The Egenhofer–Cohn Hypothesis or, Topological Relativity?

Alexander Klippel, Rui Li, Jinlong Yang, Frank Hardisty and Sen Xu

Abstract In this chapter, we provide an overview of research on cognitively validating qualitative calculi, focusing on the region connection calculus (RCC) and Egenhofer's intersection models (IM). These topological theories are often claimed to be foundational to spatial cognition, a concept we term the *Egenhofer–Cohn Hypothesis*. (The authors are aware of the limitations of the chosen title/term. Neither Egenhofer nor Cohn necessarily support this claim in a strong form but they kindly agreed to have their names used here. Additionally, there are other approaches to topology, Cohn is the third author on the classic RCC paper, and Egenhofer published his work with co-authors. However, we feel that these two names best summarize the two most prominent topological theories in the spatial sciences.) We have been particularly interested in extending existing approaches into the realm of spatio-temporal representation and reasoning. We provide an overview on a series of experiments that we conducted to shed light on geographic event conceptualization and topology's role in modeling and explaining cognitive

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A. Klippel (✉) · R. Li · J. Yang · F. Hardisty · S. Xu
Department of Geography, GeoVISTA Center, The Pennsylvania State University,
University Park, PA, USA
e-mail: klippel@psu.edu

R. Li
e-mail: rui.li@psu.edu

J. Yang
e-mail: jinlong@psu.edu

F. Hardisty
e-mail: hardisty@psu.edu

S. Xu
e-mail: sen.xu@psu.edu

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behavior. Our framework also incorporates approaches to visually analyze cognitive behavior, allowing for interactive and in-depth analyses of cognitive conceptualizations. We present tangible results that can be distilled from generalizing from several experiments. These results show that the strong version of the Egenhofer–Cohn Hypothesis is not supported by all results; we suggest amendments to topological relationship specifications that are needed to serve as a sufficient basis for bridging formal and observed human spatial cognitive processes. We term this approach *topological relativity*.

Keywords Topology · Spatial knowledge · Qualitative spatial reasoning

1 Introduction

Knowledge, including spatial knowledge, can only be created through abstraction. The myriad individual pieces of information that a cognizing agent, whether artificial or natural, has to process in every second of its interaction with the outside world—be it physical or social—can only be sensibly comprehended on an abstract level: "If every object and event in the world were taken as distinct and unique a thing in itself unrelated to anything else—our perception of the world would disintegrate into complete meaninglessness" (Abler et al. 1971, p. 149). The abstraction mechanisms used by natural cognitive agents are manifold and so are the mechanisms and algorithms implemented for artificial agents: Filtering, aggregation, aspectualization, simplification, and generalization, to name just a few.

Natural cognitive agents (NCAs) have been, for a long time, the inspiration for creating artificial agents.[1] Mimicking natural cognitive agents has provided valuable insights for the design, for example, of robots. Understanding natural cognitive agents on a level of detail where their perceptual, thought, and reasoning processes can be captured formally is also essential for the design of any kind of interface between natural and artificial systems (human—machine or human—computer interaction).

From the perspective of spatial information and knowledge, qualitative spatial reasoning (QSR) has provided many tools for capturing potentially essential information (Cohn and Renz 2008; Freksa 1991). Within QSR, topology and topological calculi are likely the single most often referenced theoretical construct used to provide a more abstract representation of spatial information—often with the goal to be cognitively meaningful. The reason for the prominence of topology is that it allows for abstracting spatial information by specifying classes of equivalence.

[1] For an example how artificial agents provide insights into cognitive agents see, for example, Braitenberg (1984) and the growing body of literature on agent based modeling.

Equivalence classes create categories (or concepts) of spatial information that make its members indistinguishable and that allow all members to be assigned characteristics that are relevant for spatial inferences. By knowing which equivalence class a spatial relation belongs to, we have found a way to powerfully utilize one of the most important cognitive abilities humans possess: categorization and conceptualization.

But how do topology and topological equivalence actually work? From a cognitive perspective, topology is connected to an important theoretical construct, namely that of an *invariant* (see Klein 1872 for one of the first formal treatments). Invariants constitute something similar to equivalence classes by acknowledging that the world that NCAs live in is dynamic and that making sense of this dynamic world requires treating objects and relations between objects as invariant. In other words, NCAs abstract from changes introduced, for example, by changing perspectives, to achieve a consistent representation of their spatial environments. Interestingly, invariants have been approached both from researchers focusing on perception as well as researchers focusing on high-level cognition.

Klix (1971) focused on invariants as a means by which the human mind identifies characteristics in its spatial environment that allow the mind to build a basis for information processing. He explicitly referred to topology as an approach for identifying those invariants. With a particular focus on dynamic characteristics, the construct of invariants has been instrumentally integrated into the work of Shaw and collaborators (1974) and famously Gibson's theory of perception (1979). Shaw is referring to properties of objects and events that do not change, from a group (set) theoretic perceptive, as *transformational invariants*. Gibson, in his seminal publications, calls temporarily constant characteristics of environments *structural invariants*.

Additionally, topology is not only seen as a construct that satisfies the requirements of theories identifying important low-level perceptual characteristics but also the invariants of high-level cognitive processes (Lakoff 1990). Most prominently, topology is featured in the most abstract theories of cognitive information processing such as the work on image schemata (Johnson 1987; Kuhn 2007; Lakoff 1987; Mandler 1992). The most commonly found definition of image schemata is that they are recurring patterns that manifest in our sensory experience. To this end, they are able to bridge very concrete perceptual images on the one hand and abstract propositional structures on the other. As Kuhn points out "Image schemas are often spatial, typically topological […]" (Kuhn 2007, p. 155).

To summarize, spatial knowledge construction depends on abstraction. Qualitative spatial reasoning provides a powerful abstraction mechanism. Prominent QSR theories (e.g., topology) are intimately linked to cognitive theories, for example, through the concept of invariants, which are relevant for both low-level perceptual and high-level conceptual information processing. This, in a nutshell, lays out the foundation for the Egenhofer–Cohn Hypothesis, that is, that topology is foundational to cognitive (spatial) information processing (compare one of the mantras of na geography: topology matters and metric refines—Egenhofer and Mark 1995b).

The remainder of this chapter is structured as follows: We continue reviewing relevant literature from different perspectives. We first briefly introduce the most prominent topological calculi in spatial information science, the region-connection calculus and Egenhofer's intersection models, and we discuss a selection of approaches that have addressed the cognitive adequacy of these calculi. As most of these approaches have targeted static spatial relations, we discuss in more depth our own research that adds several aspects to the body of literature on cognitive adequacy of topological calculi such as dynamics and domain-specificity.

2 Background

2.1 Topological Calculi

Topological information can be captured from spatially different perspectives. The two most important approaches that are addressed in this chapter are the region connection calculus, RCC, which has been proposed by Randell et al. (1992) and intersection models, IM, which have been developed by Egenhofer and Franzosa (1991). We briefly introduce these approaches (for excellent extended overviews and discussion see Galton 2000 or Cohn and Renz 2008).

The region connection calculus, as the name implies, is built around the primitive of a region and a mereotopological connection relation, C, between regions. Galton (2000) points out that an author taking this approach is not obliged to answer the question "what is a region?" in a rigorous way. Regions can simply be acknowledged as being primitive elements in a theory. Given two regions, x and y, C(x, y) means that region x is connected to region y. The connection relation C is both symmetric and reflexive. Using the connection relation, it is possible to define additional relations such as parthood, P. For example, P(x, y), means that x is a part of y as long as anything connected to x is also connected to y. Once P is defined we can build other relations such as what it means to be a proper part, PP, and what it means to overlap, O, respectively. The eight relations in Fig. 1 can be formally characterized using this framework.

In contrast, Egenhofer's intersection models approach topology from an ontologically different perspective. Rather than assigning regions the role of a primitive concept, the intersection models are built around the notion of point set topology (Alexandroff 1961). Points are associated with three locations in relation to a spatial entity: Its interior (which can be region-like/extended, but also linear), its boundary (endpoints in case the spatial entity is linear), and its complement. A 3×3 matrix based on the three locations is established for the spatial relation between two entities by assessing whether the intersection of any of the nine point sets is empty or not. Like RCC, the intersection approach allows for formally characterizing the eight spatial relations in Fig. 1 (details and overviews can be found in Egenhofer and Franzosa 1991; Egenhofer and Mark 1995a).

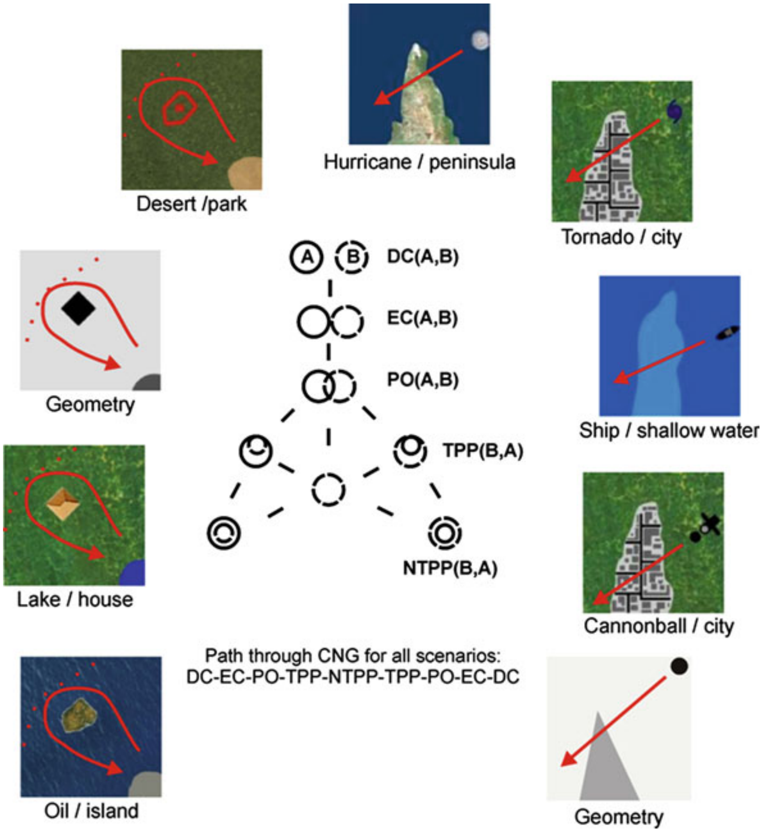

Fig. 1 Conceptual neighborhood graph (CNG) with topological relations DC (disconnected), EC (externally connected), PO (partial overlap), TPP (tangential proper part), NTPP (nontangential proper part). Patterns of the dynamic entities in the nine scenarios (referred to as semantic domains) are identical from the perspective of topology: they can be characterized by the same path through the conceptual neighborhood graph (DC-EC-PO-TPP-NTPP-TPP-POEC-DC). Hence, topology identifies a universal (i.e., invariant) aspect in humans' dynamic environments (adapted from Klippel 2012)

Topologically characterized spatial (and temporal) relations unfold their full potential when they are organized as conceptual neighborhood graphs (Cui et al. 1992; Egenhofer and Al-Taha 1992; Freksa 1992). This approach was publicized by Freksa (1992) for Allen's (1983) temporal intervals but the concept was quickly applied to corresponding spatial (topological) relations (Cui et al. 1992; Egenhofer and Al-Taha 1992). In the original work by Freksa, two temporal relations (e.g., meet and overlap) are considered being conceptual neighbors if a continuous transformation such as shortening, lengthening, or moving (translation) allows for directly transforming one relation into the other with no other (third) relation holding in between. For the spatial domain Egenhofer and Al-Taha (1992) have shown that this principle can be applied to topological relations between two spatially extended entities, that is, certain relations can be transformed directly into one another by translation, rotation, or scaling. Later on, the concept of conceptual neighborhood graphs has been shown to be universal for qualitative calculi (Egenhofer 2010; Egenhofer and Mark 1995a; Kurata 2008a). In fact, for virtually every qualitative calculus with jointly exhaustive and pairwise disjoint (JEPD) relations, a conceptual neighborhood graph can be formed (Cohn and Renz 2008).

Conceptual neighborhood graphs are essential, because they broaden the spectrum of applications of topological calculi in essential ways: They allow for measuring the similarity between topological relations. As such, they can be applied to assessing the similarities of scenes (Bruns and Egenhofer 1996), allow for relaxing queries of spatial databases in case an exact match cannot be found (Egenhofer 2010), they enable qualitative simulation (Cui et al. 1992), or allow for converting noisy quantitative video data into qualitative characterizations (Sridhar et al. 2011). Conceptual neighborhood graphs have been essential as a tool for assessing and formalizing cognitive assessments of similarity between spatial relations and are also used as a formal foundation for natural language expressions (see next section).

2.2 Behaviorally Researching Topology

Topology has been central to bridging the gap between a formal characterization of relations between spatial entities on the one side and the cognitive processing of spatial information on the other. While the number of behavioral validations of spatial calculi is small compared to the number of proposed formalisms, there is an active community that performs research on refining and tailoring formalisms through validating their cognitive adequacy.

First and foremost, there is the extensive research by Mark and Egenhofer (1995a, 1994a, b). Naturally, they focused on IMs such that their research is only partially comparable to RCC. They employed a number of different methods to evaluate whether or not the 9-IM (focusing largely on line-region relations, specifically a road in relation to a park) is indeed capturing both cognitive as well as linguistic spatial categories. They used a grouping task to assess people's conceptual knowledge (Mark and Egenhofer 1994b) and they used agreement tasks in which they created an assessment of spatial expressions in relation to formal topological descriptions (Mark and Egenhofer 1994a). Interestingly, they also reversed their approach: participants were provided with linguistic expressions and were asked to draw sketch maps. Their conclusions converge on the famous sentence that *topology matters and metric refines* (Egenhofer and Mark 1995b). There are some aspects of their research that are not as prominently discussed in the literature such as the finding that topological relations form groups, that is, not every topological equivalence class has a unique cognitive counterpart (at least not on the same categorical level). Given that their research addressed primarily line-region relations this finding may not be surprising as

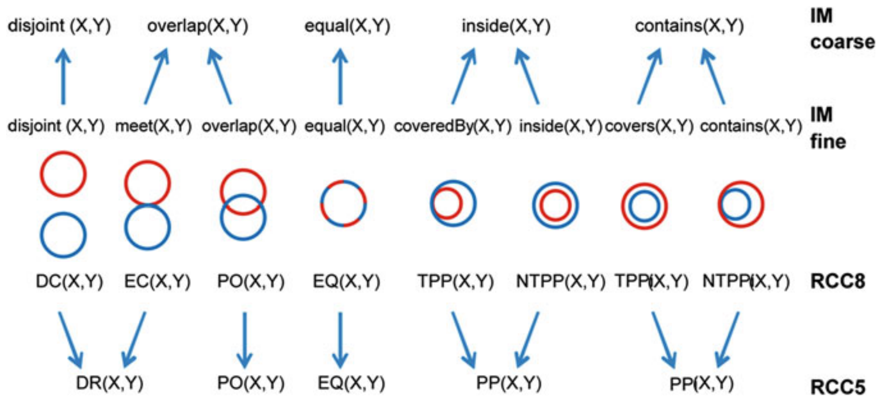

Fig. 2 Spatial relations distinguished by RCC-8 and RCC-5 and corresponding coarse and fine distinction explicated in IMs (adapted from Knauff et al. 1997)

the 9-intersection model distinguishes 19 equivalence classes (for line-region relations).

A study, or actually a set of studies that allow for a direct comparison between IMs and RCC was published by Knauff, Renz and collaborators (Knauff et al. 1997; Renz 2002); their research focused on extended spatial entities. For both approaches (IMs and RCC) two different levels of granularity can be defined and, interestingly, there is no direct mapping at the coarser level (although both distinguish five relations, see Fig. 2). Hence, it could be that either model would deserve the label "cognitively (more) adequate". Their results, however, show that actually the eight relations specified by both RCC-8 and IM are the ones that are deemed cognitively adequate and that coarsening the eight relations to five may be cognitively irrelevant (Knauff et al. 1997). Figure 2 shows the two approaches and their two levels of granularity. It has to be noted though, that the stimuli used in their experiments were geometric figures, very much like the ones used in Fig. 2. This design strongly emphasizes boundaries (although this concept does not exist in RCC) and also does not account for any influence that the semantics of a specific domain might have (as compared to the research of Mark and Egenhofer, see preceding paragraph).

There are additional studies that show that matching, for example, linguistic description and topological operators, such as those used in various GIS products, is still not a straight forward task. Riedemann (2005) asked participants in a simple agreement task whether a term used to describe an operation in a GIS corresponds to a specification of this operation as derived from the 9-IM. While she did find that terms can be matched to operations, she also showed that (a) these terms are not necessarily the ones used in GIS products and (b) that there is more flexibility with respect to the interpretation and applicability of a linguistic term as formally specified.

Other studies assessing the cognitive adequacy of topological calculi are only briefly mentioned here (without claiming that this is an exhaustive overview). Shariff and collaborators (Egenhofer and Shariff 1998; Shariff et al. 1998) did extensive work to calibrate natural language expressions (see also Schwering 2007). In addition to topological distinctions they introduced metric details that they organized into three categories: splitting, closeness, and approximate alongness. From a behavioral perspective, they largely relied on their previous work; however, they developed a formal model that allows for capturing the semantics of over 60 natural language expression such as *goes across*.

Zhan (2002) addressed the question of modeling quantifying linguistic expressions such as *a little bit*, *somewhat*, and *nearly completely*. Topology alone is not sufficient to create such a model. He performed a user study in which participants rated the appropriateness of sentences describing a spatial scene showing two spatially extended entities. To integrate the data he obtained into a model of the meaning of spatial language expressions he used fuzzy set theory.

Xu (2007) focused on the relation between two linear entities. Like Zhan and, to some extent, Mark and Egenhofer, she found that topology alone is not sufficient to capture the semantics of spatial expressions describing the relation between two linear entities. She used an agreement task and modeled the results for particular spatial expressions and whether or not they match a graphic depiction of two linear entities as input for a rule-based approach. Through this approach she was able to define, formally, the spatial semantics of terms such as *crosses* or *is parallel to*.

To summarize, topology is likely the single most often used formalism (ignoring the different perspectives on it) that is applied to bridge the gap between requirements of formal systems and spatial cognition. From this perspective, the Egenhofer–Cohn Hypothesis is an inspiring, valid, and testable assumption that has stimulated a plethora of research papers. However the cognitive validation of qualitative formalisms is still underdeveloped. We have discussed several of them that led to varying results, often finding that topological information is a start but not sufficient to model spatial cognition.

One aspect that has not received sufficient attention is the combination of space and time (although the classic *road crossing a park* and the two linear objects in Xu's work 2007 could be interpreted as spatio-temporal trajectories, see also Gottfried, van de Weghe et al. 2009). Spatio-temporal, or, from a cognitively inspired perspective, event-based approaches to spatial information systems and science are important. Cognitively inspired frameworks were proposed in the 1980s (Peuquet 1988); however, only the availability of ubiquitous computing facilities in the form of, for example, sensor networks (Worboys and Duckham 2006) has spurred the necessity to integrate both time and space into information science and systems.

In the following sections we introduce a framework that we have established to allow for evaluating topological calculi and their role in bridging the cognition of events and their formal characterization.

3 A Framework for Assessing the Cognitive Adequacy of Topological Calculi for Modeling Geographic Events

We have extended research on assessing topological relations (primarily between spatially extended entities) from a cognitive perspective. We will summarize here the main findings and provide an overview of our contributions that primarily address the role of topology in geographic event conceptualization. Table 1 provides an overview and accompanies the discussion.

One important aspect to keep in mind (which we will also come back to in the outlook) is that we addressed movement patterns from the perspective that a spatially extended entity (figure) is changing its spatial relation with a reference entity which is also spatially extended (ground). One of the reasons for this approach is that only on this level of spatial information are RCC and IM directly comparable. Additionally, regions have long been central to qualitative theories of motion (Muller 2002). It should be noted that an alternative approach is to treat the figure and its path as a point objects that leave a trail (or line) and use the flexibility of the intersection models to model the relation between a region and a line (Egenhofer and Mark, 1995a; Kurata 2008b; Kurata and Egenhofer 2009). While we have conducted experiments with DLine-Regions, too, they are less advanced and will only be mentioned briefly.

3.1 Methodology

From the various methodological possibilities we selected the grouping paradigm as one of the most central methods for assessing conceptual knowledge (and cognitive adequacy). The set-up of our experiments follows work by Mark and Egenhofer (1994b) and Knauff et al. (1997) as well as established practice in psychology experiments (Pothos and Close 2008): A set of stimuli is created, in our case animations of movement patterns (see, e.g., Fig. 1), and participants are asked to create groups (categories) in which they sort the icons. Because we are genuinely interested in the (natural/commonsense) conceptualizations of movement patterns we followed an approach that is called *category construction* (Medin et al. 1987), *free classification* or *unsupervised learning* (Pothos and Chater 2002). The main characteristic of this approach is that participants do not receive a predefined number of groups/categories but that they are free to create any number of categories that they deem appropriate for the given stimuli. The opposite of this approach is called non-free classification or supervised learning, in which participants are given a set of categories and are evaluated whether they are able to categorize a set of stimuli correctly.

Besides collecting grouping data it is also common practice to collect linguistic data, often in the form of labels that are given to the groups after they have been created. We follow this approach, too, as the linguistic data offers valuable insights

Table 1 Overview of behavioral experiments

	Publication	Topological aspect	Additional spatial information	Stimulus	Result
1	Klippel et al. (2008)	Paths through a topological neighborhood graph. Same starting relations (DC) and three ending relations that also constrain aspects such as size differences (NTPP, NTPPi, EQ)	Size differences, whether one or both entities in a scene are moving	Animated geometric figures, translation movement	Size and whether one or both entities were moving were singled out as main criteria to conceptualize movement patterns
2	Klippel (2009)	Paths through a topological neighborhood graph. Same starting relation (DC), different ending relations (DC, EC, PO, TPP, NTPP, TPP, PO, EC, DC)	Size differences, whether one or both entities in a scene are moving	Animated geometric figures, translation movement	Size was the primary grouping criterion
3	Klippel and Li (2009)	Paths through the conceptual neighborhood graph with a static ground (peninsula) and moving figure (hurricane). Same starting relation (DC), different ending relations (DC, EC, PO, TPP, NTPP, TPP, PO, EC, DC)	Randomized start and end coordinates	Animated hurricanes in relation to peninsula, translation movement	Topology was used as the main criterion. However, not all topologically defined ending relations were equally salient, that is, they formed groups
4	Klippel et al. (2010)	Same as 3	Randomized start and end coordinates plus hurricanes had different sizes	Animated hurricanes in relation to peninsula, translation movement	Participants had a clear focus on the size differences, then topology
5	Li et al. (2011)	Same as 3	Randomized start and end coordinates plus the paths of the hurricanes were either animated or represented as a static line	Animated or static paths of hurricanes in relation to peninsula, translation movement	Participants paid statistically significantly more attention to ending relations in case the trajectory is represented statically

(continued)

Table 1 (continued)

	Publication	Topological aspect	Additional spatial information	Stimulus	Result
6	Klippel (2012)	Same as 3	Randomized start and end coordinates plus five different semantic contexts/ domains. Within each domain the topological information is identical. Scenarios: Hurricane/peninsula, tornado/city, ship/shallow water, cannonball/city, geometric figures	Five different translation scenarios (see Fig. 1)	Topological relations are not equally salient across different semantic domains
7	Yang et al. (in revision)	Similar to 3 in that the topological information is identical. However, instead of using translational movement patterns, scaling movement was employed	Randomized start and end coordinates plus four different semantic contexts/ domains. Within each domain the topological information is identical (also to 6). Scenarios: Oil/island, desert/park, lake/house, geometric figures	Four different scaling scenarios (see Fig. 1)	Topological relations are not equally salient across different semantic domains
8	Klippel et al. (2011)	Meta-analysis of previous results/ experiments focusing on individual differences	div.	div.	The tools and approaches we developed allow for an in depth analysis of categorization/ conceptualization behavior

into cognitive processes as well as input to computational/formal models of natural language. The latter aspect is possible because our experiments are grounded in a formal (topological) framework. However, the primary use of the linguistic data in our experiment has been on providing additional insights into cognitive conceptualizations.

One important development that reflects the symbiotic and mutually beneficial influence of the spatial and cognitive sciences is the development of tools to analyze behavioral data. Especially in the area of visual analysis, promising results have been obtained (Fabrikant et al. 2010). We have invested in this line of research as well and have created a number of tools that allow for overview or in-depth analysis of participants' behavior. *CatScan*, the tool that administers the experiment collects data such as the time spent on the grouping task, the order in which icons are selected, and the linguistic descriptions; *KlipArt*, is a visual analytics tool based on Weaver's *improvise* programming environment (Weaver 2004). This tool allows for an in-depth analysis of grouping behavior and for the identification of individual differences in conceptualizing the stimuli; *MatrixViewer*, is again realized within *improvise* and allows for an overview of similarities between stimuli (within one experiment) and for comparing the grouping behavior between participants (again within one experiment) both visually as well as using similarity measures such as the Levenshtein distance (Levenshtein 1966). We have written about these tools extensively and will not provide a detailed discussion here (see Klippel et al. 2011).

3.2 Tangible Results

We call this section 'tangible results' as we are summarizing some of our and other researchers' results on cognitively validating and evaluating topological calculi that may prove useful to researchers interested in the relation between qualitative formalisms and cognition. Our results show that purely topological approaches, as the strong version of the Egenhofer–Cohn Hypothesis, are difficult to defend. In a comprehensive model other aspects (the unequal salience of topological relations, competing spatial information, the semantics of a domain, and the way information is presented) need to be integrated.

Topological relations (as identified by RCC-8 and IMs) are not equally salient from a cognitive perspective. Despite the results of Knauff and collaborators (1997) which assert that the eight relations—identified in RCC-8 and IM—are cognitively adequate, we claim, with some certainty, that this is not the case. Earlier research by Mark and Egenhofer (1994b) already showed that several topological relations form groups (superordinate categories). While Mark and Egenhofer's experiments used 19 topological equivalence classes and creating superordinate categories therefore may be a more natural cognitive behavior, we did not find in any of our experiments that topological relations (which used RCC/IM relations as ending relations of movement patterns) were treated as being equally salient; not in purely geometric scenarios, not in scenarios with domain semantic, neither in translation nor in scaling experiments, and not in static or dynamic representations of trajectories.

Our experiments thereby confirm assumptions (and render them precise) that have been made by several researchers, that is, that in order for topology to be cognitively adequate we need to reduce the number of relations to less than eight. We find this approach in Clementini's work (Clementini et al. 1993), who proposed a maximum of five relations as being a cognitively adequate number, in Li and Fonseca's (2006) approach to build a comprehensive model for the assessment of similarity based on qualitative spatial calculi, and, last but not least, we also find this aspect surfacing in research on Allen's temporal calculus (Allen 1983) conducted by Lu and colleagues (Lu and Harter 2006; Lu et al. 2009).

Topology, while certainly of great importance, is not always the (spatial) aspect that is selected as the main criterion for conceptualizing spatial information. This has been shown in several results we presented and casts some doubts on the unequivocal truth of the statement that *topology matters and metric refines*. It is important though to make a distinction between experiments (scenarios) in which geometric figures are used and those that use examples from the real world. The difference is that geometric figures do not inherit constraints from the domain that they represent. Therefore, it is, for example possible to create scenarios in which one out of two spatial entities or both spatial entities are moving. While there are scenarios in the real world that would allow for such a distinction (two medieval armies conceptualized as extended spatial entities running into each other), it is definitely the case that geometric figures have more degrees of freedom (would those armies also run unaffectedly through one another). Hence, it may be easier for non-topological information to dominate as a category construction criterion in cases in which no real world constraints apply. However, in scenarios which reflect real world movement patterns we find that aspects other than topology may be responsible for guiding human conceptualizations prior to topology, too. One such aspect is direction information. Figure 3 shows an analysis that we performed using KlipArt for the hurricane scenario (see Fig. 1 and Table 1). The majority of participants used topology (which surfaced as the main distinguishing criterion); however, several participants, in addition to making a topological distinction created subgroups based on the direction of the hurricane (relative to the peninsula). A second aspect, which actually dominated topology, is size. For example, employing differently sized hurricanes leads participants to clearly separate animations by the size of the hurricanes (Klippel et al. 2010). In case of a hurricane this would make perfect sense as small hurricanes often injure no-one while the big ones pose a considerable threat. Additionally, this aspect is also prominent in experiments which use geometric figures (Klippel 2009; Klippel et al. 2008) and should therefore be regarded as a serious competitor to topology. If we look into the literature on size we find a couple interesting correspondences:

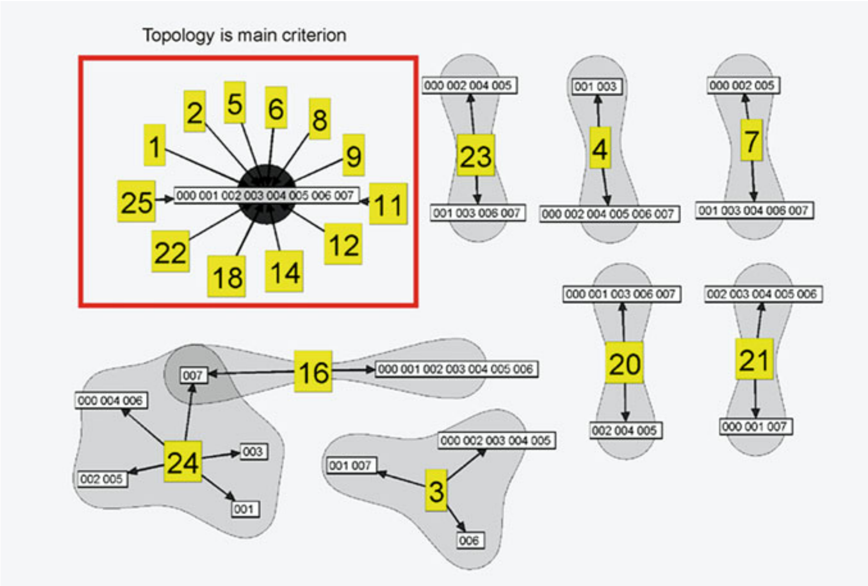

Fig. 3 Depicted is the grouping behavior of participants for the topological relation DC, disconnected. This relation has eight topologically equivalent instances numbered from 000 to 007. Most participants (*red box*) used topology as their criterion for conceptualizing hurricane movement patterns, that is, they placed all icons into the same group. The remaining participants used primarily direction concepts (exception: participant 4 distinguished the length of paths)

- Size (scale) is an important aspect in many geographic theories (Freundschuh and Egenhofer 1997; Montello 1993).
- Size is an important criterion for selecting reference entities (Gapp 1995).
- Size differences, in contrast to changing spatial relations, are continuously present. As such they are potentially easier to conceptualize as movement patterns. This perspective would correspond to research on categorization by Chater and Pothos and colleagues (Chater 1999; Pothos and Close 2008) on the principle of simplicity that they propose as a means to explain perceptual organization as well as conceptual aspects of categorization. In a similar vein research by Gentner and Boroditsky (2001) can be interpreted. They found that children have more difficulties naming events compared to naming objects. It may be the case that topologically characterized changing relations are more difficult to conceptualize as continuously present object characteristics. While an argument could be made that this may only be the case for dynamic presentations, recent research on static spatial relations argues in a similar direction (Schwering 2011).

The cognitive salience of topological relations varies across semantic domains. In several experiments we have compared topologically identical movement patterns across different domains (see Fig. 1). We were able to show

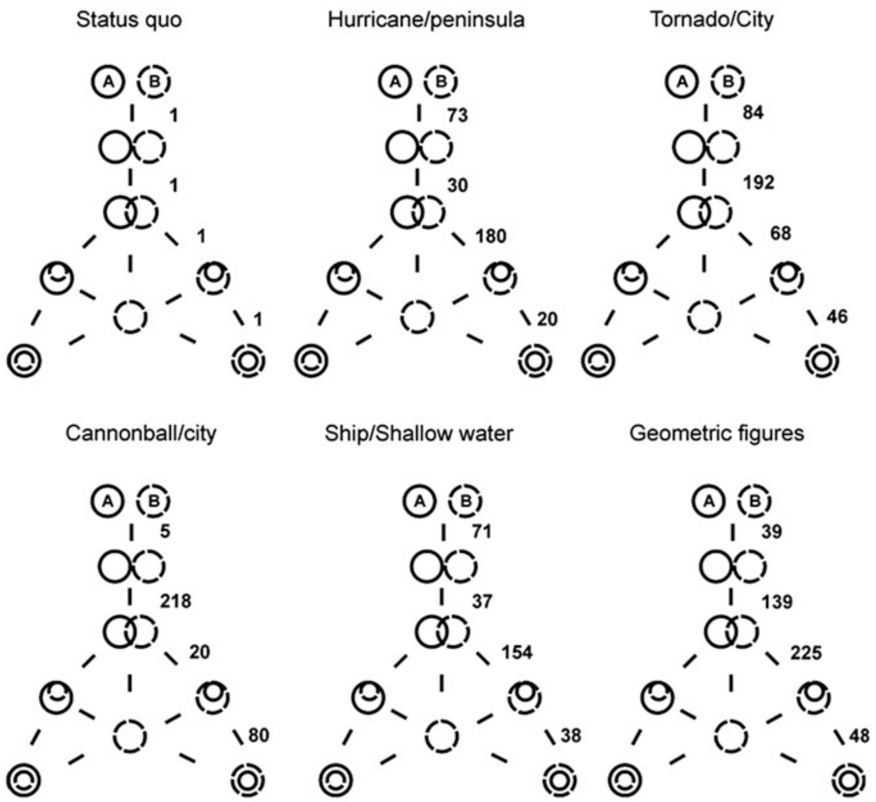

Fig. 4 Conceptual neighborhood graphs with weighted edges. Weights are derived from cluster analysis using fusion coefficients (Ward's method; see also Fig. 1)

that topologically equivalent paths through the conceptual neighborhood graph are not equally salient across different domains. Topologically defined ending relations are meaningfully (from the perspective of the domain semantics) grouped together resulting in different category structures across domains. To illustrate, Fig. 4 shows a first approach towards deriving weights for edges in the conceptual neighborhood graph based on the grouping behavior of participants (see also Fig. 1). It is clear that (a) semantics (and associated background knowledge) has an influence on which topological relations are perceived as being more similar to each other, and (b) that the similarities vary across domains. We performed studies with translation movement patterns (Klippel 2012) and recently also scaling (Yang et al., in revision). In both cases the results show influences of domain semantics.

To some extent these results are not surprising. The cognitive literature is discussing domain specific factors in several ways (e.g., Hirschfeld and Gelman 1994), however, in the light of manifold proposals suggesting to assess similarities between spatial relations on a purely spatial basis, our findings suggest some caution.

The mode of presentation, static or dynamic, of geographic events has a statistically significant influence on how topological information is used to create a conceptualization. In the age of unprecedented digital opportunities this is an important finding that goes, however, beyond our immediate work. In our experiments representing trajectories statically—in contrast to showing an actual animation—had an effect on how the ending relation of a trajectory was used resulting in more participants placing icons of the same topological equivalence class into the same category. It is, of course, easier to attend to endpoints in case a trajectory is statically presented and further research is necessary; however, in recent experiments by Maguire and collaborators (2011) on the segmentation of trajectories that were presented either statically (objects) or dynamically (events) differences were found, too. This research allows for some basic understanding of the effects of animation that has long been a topic of intensive discussions (Tversky et al. 2002).

4 Conclusions and Future Work

We have presented and summarized work on cognitively evaluating topological calculi. Topology, as a way to qualitatively characterize static and dynamically changing spatial relations, has long been recognized as an important construct in both spatial and cognitive sciences. We termed the claim that topology lays (always) the foundation for modeling and explaining cognitive behavior the Egenhofer–Cohn Hypothesis. While research exists that requests a modification of this hypothesis, we found some experiments in which not even the naïve geography mantra that *topology matters and metric refines* (Egenhofer and Mark 1995b) holds and that other spatial aspects such as size may have primacy over topological information. Hence, just like the approach of linguistic relativity (Gumperz and Levinson 1996) seeks to draw a more concise picture of the relation between language and thought we need *topological relativity* as a theoretical construct to provide better models of human spatial reasoning.

To this end, spatial and cognitive sciences have a potential that seems to be not fully explored yet, that is, spatial science provides tools such as RCC and IMs that allow for rendering spatial information precise. This precisely defined information can then be scrutinized in behavioral experiments. We have discussed a number of experiments addressing QSR approaches that primarily originated in spatial sciences and associated fields. Exceptions from a more cognitive science side are the experiments by Knauff et al. (1997) and more recently research by Lu and collaborators (Lu and Harter 2006; Lu et al. 2009). This distinction is based on the home disciplines of the authors but it shows that only a few truly interdisciplinary approaches have been established.

Such a development would be important as topology is not only a potential bridge between formal and cognitive perspectives on space and spatial relations, but it is also a bridge between perceptual and cognitive aspects of space. This insight is manifesting itself in manifold theories that center on invariants that we briefly discussed in the introduction. To this end, topology might also play a central part in theories on concepts and conceptualization. Work by Barsalou, Goldstone, and colleagues (Barsalou 2008; Goldstone and Barsalou 1998), who address the relation between perception and perceptual aspects of environments and its relation to categorization, assign directly perceivable characteristics of environments an important role in theories on categorization. Again, the spatial sciences potentially allow for rendering the notion of environmental characteristics precise and can help design targeted investigations.

With a large group of researchers working on new and/or refined spatial calculi it is not possible to put all of them under the scrutiny of behavioral validation (and many of them are not claiming cognitive adequacy but are important from other, such as computational perspectives—Renz 2002). However, we have clearly seen that the strong version of the Egenhofer–Cohn Hypothesis is addressing cognition too narrowly and that *topological relativity* is the more fruitful approach. To this end, some future behavioral research directions that we consider important should be briefly discussed.

One of the most important research directions is the combination of both spatial and semantic information to fully understand (or model) cognitive behavior. The majority of research in the spatial sciences that develops spatial formalisms is, for obvious reasons, addressing the spatial component of spatial information rather than the semantic aspect. However, several approaches exist which aim for a more comprehensive framework such as early work by Gapp (1995) on selecting cognitively salient reference objects. In line with a tremendous amount of research on ontological characterizations of spatial information (e.g., Kuhn 2001), a cognitively inspired ontological characterization is necessary to structure domains into categories. This view, of course, is not new. Hirschfeld and Gelman (1994) edited a book that addresses the topic of domain-specificity of the mind (although domain in their case is not restricted to semantic domain). From the perspective of concept theories the still somewhat elusive *theory* (Laurence and Margolis 1999) has developed; and, from the perspective of event segmentation Zacks' (2004) model explicitly incorporates knowledge structures (background knowledge) as a factor that identifies meaningful (event) units. These are but a few examples. However, we are still not at a stage where results from spatial and cognitive sciences are intimately intertwined to be applicable to cognitive models and geospatial tools (see also Stock and Cialone 2011).

So far, research on cognitively validating topological calculi has addressed changing spatial relations between spatial entities. However, there are also topological transformations that an individual entity can undergo. Medak (1999) refers to these as lifelines; in a recent article Jiang and Worboys (2009) laid the formal foundation for identifying primitive states of an evolving spatial entity (see also Galton 1997; Renolen 2000). The application areas for these formalisms are substantial and reach from oil spills to heat islands. However, to the best of our knowledge, there is no behavioral research on this aspect of topology and its role in modeling cognitively changing spatial relations. We have started to make plans for assessing continuous change of individual spatial entities to extend our work on assessing the adequacy of current topological formalisms to continuous topological change.

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