat map and consist of the relation name plus a number from 1-3. The heat map visualizes raw similarities such that higher similarities are displayed in darker gray and lower similarities are displayed in lighter gray. The combination of heat map and cluster analysis allows for a better interpretation of the grouping behavior as the clustering structure revealed by the dendrograms can be directly related to actual grouping behavior.

A first observation is that topological equivalence is a strong predictor for the similarity ratings; this is indicated by the fact that all three instances of all topological relations are in neighboring columns/rows, that is, they are grouped together most frequently compared to all other grouping possibilities (the dark gray cells along the diagonal, top-left to bottom-right). To this end, these results are largely consistent with data from other experiments (Klippel et al. in press; Mark & Egenhofer, 1994b) that topology at the base level is a strong grouping criterion. Equally interesting is, however, the overall grouping structure, and the combination of heat map and dendrograms allows for a deeper interpretation.

Figure 4 reveals—on a coarse level—a three cluster solution using Ward's method that has, however, to be somewhat modified if three clustering methods (Ward's, average linkage, complete linkage) are compared. The result of this synthesis is indicated by the dashed-line-boxes. To additionally visualize the solution indicated by the combined analysis (i.e. the dashed-line-boxes) we have also depicted these results in

Figure 5 using a merged CNG (compare Figure 1) and using dashed lines reflecting the cluster solution shown in Figure 4.

The synthesis of all three clustering methods allows for identifying two large clusters that are identical across all three clustering methods and one cluster that requires refinement. The two large clusters identical across methods are: cluster 1 with DLine-Region relations a, b, m_1, m_2, n_1, n_2, g, h, and l; cluster 2 with DLine-Region relations c, o_1, o_2, i, j, and k; and cluster 3, which has to be analyzed in more detail, contains on the coarsest granularity the following relations: p_1, p_2, q_1, q_2, r_1, r_2, s_1, s_2, d, e, f.

Besides the fact that topological equivalence is at the core of the similarity ratings, it is worthwhile to note that the clusters in general also reflect topologically induced similarities. In other words, the general clustering structure does not violate topological similarity in the sense that the groups formed by participants are connected subgraphs in the DLine-Region CNG (see Figures 1 and 5). However, the granularity required by a formal topological characterization does not seem to be reflected in the grouping behavior of the participants. Participants focused on more abstract characteristics of the movement patterns. In the following we summarize these characteristics:

<u>Cluster 1:</u>

- No part of the movement is taking place outside the region, meaning that the intersection of any component of the DLine with the exterior of the region is empty.
- The movement starts either on the border of the region or inside the region.
- The movement ends either inside or on the border.
- Parts of the movement can take place along the border.

<u>Cluster 2:</u>

- Part of the movement has to take place outside the region but it is neither the beginning nor the ending.
- Start and end of the movement can be on the border or in the interior of the region.

<u>Cluster 3:</u>

- Part of the movement has to take place outside the region.
- The movement can end in all three possible locations: outside, inside, and on the border.
- Part of the movement can take place in the interior of the region or not.

As indicated above, clusters 1 and 2 are stable across different clustering methods while cluster 3 seems to require a finer level of analysis, that is, it does not show up consistently across different methods. The clustering structure that is indicated in Figures 4 (dashed boxed) and Figure 5 (dashed lines) reflects this finer level of granularity at which all three clustering methods (Ward's, average linkage, complete linkage) agree. Topologically this finer level of distinction makes sense in that it reveals connected subgraphs of the CNG that are singled out. This finer level of granularity in cluster 3 can be summarized as follows: 3a contains the relations p_1, q_1, and d; the main characteristic here is that the movement ends outside the region while the starting location can be outside, inside, or on the boundary. Cluster 3b contains relations p_2 and q_2; the main characteristic is that the movement starts outside and ends either inside or on the boundary (after having been inside). Cluster 3c contains relations s_2 and r_2; the movement starts outside and ends on the border without intersection the interior. Cluster 3d (r_1 and s_1) contains relations whose movement starts on the border and ends outside the region without intersecting the interior. Cluster 3e singles out relation f which is the only movement pattern that takes place completely outside the region. Cluster 3f singles out relation e which almost takes place completely outside the region except for the interior of the line that intersects with the boundary of the region.

Finally, we would like to point out the somewhat special role of relation l. While it does seem to be integrated into cluster 1, the analysis of the raw similarities clearly indicates its different role in this cluster. This is not surprising as movement pattern l takes place completely on the boundary of the region.

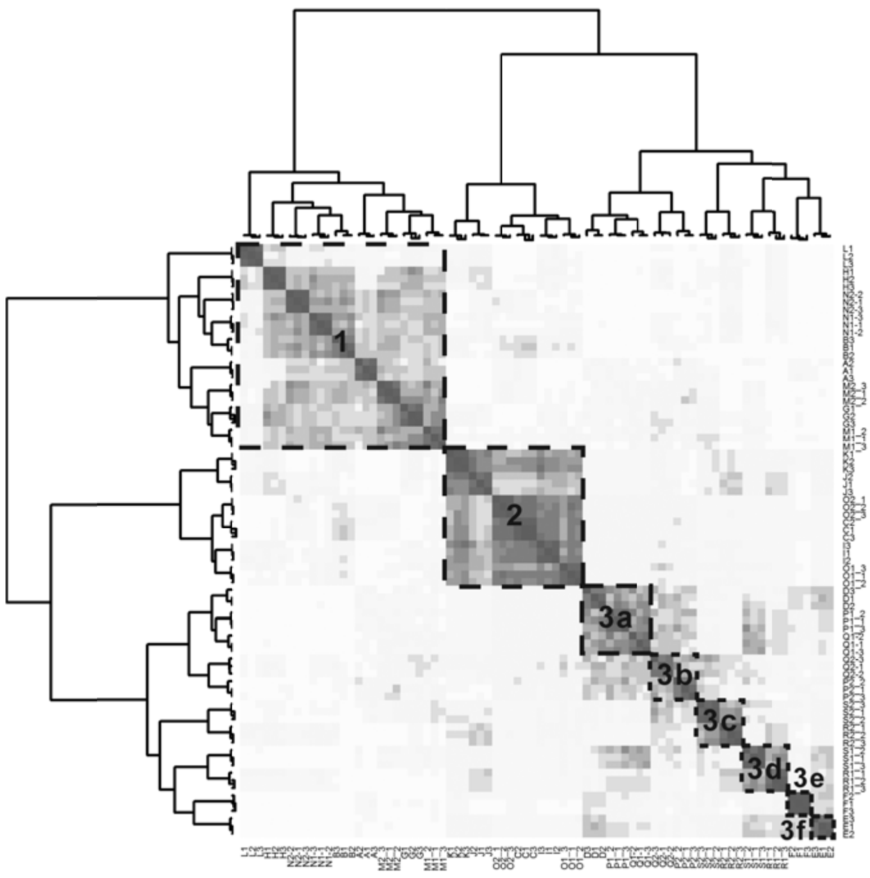

Fig. 4. The figure shows a combination of a heat map and cluster analysis (Ward's method). Additionally, rectangles indicate a synthesis of analyzing different clustering methods. The numbers identify clusters discussed in the text. A color and high resolution version of this figure is available at min.us/mSDH2012_figure4.

The cluster analysis shows obvious that we need a coarser granularity of movement primitives than offered by the DLine-Region calculus. As revealed by the general characteristics of the three clusters, important distinctions are made based on the movement in relation to the region focusing particularly on distinction of inside versus outside movements or combinations thereof. We therefore looked into the linguistic descriptions (short labels) that participants provided. As the grouping behavior differs from participant to participant we looked into the descriptions here from a general level using a word cloud to reveal frequencies of individual terms (additionally we performed an actual quantitative word count). Figure 6 shows the results that seem to reinforce our interpretation that the three basic distinctions made in the intersection models (including the 9+ model) are crucial, that is, movements are distinguished on whether they are going in or out, and whether they take place inside or outside. The most frequently used movement related terms are (in this order): *in*, *out*, *to*, *on*, *outside*, *straight*, *inside*, *through*, and *arch*.

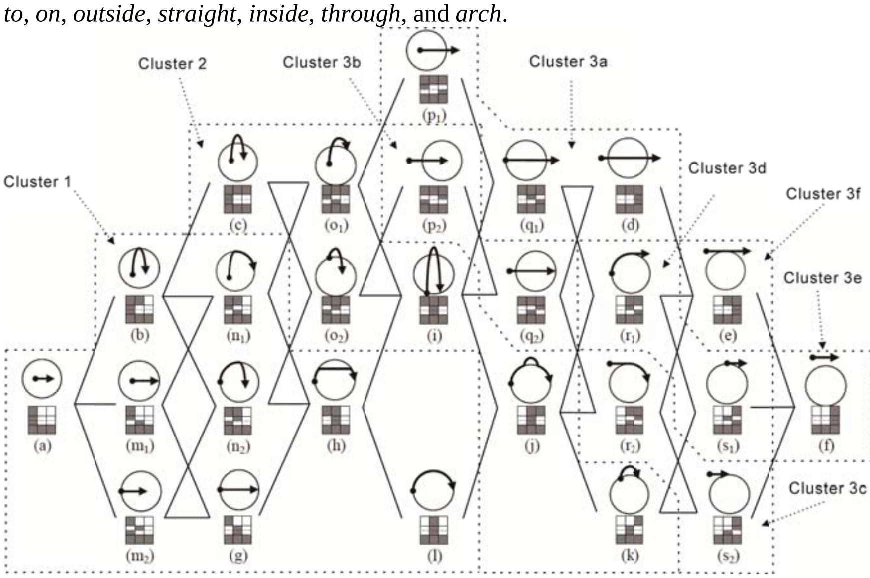

Fig. 5. Merged DLine-Region CNG reflecting the analysis discussed in Figure 4, Section 4. The color coding corresponds to the clusters identified by comparing three clustering methods. A color and high resolution version of this figure is available at min.us/mSDH2012_figure5.

Interestingly, most of these terms can be directly related to some topological characteristics. However, there are also several non-topological terms such as *straight* and *arch*. We will discuss the latter in the next section.

5 Discussion

In our discussion of the results, we will draw comparisons to the previously mentioned research by Mark and Egenhofer (1994b, referred to henceforth as E&M94).

Although their research setup focused on line-region relations and methodologically used a different set-up, several of their findings are worth looking into in the light of our results.

One of E&M94's central findings indicated that the 19 most frequently grouped pairs correspond to the 19 that were within the 9-intersection classes. We do find similar results in our data visualized in Figure 4 indicated by the fact that all three instances of <u>all</u> topological relations are in neighboring columns/rows, that is, they are grouped together most frequently compared to all other grouping possibilities. This shows that topology is indeed a major grouping criterion at the fine granularity analysis level.

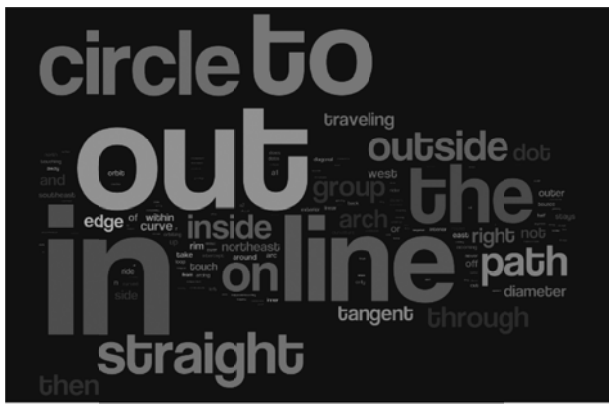

Fig. 6. Wordle showing the frequencies (larger meaning more often used) of words used by participants to characterize their groups (short labels).

Equally important, E&M94 found a comparable pattern with respect to creating clusters of line-region relations, that is, cluster analysis reveals that the 26 original DLine-Region relations are conceptually not the primitives. Additionally, we found similarities in that larger clusters are formed by relations on the left side of the CNG (compare Figure 10 in E&M94 and Figure 5). While there are an additional 7 relations in the DLine-Region calculus and several differences in the research methodology, this is an interesting finding. In both CNGs the left side has movement patterns that do not take place outside the region while the right side shows more variety including the exterior of the region as a place where movement happens. Taking additionally into consideration the linguistic analysis (see Figure 6), we find that in/out and inside/outside distinctions are both linguistically and conceptually a dominating criterion.

E&M94's analysis also singled out several relations as most likely forming their own clusters. Specifically, relations *a*, *l*, and *f* (for English speaking participants). We have discussed already the somewhat prominent situations of relations *l* and *f*, that is, that in our experiments they form more individualistic clusters as well. That relation *a* is not singled out may have to do with the different experimental setup: According to current event conceptualization theories, the ending relations of movement patterns play an important role in their conceptualization (Regier & Zheng, 2007). From this perspective relation *l* is not that different from, for example, relation m_2. However, E&M94's results are slightly different for different language groups (English versus German). Our research focused on English speaking participants but we will discuss the opportunity to use our research framework in cross-linguistic studies in the outlook.

As the linguistic analysis reveals, participants did not group solely on the basis of topological information although it may appear this way. The question of the primacy of topology as a way to think spatially has received more attention recently (Klippel et al. in press; Schwering, 2011) calling into question the seminal statement that "topology matters and metric refines" (Egenhofer & Mark, 1995). Our experiment was not explicitly designed to address this question. However, there are certain constraints that inevitably lead to the introduction of factors other than topology to realize the 26 DLine-Region relations. For example, we used a circle as our region and thereby making it impossible for a straight line to start and end in the circle while having been outside it in between. Most prominently this aspect is featured in linguistic descriptions *straight* and *arch*, which made it into the top ten of the most frequent terms. There is current research in event conceptualization that stresses the importance of path characteristics on the conceptualization of movement patterns (Maguire, Brumberg, Ennis, & Shipley, 2011; Shipley & Maguire, 2008).

6 Conclusions

To conclude, our research adds to the body of knowledge that asserts that distinctions—in form of equivalence classes—made by qualitative formal calculi are not necessarily the ones that are foundational to the human cognitive system. Several research approaches have shown that the granularity of formal calculi is inadequate for modeling human conceptualizations of both static and dynamic spatial relations. To address this issue the majority of approaches (e.g., Clementini, Di Felice, & van Oosterom, 1993; Schneider & Behr, 2006) define formal criteria on how to cluster topological equivalence classes such that the overall number of topological predicates is reduced. Clementini and collaborators (1993) suggest five basic relations that are derived on the basis of the emptiness and non-emptiness of component intersection, inclusion and non-inclusion of one object in another object, and the dimension of the component intersection. Schneider and Behr (2006) developed a method based exclusively on the emptiness and non-emptiness of component intersection. Coming from a database user perspective, Schneider and Behr developed the concepts of *topological cluster predicates* and *topological predicate groups* to reduce the number of predicates in a user-defined or application-specific manner.

Our research adds to this body of knowledge by having behaviorally evaluated the DLine-Region calculus that requires, formally, the distinction of 26 relations between a directed line and a region based on an extended version of Egenhofer's intersection models. Kurata and Egenhofer (2009) discuss several approaches on reducing the 26 relations as their primary goal is to model human concepts of motion. While we find some commonalities in the approaches they discuss and the results of our experiments, there is no complete agreement between any of the discussed approaches and our results. This demonstrates once more the importance of behavioral evaluations of qualitative calculi that is often called for (e.g., Clementini et al., 1993) but rarely delivered.

Given the ubiquity of qualitative spatio-temporal calculi as tools and means to bridge the gap between a formal systems and human conceptions of space and time, our research has the potential to provide insights into necessary adaptations/modifications of qualitative calculi to deserve the label "cognitively adequate". Our research methodology, in general, is tailored to calculi based on jointly exhaustive and pairwise disjoint relations that all form conceptual neighborhood graphs (Cohn & Renz, 2008). The use of JEPD and CNGs in areas such as linguistics (Ross, Hois, & Kelleher, 2010), robotics, database query languages and information retrieval, and ontological modeling (e.g. for the semantic web) can be greatly enhanced by behavioral research that provides the necessary bridge between cognitive and formal spatio-temporal semantics.

Future research directions are manifold given both the ubiquity of QSTR in research and application and the paucity of behavioral evaluations. The following ones strike us as important: We have recently demonstrated that domain semantics has a meaningful influence on the grouping behavior of participants, that is, which original topological relations form cognitive conceptual clusters (Klippel in press). To this end, a theory is needed that would allow for specifying meta-domain characteristics and how they influence cognitive conceptualizations of movement patterns.

Mark and Egenhofer (1994b) raised already the question of the influence of language on the conceptualization of line-region relations. Linguistic (and potentially cultural) influences surface in the spatial science sporadically (see Mark, Turk, & Stea, 2007 for a more substantial treatment) but are still not integrated into core theories. A transdisciplinary research agenda is needed to deliver results that could influence spatial theories more fundamentally.

We have developed an approach to characterize movement patterns based on the notion of conceptual primitives (Klippel 2011) that is built on the basic distinctions used to define topological relations between a line and a region: interior, exterior, and boundary (the latter distinguished as movement on a spot and extended movement on the boundary, see also Kurata & Egenhofer, 2009). This approach is comparable to work on movement patterns by Stewart Hornsby and Cole (2007) in that basic topological distinctions constitute primitive distinctions that could be additionally annotated by using, for example, direction information. We consider it important to deepen this line of research as it potentially allows for linking linguistic expressions with formal spatial characterizations more flexibly and has the capability of modeling and interpreting continuous movement behavior.

7 References

Adrienko, G., Adrienko, N., Dykes, J., Fabrikant, S. I., & Wachowicz, M. (2008). Geovisualization of dynamics, movement and change: Key issues and developing approaches in visualization research. *Information Visualization*, 7(3/4), 173–180.

Allen, J. F. (1983). Maintaining knowledge about temporal intervals. *Communications of the ACM, 26*(11), 832–843.

Clementini, E., Di Felice, P., & van Oosterom, P. (1993). A small set of formal topological relationships suitable for end-user interaction. In D. Abel & B. C. Ooi (Eds.), *Advances in Spatial Databases. Third International Symposium, SSD '93 Singapore, June 23–25, 1993 Proceedings* (pp. 277–295). Berlin: Springer.

Cohn, A. G. (2008). Conceptual neighborhood. In S. Shekhar & H. Xiong (Eds.), *Encyclopedia of GIS* (p. 123). Boston, MA: Springer.

Cohn, A. G., & Renz, J. (2008). Qualitative spatial representation and reasoning. In F. van Harmelen, V. Lifschitz, & B. Porter (Eds.), *Foundations of artificial intelligence. Handbook of knowledge representation* (1st ed., pp. 551–596). Amsterdam: Elsevier.

Egenhofer, M. J., & Al-Taha, K. K. (1992). Reasoning about gradual changes of topological relationships. In A. U. Frank, I. Campari, & U. Formentini (Eds.), *Theories and methods of spatio-temporal reasoning in geographic space* (pp. 196–219). Berlin: Springer.

Egenhofer, M. J., & Franzosa, R. D. (1991). Point-set topological spatial relations. *International Journal of Geographical Information Systems, 5*(2), 161–174.

Egenhofer, M. J., & Mark, D. M. (1995). Naive geography. In A. U. Frank & W. Kuhn (Eds.), *Spatial Information Theory. A Theoretical Basis for GIS. International Conference, COSIT 95, Semmering, Austria, September 21-23, 1995, Proceedings* (pp. 1–15). Berlin: Springer.

Freksa, C. (1992). Temporal reasoning based on semi-intervals. *Artificial Intelligence, 54*(1), 199–227.

Galton, A. (2000). *Qualitative spatial change. Spatial information systems.* Oxford: Oxford Univ. Press.

Klippel, A. (in press). Spatial information theory meets spatial thinking - Is topology the Rosetta Stone of spatio-temporal cognition? *Annals of the Association of American Geographers.*

Klippel, A. (2011). Movement choremes: Bridging cognitive understanding and formal characterization of movement patterns. *Topics in Cognitive Science, 3*(4), 722–740.

Klippel, A., Li, R., Yang, J., Hardisty, F., & Xu, S. (in press). The Egenhofer-Cohn hypothesis: Or, topological relativity? In M. Raubal, A. U. Frank, & D. M. Mark (Eds.), *Cognitive and Linguistic Aspects of Geographic Space - New Perspectives on Geographic Information Research.* Berlin: Springer.

Knauff, M., Rauh, R., & Renz, J. (1997). A cognitive assessment of topological spatial relations: Results from an empirical investigation. In S. C. Hirtle & A. U. Frank (Eds.), *Spatial information theory: A theoretical basis for GIS* (pp. 193–206). Berlin: Springer.

Kos, A. J., & Psenicka, C. (2000). Measuring cluster similarity across methods. *Psychological Reports, 86,* 858–862.

Kurata, Y. (2008). The 9+-intersection: A universal framework for modeling topological relations. In T. J. Cova, H. J. Miller, K. Beard, A. U. Frank, & M. F. Goodchild (Eds.), *Geographic information science. 5th international conference, GIScience 2008, Park City, UT, USA, September 23 - 26, 2008 ; proceedings* (pp. 181–198). Berlin: Springer.

Kurata, Y., & Egenhofer, M. J. (2007). The 9+-Intersection for Topological Relations between a Directed Line Segment and a Region. In B. Gottfried (Ed.): *Vol. 42. TZI Technical Report, 1st Workshop on Behaviour Monitoring and Interpretation (BMI'07), in conjunction with 30th German Conference on Artificial Intelligence* (pp. 62–76). Universität Bremen.

Kurata, Y., & Egenhofer, M. J. (2009). Interpretation of behaviors from a viewpoint of topology. In B. Gottfried & H. Aghajan (Eds.), *Behaviour monitoring and interpretation. Ambient intelligence and smart environments* (pp. 75–97). Amsterdam: IOS Press.

Lu, S., Harter, D., & Graesser, A. C. (2009). An empirical and computational investigation of perceiving and remembering event temporal relations. *Cognitive Science, 33,* 345–373.

Maguire, M. J., Brumberg, J., Ennis, M., & Shipley, T. F. (2011). Similarities in object and event segmentation: A geometric approach to event path segmentation. *Spatial Cognition and Computation*, (3), 254–279.

Mark, D. M., & Egenhofer, M. J. (1994a). Calibrating the meanings of spatial predicates from natural language: Line-region relations. In T. C. Waugh & R. G. Healey (Eds.), *Advances in GIS Research, 6th International Symposium on Spatial Data Handling* (pp. 538–553).

Mark, D. M., & Egenhofer, M. J. (1994b). Modeling spatial relations between lines and regions: Combining formal mathematical models and human subject testing. *Cartography and Geographic Information Systems, 21*(3), 195–212.

Mark, D. M., & Egenhofer, M. J. (1995). Topology of prototypical spatial relations between lines and regions in English and Spanish. In *Proceedings, Auto Carto 12, Charlotte, North Carolina, March 1995,* (pp. 245–254).

Mark, D. M., Turk, A. G., & Stea, D. (2007). Progress on Yindjibarndi ethnophysiography. In S. Winter, B. Kuipers, M. Duckham, & L. Kulik (Eds.), *Spatial Information Theory*. *9th International Conference, COSIT 2007, Melbourne, Australia, September 19-23, 2007 Proceedings* (pp. 1–19). Berlin: Springer.

Mennis, J., Peuquet, D. J., & Qian, L. (2000). A conceptual framework for incorporating cognitive principles into geographical database representation. *International Journal of Geographical Information Science, 14*(6), 501–520.

Muller, P. (2002). Topological spatio-temporal reasoning and representation. *Computational Intelligence, 18*(3), 420–450.

Randell, D. A., Cui, Z., & Cohn, A. G. (1992). A spatial logic based on regions and connections. In B. Nebel, C. Rich, & W. R. Swartout (Eds.), *Proceedings of the 3rd International Conference on Knowledge Representation and Reasoning* (pp. 165–176). Morgan Kaufmann.

Randell, D., & Cohn, A. (1989). Modelling Topological and Metrical Properties in Physical Processes. In R. Brachman, H. Levesque, & R. Reiter (Eds.), *Proceedings 1st International Conference on the Principles of Knowledge Representation and Reasoning* (pp. 55–66). Los Altos: Morgan Kaufmann.

Regier, T., & Zheng, M. (2007). Attention to endpoints: A cross-linguistic constraint on spatial meaning. *Cognitive Science, 31*(4), 705–719.

Ross, R. J., Hois, J., & Kelleher, J. (Eds.) (2010). *Computational Models of Spatial Language Interpretation (CoSLI) Workshop at Spatial Cognition 2010.* CEUR Workshop Proceedings.

Schneider, M., & Behr, T. (2006). Topological relationships between complex spatial objects. *ACM Transactions on Database Systems, 31*(1), 31–81.

Schwering, A. (2011). *Does metric really define topology (personal communication). May 20th, 2011*.

Shariff, A. R., Egenhofer, M. J., & Mark, D. M. (1998). Natural-language spatial relations between linear and areal objects: The topology and metric of English-language terms. *International Journal of Geographical Information Science*, *12*(3), 215–246.

Shipley, T. F., & Maguire, M. J. (2008). Geometric information for event segmentation. In T. F. Shipley & J. M. Zacks (Eds.), *Understanding events: How humans see, represent, and act on events* (pp. 415–435). New York: Oxford University Press.

Shipley, T. F., & Zacks, J. M. (Eds.) (2008). *Understanding events: How humans see, represent, and act on events.* New York: Oxford University Press.

Sridhar, M., Cohn, A., & Hogg, D. (2011). From Video to RCC8: Exploiting a Distance Based Semantics to Stabilise the Interpretation of Mereotopological Relations: Spatial Information Theory. In M. Egenhofer, N. Giudice, R. Moratz, & M. Worboys (Eds.), *Lecture Notes in Computer Science. Spatial Information Theory. 10th International Conference, COSIT 2011, Belfast, ME, USA, September 12-16, 2011. Proceedings* (pp. 110–125). Springer.

Stewart Hornsby, K., & Cole, S. (2007). Modeling moving geospatial objects from an event-based perspective. *Transactions in GIS, 11*(4), 555–573.

van de Weghe, N., Billen, R., Kuijpers, B., & Bogaert, P. (Eds.). 2008. *Moving Objects: From Natural to Formal Language: Workshop held in conjunction with GIScience 2008, Utah.*

Yuan, M., & Hornsby, K. S. (2008). *Computation and visualization for the understanding dynamics in geographic domains: A research agenda.* Boca Raton, Fla.: CRC Press.