Reasoning with Mental and External Diagrams: Computational Modeling and Spatial Assistance

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Diagrammatic Representation and Reasoning: Three perspectives

Over the past three decades, the role of diagrammatic representations in reasoning processes has been investigated from three distinct perspectives: (i) a *computational modeling* perspective, (ii) a *spatial assistance* perspective, and (iii) with respect to the *interplay of mental representations and external diagrams*. Despite their different foci, these perspectives are in fact highly complementary because they all address questions of how diagrams support intelligent reasoning processes, both in humans and in machines.

Computational Modeling

In computational modeling of cognitive processes, models addressing *specific cognitive phenomena* have been developed. These include models for perceptual subsystems (e.g. Schill et al., 2001), visual attention (e.g. Mozer & Sitton, 1998), memory (e.g. Raaijmakers & Shiffrin, 2002), and manipulation processes such as mental scanning, rotation, and animation (e.g. Hegarty, 1992). In addition to these models for specific cognitive phenomena, there are broader models dealing with aspects such as mental imagery (e.g. Kosslyn, 1980), working memory (e.g. Just, & Carpenter, 1992) etc. Integrative conceptions have also been developed that aim to unite these various individual models (i.e. *cognitive architectures*, cf. Anderson et al., 2004; Kieras & Meyer, 1997; Newell, 1990).

Spatial Assistance

Research on spatial assistance has concentrated on how to support (i) *human spatial reasoning* (e.g. in spatial configuration tasks, e.g. Schlieder & Hagen, 2000), (ii) *spatial interaction and communication about spatial issues* (e.g. through verbal descriptions, sketches, gestures, etc., cf. Blaser et al., 2000), and (iii) *actions in space* (e.g. in wayfinding tasks, cf. Richter & Klippel, 2005; Baus, Krüger & Stahl, 2003). Key topics of interest include spatial ontologies and models of spatial context (e.g. for brokering information needed by location-based services, e.g. Schlieder et al., 2001), approaches for understanding human mental processing of diagrams (e.g. with respect to information in static or dynamic depictions, e.g. Hegarty, 2004), as well as adequate user models that capture a user's intentions, possible actions, cognitive needs, and preferences.

Mental Images and External Diagrams

Research on the interaction between mental and external diagrams focuses on the *coupled system* formed between these two types of representation and its role in reasoning processes (e.g. Chandrasekaran et al., 2004). Typical questions concern how visual perception and mental representation are interrelated (e.g. Laeng & Teodorescu, 2002), which cognitive faculties underlie the understanding of complex external diagrams (e.g. Scaife & Rogers, 1996), and what effects flow from disparities between the perceptual salience of information in a diagram and its relevance for the task to be performed (e.g. Goldschmidt, 1991). One goal of this research is to develop principled guidelines for designing diagrams that are more effective as tools for reasoning, understanding, and learning.

Intelligent Processes for Humans and Machines

Although all three fields described above address related questions, interaction between them to date has been very limited and so has fallen well short of its potential. Therefore, a central goal of this symposium is to bring together researchers from the fields of computational cognitive modeling, spatial assistance, and reasoning with mental and external diagrams to *explore the role of diagrams in supporting intelligent processes* in humans and technical systems, as well as in human-machine interaction. Examples of the types of questions entailed by integration of the three perspectives include:

- how do mental representations and external diagrams influence each other during the solving of spatial problems?
- how can computational cognitive models be used to better assess a user's cognitive needs for performing a spatial task?
- what does knowledge about human imagery abilities tell us about the designing and understanding of external depictions?
- what is the role of pictorial space as a representation medium for dealing with problems on various scales (e.g. in geographic, environmental, tabletop spaces)?
- how does subject matter expertise influence the building of mental models from external diagrammatic representations?
- how are spatial dynamics best conveyed in diagrams and how is dynamic information processed in the mind?

In addition to opportunities for basic research on these fundamental issues, there is considerable scope for their practical application in fields such as urban planning, architectural design, location-based services, instruction, and education.

The Contributions of this Collection

The contributions collected in this report provide an overview of some central issues that are currently the focus of research. There are papers that:

- investigate the role of animation in diagrammatic presentation of information and how humans interact with diagrammatic representations;
- deal with problems in conducting research on techniques for spatial assistance systems;
- present tools for assisting human spatial problem solving;
- try to elaborate the relation between external diagrams and the mental representation of graphic information,
- deal with general aspects of the role and function of diagrams in problem solving.

Animation and Interactivity

Dynamic features intended to emphasise important pieces of information are easy to incorporate into computer-generated diagrammatic representations. But under which circumstances are such additions actually useful? For instance, inappropriate dynamics in diagrams may distract attention from task-relevant aspects in spatial problem solving. Lee and Klippel investigate the usefulness of dynamics in air traffic controller displays.

Fabrikant aims to empirically investigate the usefulness of dynamics in diagrammatic representations through controlled animation experiments in the domain of geo-visualization. She questions the effectiveness of dynamic features when used in highly interactive visual forms of knowledge construction and decision making because of their potential to increase information density.

Research into using animation in diagrams needs to probe both general aspects of processing and the effects of individual differences. Cohen describes protocol studies that investigate individual differences in problem solving strategies among participants with low and high spatial ability. She studied participants' accuracy in drawing cross-sections of unfamiliar 3-dimensional objects and how often they made use of animation facilities.

Keehner and Khooshabeh explore the interrelationships between individual factors such as spatial ability, the characteristics of the representation used, and training strategies in the domain of medical education. Likewise, Otero and coworkers investigate differences between learners in computer-based training environments that provide different levels of diagrammatic interactivity. They also find correspondences between diagrammatic interactivity and individual cognitive abilities.

Problems for Spatial Assistance Research

An important application for spatial assistance research is the support of wayfinding when using mobile computing devices such as personal digital assistants (PDAs). Caduff and Timpf investigate assistance strategies that employ dynamically generated maps based on cues perceivable in the environment. Their aim is to develop a conceptual model for designing algorithms that make use of these cues while generating route descriptions. Gartner and Radoczky report their investigation of the usefulness of different levels of abstraction in maps for pedestrian wayfinding assistance. They assume that a cross between topographic and schematic maps provides the most helpful source of information for pedestrian navigation tasks.

To use a map for finding one's way through an unfamiliar environment, it is necessary to know which direction one is facing with respect to the map. This *orientation problem* is addressed by Davies through a cognitive modeling approach. This research also focuses on map designs that are more usable for situations where orientation is a problem.

Spatio-temporal planning is another task that may be assisted through a computational system. Seifert discusses requirements for cognitively effective interactions in a mental model-based spatio-temporal assistance scenario. Steinhauer presents a qualitative model for natural language communication about spatial relations in the domain of traffic situations. Her approach allows traffic maneuvers to be described by using varying reference objects.

Tools for Spatial Assistance

The field of interactive (i.e. human-computer) design of diagrams is a highly appropriate domain for the application of spatial assistance tools. However, it is imperative that the computational tool provided is compatible with human conceptions of design, when applied to tasks such as modifying an existing diagram. Hagen presents a framework based on the *principle of least astonishment* for assessing the transformation-based similarity of spatial configurations in interactive layout tasks. He offers his framework as a way to validate existing layout algorithms or to develop strategies for designing new algorithms.

In a similar vein, Ferguson and coworkers deal with the interactive modification of existing diagrams. They state that common drawing software introduces 'disfluencies' in interactive design processes because the techniques it uses for modifying diagrammatic representations are incompatible with the flow of human problem solving. As a solution, they propose using *place vocabulary constraints* to provide an interface between a particular (domain-dependent) place vocabulary and general geometric constraints.

Spatial assistance tools are also useful for communication and knowledge management. Green discusses the use of computer-generated diagrammatic representations for communicating medical information to lay audiences, i.e. patient-tailored information in the field of clinical genetics. Tergan considers how digital concept maps may be used as cognitive tools for managing knowledge and knowledge resources. Applications are found in knowledge acquisition, in knowledge organization, and in visualization tools for knowledge management.

Mental and External Diagrams

A central theme of research on diagram comprehension is the relationship between external diagrams and their internal (i.e. mental) representation. One major concern in this research is to find ways of applying basic research on the internal representation of diagrams for improving the design of external diagrams. Bertel proposes that for collaborative human-computer reasoning in asymmetric reasoning situations, it is useful to employ predictive cognitive processing models of the human reasoning component. He suggests basic spatial mechanisms for control of focus in reasoning processes with diagrams. Knauff argues that only carefully conducted psychological experiments provide a valid basis for computational models. He reports findings of relevance to understanding human reasoning with spatial knowledge. His aim is to derive criteria for diagrammatic representations that will provide efficient support for human reasoning processes.

Klippel and coworkers present a cognitive conceptual approach to map design. Their ideas are based on conceptual spatial representations, i.e. mental representations that are generated during spatial problem solving in interaction with a real spatial environment or with a representational medium. The way people interact with route instructions and assembly instructions is examined by Tversky and coauthors. They analyze how diagrams, words, and gestures are used in explanation tasks. Three interlinked levels are identified - the content proper, its causal structure, and the narrative context of the explanation.

Arrows serve important and varied communicative purposes in many kinds of diagrams. In their contribution, Kurata and Egenhofer investigate the semantics of arrows in diagrams. They suggest three structural properties that contribute to the interpretation of arrows. Understanding the semantics of arrows may help improve the usability of interactive pen-based systems.

An issue of fundamental importance to the study of diagrammatic representations is contributed by Chandrasekaran. He asserts that the specific distinction between diagrammatic and propositional representations has not yet been conclusively characterized. To address this deficiency, he offers a framework for precisely characterizing the distinctions between diagrammatic and sentential representations.

Diagrams in Problem Solving

Diagrammatic representations play a key role in the solving of problems by both computational systems and humans. Chandrasekaran and coworkers describe a bimodal computational architecture for diagrammatic problem solving that combines symbolic and diagrammatic representations. Solutions to problems are found through inference and perception processes for the symbolic and the diagrammatic part of the representation, respectively.

A human perspective on diagrammatic problem solving is provided by Ho and coauthors who investigate how different representations and strategies influence spatial problem solving. Their hypothesis is that individuals differ in the amounts of information they perceive from the different types of representation. From the field of chemistry education, Stieff investigates how students employ visualization while performing scientific reasoning tasks. He finds that students' reasoning depends on the form of diagram given together with self-generated inscriptions, not on visualizations.

The use of diagrams for problem solving in the domain of architectural design is discussed by Vrachliotis. He investigates the role and function of diagrams in early steps of the architectural design process in comparison with the building as the final product.

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