A Cognitive Perspective on QSR: Navigation as an Example

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Abstract

One of the central motivations for developing qualitative reasoning was the investigation of a "naïve physics", with the aim to describe the physical world with human "everyday" concepts. This implies the idea that a formal description alone is not sufficient – it should take into account relevant findings from Cognitive Science about human concepts. In this article we (i) present main findings from Cognitive Science about QSR and cognitive modeling, (ii) relate them to current research about QSR, (iii) suggest methodological adjustments that allow both for a more comprehensive evaluation of formalisms and for more realistic and varied test-beds. Finally, we argue that the field of navigation is a drosophila of a more cognitively inspired QSR.

Introduction

Naïve physics "formally describe[s] the world in the way that most people think about it, rather than describing it in the way that physicists think about it" (Hayes 1985). This implies the idea that a formal description alone is not sufficient – it should be combined with cognitive features. With this intention, research is to go beyond formal aspects by taking cognitive concepts into account. Furthermore, cognitive adequacy is a necessary condition for non-expert human-machine interaction. According to Strube (1996), cognitive adequacy is defined as (i) representations that resemble (human) mental knowledge representation and/or (ii) as representations that support cognitive processes. Thus, representations in cognitively adequate formalisms should at least fulfill one of these criteria. Whereas the former might not necessarily matter for all researchers who model intelligent systems, the latter is potentially relevant for all attempts to develop efficient algorithms. Structural features, representations and the processes of reasoning mechanisms can of course influence results. Thus, knowing which internal structures and processes make us outperform artificial systems in daily tasks is of significance even for traditional AI.

In addition, Cognitive Science has an outstanding tradition in cognitive modelling. Many lessons learned are beneficial for other fields of research. For example, additional criteria for evaluating cognitive models and cognitive architectures allow for a better comparison of models. The aim of comparing models, though, should not be achieved at the expense of too dissimilar, specific and static scenarios for each model (group) or domain: This might cause fragmented results and thus complicate integration of findings. The same danger is inherent in benchmarking, which is typically based on highly standardized scenarios. Standardization is important, of course, but it should not be done at the price of too much uniformity of test-beds. Otherwise, conclusions for varied scenarios or tasks are impaired. To sum up, the field of QSR might profoundly benefit from empirical findings and methodological developments of Cognitive Science.

In recent years, however, research has primarily focused on formal understanding and on the analysis of computational complexity. The motivation of this article is to (i) present main findings from Cognitive Science about QSR and cognitive modelling, (ii) to relate them to current research about QSR, (iii) suggest methodological adjustments that allow both for a more comprehensive evaluation of formalisms, and for more realistic and varied test-beds. Both the goal of benchmarking and central applications like natural language processing and human- machine interaction might benefit from such adjustments. We suggest using the complex task of (human) navigation as a rich test-bed for QSR. This task can be decomposed to subtasks relevant to real-world spatial problem solving and allows for a reintegration to more comprehensive accounts afterwards.

State of the art

From a rather formal point of view there are several established qualitative concepts for describing situations: For instance topological relations like inside vs. outside, information about orientation (like cardinal directions), about distance (e.g., far vs. near), and about reference frames (e.g., egocentric vs. allocentric representations). Wayfinding choremes (Klippel 2003) are an approach for describing mental conceptualizations of functional wayfinding and route direction elements. Despite the fact that navigation is an important topic in psychological research (Montello 2005), contemporary computational systems do not make much use of qualitative concepts and related findings so far. In settings like robocup rescue, purely quantitative and probabilistic approaches are still predominant. A rough understanding of human spatial cognition is rather sought in other fields like human-machine interaction, but not in order to improve the robot's performance itself, but rather to make the interaction understandable to the human partner (cp. the second aspect of Strube's (1996) notion of cognitive adequacy and the museum robot MINERVA, Thrun et al. 2000). Similarly, assumptions about reference frames and spatial ambiguities play a major role in human-machine interaction.

Unfortunately, quite few works extend the methodological conventions of the QSR community and thus foster mutual methodological learning. One exception is the use of spatial relations (e.g. Hois and Kutz 2008). This may serve as a linguistic sieve – helping to discover more cognitively adequate relations. As notable, Knauff et al. (1998) started analyzing the cognitive adequacy of the RCC8 calculus, and Knauff et al. (1999) analyzed the adequacy of Allen's interval calculus. Two facets of these theoretical and empirical investigations can be distinguished so far: conceptual adequacy and inferential adequacy of calculi. The former deals with the question how natural qualitative relations are to humans: Do humans discern these relations and do they use them? Here, different cultural and linguistic differences certainly play an important role (as shown in cross-cultural studies, e.g. Mark and Egenhofer 1995). Thus, also linguistic methods are of relevance. The latter facet is concerned with the question whether the (formal) reasoning mechanism is in some sense human-like or whether there are important differences.

Different spatial representations have different spatial complexity (Schlieder and Werner 2003; Vögele et al. 2002) – so far there is only a small number of research covering this topic. Especially, for all questions concerning human-machine interaction "simpler" solutions are preferred over others. Investigations about topological calculi (Ragni et al. 2007b) have demonstrated that solutions with a smaller overlapping complexity are cognitively more simple. Typical human solutions can be explained by transformations in the neighborhood graph (Ragni et al. 2007; despite some limitations: Knauff 1997).

The question to what extent the formal reasoning process reflects the human one can be answered only by comparing models with human behavior in identical tasks along relevant dimensions like the criteria above. Who wants to make strong claims in this respect will not only study relevant literature, but will also conduct informative experiments. We will describe several experimental paradigms in the context of cognitive criteria for qualitative calculi.

Navigation as an example

In the following, we discuss human navigation and demonstrate why it should be considered more comprehensively as a test-bed and research agenda. There is a variety of possible tasks, including route following, route planning, and exploration. We will concentrate on route following to demonstrate that there are different cognitive criteria which have an important effect on the selection and design of appropriate calculi. Kuhnmünch and Strube (in preparation) had participants navigate on an unfamiliar campus area. They had to follow a route given on a map and were asked to lower the map when it was not needed. Experimenters logged when and where participants looked at the map and when it was lowered. Fig. 1 shows the pattern of one participant.

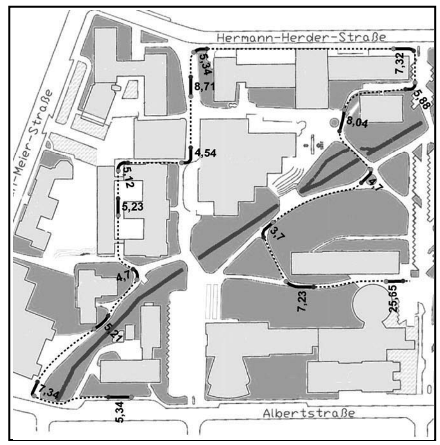

Fig. 1. Pattern of map use while route following (one participant). Black line: Segments with map use. Dotted line: Segments on the route without map use. Numbers: Duration of map use in seconds.

Thus, their task was embedded in an authentic urban environment and comprised several subtasks relevant for human navigation (cp. Lobben 2004), for instance:

- Map reading and remembering their position on the map
- Alignment (fit of orientation between map and reality)
- Self-localization
- Representation and visualization, e.g. transformation of a 2D-map in a "3D-expectation" of what is ahead
- Building up new or refined survey knowledge based on locomotion or maps
- Use of background knowledge (e.g., use of landmarks for self-localization and error recovery and other wayfinding strategies, map literacy)
- Maintaining a sense of direction; building up of and switching between reference frames

- Locomotion with perceptual and motor components; take prescribed turning actions at decision points
- Path integration
- Error recovery: self-localization and reorientation
- Coping with limited resources (e.g., working memory, perception, costs of detours and errors)

The experiment comprised a training and a test phase in which participants became familiar with the task and the given type of map. Especially in the training phase of the experiment they had to *learn* several things: They made typical *errors* because they still had to get an idea for the scale of the map. Once they had learned it, such errors like ignoring a branch-off because it seemed too small to be depicted on the map became much rarer. Likewise, they ignored a branching-off in the test phase because a narrow street canyon suggested at first sight that an upcoming segment of the route is an impasse. As a consequence, some participants took the turning action afterwards and got lost. The ensuing *error recovery and overcoming of impasses* is a typical task when wayfinding. Thus, they learned that not all impasses were such, and to read the map more correctly. In addition, one map type only displayed which turning actions to take at decision points. No information was given about the situation between those points. As compared to the usual city maps, participants had to adapt their navigation strategy or even use heuristics (like the assumption that usually, paths ending at house entries are not relevant decision points for outdoor navigation). With this map, self-localization was only possible at decision points by referring to given landmarks and the local structure of the path network.

A qualitative calculus sufficient for realistic navigation tasks would need to determine an appropriate hierarchical structure, to decide which kind of primitives are necessary to describe routes and to switch between perspectives or between reference frames. Furthermore, process-related aspects play an important role, for example how different paths are integrated into one representation. During navigation, the environment changes dynamically and sometimes surprisingly. How do humans reconcile internal and external sources of information? What heuristics are necessary and useful to come to a conclusion in time? When are they applied? Learning occurs in many aspects: Map literacy, survey knowledge, and error recovery with specific map types or representations to mention only a few. How do the different requirements and transformational needs provoke a change of the primitives over time? Is the granularity a different one? And finally the appropriateness of primitives for other navigation tasks. We cannot mention all relevant aspects, but we intended to demonstrate that there is a multitude of aspects that can be used to optimize and evaluate QSR calculi. Nonetheless, there is no qualitative calculus today that can deal successfully with such complex real-world tasks. Therefore, testing scenarios are typically abstracted from realistic, complex environments and rather isolated subtasks are investigated. This is legitimate if the goal is exactly that. If, on the other hand, a more comprehensive theory of spatial cognition is intended in the long run, important preconditions for a reintegration should be met in advance.

Cognitive Criteria

We discuss those additional criteria we consider potentially beneficial for the QSR community. Which criteria are needed to what extent is an ongoing debate, and one that should not be neglected in communities that implement (cognitive) models with a claim of adequacy.

- *Representational adequacy*: This property extends the notion of conceptual adequacy (Knauff et al. 1998), claiming that in addition to some relations, certain representations are more suitable for the human cognitive system (cp. i. in the Definition of Strube 1996). It is relevant when information is potentially ambiguous (i.e. the theory of preferred mental models, e.g. Knauff, Rauh, and Schlieder 1995), when information is represented hierarchically (see above) in large scale spaces (Stevens and Coupe 1978), and when reference frames are chosen (cp. projection-based representations of cardinal directions versus cone-based representations; Ligozat 1998; Majid et al. 2004). Depending on the situation, humans have to switch between "cognitive" spaces like vista, figural, environmental, and geographical spaces (Montello 2005). <u>A central question is</u>: To what extend do different representations influence performance of calculi? A <u>useful method</u> to identify representational adequacy of a calculus are so-called classification experiments (as conducted by Knauff et al., 1998 for RCC8) and the thinking-aloud method (Tenbrink 2007). The first method typically consists in giving participants certain spatial configurations and ask them to group these scenarios in equivalence classes. In this sense it was possible to show that RCC8 (with its differentiation of boundaries) is cognitively adequate. A similar study has been performed by Mark et al. (1995). Think aloud protocols and corpus analysis are another useful way to investigate adequate relations. <u>In our navigation example</u> we can use both methods to identify (i) which relations are used to describe paths, and (ii) which limitations arise (due to the granularity of the used relations).
- *Processual adequacy*: This concept can be understood in a weak or strong sense: In the weak sense human information processing is not necessarily modelled in depth and detail, i.e. by using logic rules. A sophisticated, cognitively inspired understanding of strong processual adequacy would reflect more levels and processual details on each level, e.g. correspondence of intermediate steps towards problem solution (Simon and Wallach 1999). <u>A central question is:</u> Which subprocesses constitute the human reasoning mechanism? A <u>useful method</u> are so called conclusion generation experiments (Ragni et al.

2007b; for instance to identify the preferred composition table). It is a well supported result that in multiple solution scenarios humans prefer certain solutions which suggests the human composition table is a proper subset of the formal one. In our navigation example we can use this method to find out which relations are typically neglected.

- *Functional equivalence*: If the central question is not concerning the processes, but whether the output of a calculus corresponds with human solutions, this common criterion is addressed. A useful method to test this are verification experiments, i.e. participants receive different answers described by a calculus and have to decide whether they are a solution (Ragni et al. 2007a). Reaction times are a useful additional measure in this case. In a navigational setting, different route descriptions might be presented and participants have to evaluate their appropriateness.
- *Ability to use heuristics*: Humans often use heuristics and strategies (Gigerenzer and Goldstein 1996; Montello 2005) when problem spaces are too extensive or when deciding under uncertainty. For example, Montello (2005) discusses some strategies in human navigation. As opposed to strategies, heuristics do not guarantee optimal solutions (Russell and Norvig 2002) but support resource-adaptivity and reaction in real-time when complete processing would be too expensive or impossible (cp. fast and frugal, Gigerenzer and Goldstein 1996). A central question is: Does a calculus always work with brute force or is it able to use smart heuristics? In a navigational setting heuristics are typically abstractions in some sense (e.g. the airline distance in Russel and Norvig 2005) and so a calculus must be able to differentiate between different granularities.
- *Ability to learn*: If necessary for problem solving, humans are able to learn and use new relations and to combine them with known ones. Thus, learning is an import factor. A central question is: How easy is it to extend given calculi by new relations? In a navigational setting participants might learn to use cardinal directions in order to support their sense of direction.
- *Degree of background knowledge*: Related to the former point is the question how much background knowledge should be implemented in models and to what degree knowledge is acquired on-line or pre-programmed. If one tests a system's ability to adapt to new situations, even pre-programmed world knowledge should be modifiable or at least extensible. This adaptivity also matters for the claim of *robustness* in case of errors or unknown situations. Again, a useful method are think aloud protocols. In our navigational example, participants might be asked to verbalize their reasoning processes (either while navigation or while inspecting the video recording of the experiment). In addition, questionnaires might measure vaious aspects of background knowledge.
- *Generality*: It has become common sense that models with too many free parameters can always be given a perfect fit to empirical data. A central question is: What enables humans to solve spontaneously such a bandwidth of tasks? A useful method is testing the same calculus in systematically varied tasks without tuning parameters "manually" for each scenario. The more bandwidth there is in the tasks, and the less they are known to the model in advance, the less likely it is the model will only fit because it is specialized in a single testing scenario. In a navigational setting, the same heuristics and strategies should be tested in a variety of scenarios and tasks.

Especially for human-machine interaction, there are additional desiderata:

- *Ability to cope with limited resources*: Cognitively plausible models take into account limited resources of humans like restricted short-term memory. Especially cognitive architectures are informative in this respect. When an artificial agent is to communicate efficiently to humans, such aspects cannot be ignored.
- *Solution adequacy*: The representation of a solution can influence how understandable it is when communicated to a human. For instance, this is relevant when dealing with multi-agent systems. As Rauh et al. (2000) and Ragni et al. (2007a) have shown, humans produce continuous transformations between alternative solutions and these are represented quite adequately by a generalized neighbourhood graph which has the additional advantage that changes can be identified more easily. Solution adequacy makes it more likely a solution (an output) will have a plausible and understandable format for non-expert humans (beyond the aspect of limited resources). The more general representational adequacy focuses on how similar QSR-calculi are to the way humans would describe (and represent and conceptualize) relational real world information.

Finally, QSR calculi might be implemented in a cognitive architecture like ACT-R (Anderson et al. 2004), in order to test whether they are compatible with a detailed model of the human cognitive system. However, there is not much work on these aspects.

A cognitive perspective on future QSR research

First, one of the most intriguing problems from a cognitive viewpoint is the need to represent different spaces and to allow for transformations of one representation space into the other – a task important as well for cognitive modelling as for qualitative reasoning in navigational tasks. Allocentric representation systems and relative calculi like the Double-Cross Calculus (Freksa 1992) should be considered. In this context, questions of granularity of a calculus play an important role. Most aspects of representational adequacy are still missing in QSR research (e.g., hierarchical representations).

Second, cognitive adequacy must be corroborated empirically – and be inspired and driven by applications. Applications like navigational assistance systems or geographical information systems (GIS) require a proper representation of certain knowledge and reasoning processes. This formal requirement should then in turn be tested for its cognitive plausibility (mirroring the points mentioned above). Test results can then inspire further formal development.

Third, despite the analysis of cognitive adequacy (or soundness) of calculi, assumptions about how humans process this information play an underestimated role in the "classical" QSR community. Two additional aspects in human cognition – (background) knowledge and the ability to learn – are main challenges for bringing together QSR and findings from Cognitive Science. Background knowledge plays a fundamental role in complex human reasoning and implies more than using knowledge bases like composition tables. Important calculi should be modelled and if required even integrated in cognitive architectures (e.g. ACT-R, Anderson et al. 2004) or spatially specialized architectures (Barkowsky 2002). A mutual influence of Cognitive Science and formal requirements for calculi may lead to a refined and broader theory – and certainly to an improved and broader application of these calculi in human-machine interaction.

Fourth, as the navigation example demonstrates, dynamic aspects (like temporalized calculi) play a major role in everyday tasks. In recent years some research has investigated the question of temporalizing topological calculi (Gerevini and Nebel 2002) or cardinal directions (Ragni and Wölfl 2006). This research line is a conditio sine qua non for navigational tasks.

Summary

A number of applications like navigation, (driver) assistence systems, and geographical information systems strongly require cognitive analyses beyond formal aspects. We suggested several cognitive criteria that might help to benchmark and evaluate qualitative calculi. We argue that an assistance system must be able to cope with errors and transform different relational systems and reference systems. These typical human features also play an important role in the field of navigation. We could cover only some aspects of cognitive criteria – especially conceptual and inferential adequacy (Knauff et al. 1998), criteria for "good" cognitive models (Simon and Wallach 1999), and some aspects of cognitive architectures (Sun 2008).

Navigational tasks and geographical information systems in general allow for rendering more precisely the frontier of pure qualitative reasoning in the sense of topology matters (in GIS) while metric refines (Mark and Egenhofer 1995). Similarly, Montello (2005) defined a qualitative level (topological level) and a quantitative level (metric level). Both levels are relevant to navigation and dealing with them poses a central challenge for QSR models of spatial cognition.

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