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Mental Processing of Geographic Knowledge[1]

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Abstract. The contribution presents a computational modeling approach to geographic knowledge processing in mind. Geographic knowledge is assumed to be stored in a piecemeal manner. *Spatial knowledge fragments* form a hierarchical structure of lean knowledge. An actual mental image representation is constructed when needed to perform a specific task. In this construction process missing information is complemented to create a determinate mental image. – First, the artificial intelligence perspective taken is elaborated. After a short review of conceptions on mental processing of spatial knowledge from psychology and artificial intelligence we outline the model MIRAGE. The internal structure and the operating of the model is elaborated using an exemplary scenario. Problems in constructing mental images from given pieces of knowledge are demonstrated and discussed. The paper concludes with a discussion of the approach with respect to its modeling objective. We point to further research questions and to potential applications.

Keywords. Cognitive maps, spatial knowledge construction, mental imagery, diagrammatic reasoning, experimental computational modeling.

1 The Construction of Geographic Knowledge

Mental representations of geographic or large-scale spaces are commonly referred to as *cognitive maps* (Tolman, 1948; Downs & Stea, 1977). However, numerous research findings in cognitive psychology have revealed that mental representations of large-scale spaces differ from maps in important respects. For example, mental representations of spatial knowledge are distorted, fragmented, and incomplete (for an overview, see Montello, 1992; Tversky, 1993; Hirtle & Heidorn, 1993). Processing geographic information can be described as a *mental construction process* in memory (Tversky, 1992; Portugali, 1996a) rather than a mere recall of static spatial information. This conception is supported by findings that indicate that mental

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representations often are not based on facts that are known, but rather on assumptions that are likely to be true and that are filled in during retrieval processes (Bransford et al., 1972; Sulin & Dooling, 1974; Intraub & Hoffman, 1992; Friedman & Brown, 2000).

1.1 Motivation

Although mental representations of spatial configurations are not map-like in a literal sense, it is generally assumed that spatial mental representations are organized in spatio-analogical form. There is neuropsychological evidence that the same neural subsystems are involved in mental reasoning about spatial configurations as for visual comprehension of external scenes. For example, thinking about geographic configurations activates the same neural systems as studying (external) geographic maps (Kosslyn, 1987; Kosslyn et al., 1994). *Mental images* (Finke, 1989; Kosslyn, 1980, 1994) are constructed in working memory when needed using pieces of information retrieved from long-term memory.

The perspective on spatial knowledge processing as a construction process that involves mental images points to a very efficient way of dealing with geographic information. We identify the following features of mental image construction:

(1) Mental representations of spatial configurations can be customized with respect to the specific task to be solved (which entities are involved, which scale and resolution is needed, what characteristics of the representation are needed etc.).

(2) More or less scarce (or lean) knowledge about space can be efficiently stored in memory and can be used in a flexible manner.

(3) Although adequate pieces of information may not be available in memory for all conceivable tasks, the construction on demand allows for compensating for missing information by using default knowledge. Default knowledge may fill gaps with details that are likely to be true.

(4) Knowledge from different information sources and of different modalities can be combined in a unique representation. Especially, the two general types of knowledge distinguished in artificial intelligence (AI) and cognitive psychology, propositional and pictorial knowledge (Paivio, 1971; Larkin & Simon, 1987), are combined in a common representation in the mental image. Thus, the mutual advantages of both forms of representation can be exploited (cf. Freksa et al., 1999).

(5) Both forms of knowledge may be used to exhibit information that is only implicitly contained in the knowledge stored in memory by constructing a quasi-pictorial representation for exploring the task to be solved. This characteristic is related to the ideas of diagrammatic reasoning in AI (Koedinger, 1992; Glasgow et al., 1995).

The following example illustrates the construction of geographic knowledge in memory.

1.2 An Example

In a famous experiment aimed at exhibiting the hierarchical structure of human memory Stevens and Coupe (1978) asked the participants (students at University of California, San Diego) to decide about the relative orientation of some well known locations with respect to a global geographic reference system. For example, they asked which of the two cities Reno (Nevada) and San Diego (California) is located farther west. Presumably, the participants never had been explicitly asked this question before. Nevertheless they were able to answer the question. However, most participants answered that San Diego is farther west than Reno, which is not the case.

Stevens and Coupe explained this effect by the fact that California is west of Nevada. They argued that the participants derived the relative location of the two cities from the relative position of the two states in which they are located.

We will assume that the participating subjects had no explicit representation of the relative location of the two cities in their minds (otherwise they should have known the answer correctly). Therefore, to answer the question they had to construct a mental image of the relative position of the two cities on the basis of some other information available – here the relative orientation of California and Nevada.

1.3 An Artificial Intelligence Perspective

The above example points to an interesting class of phenomena in spatial cognition. We must frequently conceive of spatial configurations that we have never seen and that are not explicitly represented in memory. Nevertheless, we need a fast and pragmatic decision procedure. On the basis of some available information a tentative reconstruction of the real situation is built up to answer a question or to solve a task.

From an AI point of view we would like to answer the question of how the cognitive processes and representations are structured and how they can be described in a computational model. In the present paper we report about an *experimental computational modeling* approach to answer this question. The three notions *experimental*, *computational*, and *modeling* will be further elaborated in the following.

We are concerned with *modeling*, in so far as we want to provide a construction that maps certain types of phenomena to structural descriptions. The question is approached from an architect's point of view (cf. Braitenberg, 1984; Sloman, 1994): Which structures explain the behavior of the cognitive system in a given situation?

For this purpose we must provide a 'metadescription' (Kosslyn, 1980) of the model to be designed. This metadescription must bridge the gap between the theoretical assumptions (e.g. derived from psychological findings) and the computational model. The resulting model is intended to serve as an embodiment of the underlying theories. This goal can be achieved by documenting the theoretical principles and their correspondence to components in the model. In this way, we separate between aspects in the model that are intended as literal modeling components and those which are needed to hold those components together in an implemented computer program.

The modeling task is performed using a *computational* approach. This means that a system will be described by specifying representational structures and processes that can be implemented on a digital computer. As a consequence, the model's dynamic operation can be observed in the computer simulation.

This is why the method is called *experimental* computational modeling: The observation of the running model allows for experimentation under various conditions. This enables critical reflection of the model's preconditions as well as of the computer implementation in a similar way as experimentation with human participants. Alternative design decisions can be tested to extend, to elaborate, and to refine the model. In comparison to an exclusively theoretical explanation of cognitive phenomena computational modeling provides a concrete realization of a dynamic system. This method forces us to completely specify every component of the model up to the degree necessary for computer implementation.

A model built up in this way is open to criticism regarding the modeling decisions taken by the designer. Usually there is no definite reason for particular modeling decisions, as the observed phenomena do not determine the internal structure of a system (cf. Anderson, 1978). Nevertheless, a computational model provides a concrete embodiment of scientific conceptions that formerly existed as a bunch of – frequently disconnected – theoretical descriptions that each accounted for a different phenomenon. So a computational model is a specifically instantiated form of a scientific conception, and it provides a new basis for further discussions and explorations of a cognitive phenomenon.

In the work described here we will provide the computational model MIRAGE that describes geographic knowledge processing in mental images. It starts from pieces of spatial knowledge stored in memory, describes the construction of quasi-pictorial representations in working memory, and deals with the exploration and refinement of the representations when required.

The remainder of the paper is structured as follows. In Section 2 we provide a short review of existing conceptions on mental processing of geographic knowledge in cognitive psychology and AI. Section 3 presents an outline of the MIRAGE model and explains its substructures and the processes that operate on them. We discuss examples for mental image constructions. The paper concludes with a discussion of MIRAGE with respect to its modeling objective. We indicate essential issues for further research and point to promising perspectives for the application of the approach in intelligent spatial assistance systems.

2 Conceptions on Mental Processing of Geographic Knowledge

In this Section we review metaphorical conceptions on mental processing of geographic knowledge from cognitive psychology. The relation between mental models, human memory, and mental imagery is sketched out. AI approaches to spatial knowledge processing in qualitative spatial reasoning and diagrammatic reasoning are outlined.

2.1 Cognitive Maps and Other Metaphors

Metaphorical conceptions play an important role in scientific development. They allow for transferring well-tried ideas between research areas, they ease communicating about phenomena that are only roughly understood, and they are of importance in theory and model building processes (Kuhn, 1993; Hirtle, 1998).

Numerous metaphorical conceptions have been proposed to capture the shortcomings of the cognitive map metaphor. Among them are *spatial images* and *rubber sheet maps* (Lynch, 1960), *spatial schemata* (Lee, 1968), *environmental images* (Appleyard, 1970), *cognitive atlases* (Kuipers, 1982; Hirtle, 1998), *spatial mental models* and *cognitive collages* (Tversky, 1991; 1993), *(human) geographic* *information systems (GIS)* (Peterson, 1995; Hirtle, 1998), and *inter-representation networks* (Portugali, 1996b).

The most interesting metaphors in the present context are the cognitive collage metaphor, the cognitive atlas metaphor, and the spatial mental model conception. The former two emphasize that spatial mental representations are generally incoherent (involving different reference systems), spatially distorted, multimodal, hierarchically organized, and partially contradictory. The latter emphasizes the characteristic of mental representations of large-scale spaces as mental constructions. The GIS metaphor can be considered an extension of the cognitive atlas metaphor. Both involve structural aspects of internal representation (i.e., whether it resembles a raster or a vector representation format, cf. Couclelis, 1992), issues of varying accuracy, scale, and resolution, and the combination of partial representations held in different 'layers' of spatial information.

The spatial mental model metaphor also relates to the construction of working memory representations for reasoning and problem solving; it is closely related to employing mental images for thinking about spatial configurations.

2.2 Mental Images, Human Memory, and Mental Models

Johnson-Laird (1983) proposed mental models to grasp mental reasoning processes that require the integration of a set of premises into a common representation to solve a given task. The representation is assumed to exhibit a representation structure analogical to the structure of the domain represented.

For visual and spatial information (as well as for abstract information that can be mapped to a spatial structure) mental models are realized by mental images (Kosslyn, 1994). Mental images are evoked and operated with in working memory. Working memory for visual information according to Baddeley (1986) comprises a spatio-analogical representation structure (the visuo-spatial scratchpad) that is controlled by a central executive module (that also drives other short-term storage subsystems).

So working memory for visual and spatial information comprises both a quasi-pictorial representation structure for short-term storage and a structure that holds the underlying facts and controls their treatment in the image proper. The facts that are used in evoking the mental image stem from long-term memory. They are retrieved for forming a mental image to reason about some question at hand. Retrieval from long-term memory is assumed to be done by activation of stored pieces of knowledge to make them vivid for subsequent usage, for example for mental imagery.

Mental images comprise both, facts that are retrieved from long-term memory and inventions of states of affairs not explicitly contained in memory (Finke, 1989). As resulting from construction in working memory they are not retrieved as a whole from long-term memory. Regarding the type of knowledge processed they make use of pictorial as well as of propositional pieces of knowledge.

2.3 Spatial and Diagrammatic Reasoning

In AI, the mental capability to operate on spatial and pictorial structures has been adopted in qualitative spatial reasoning (QSR) (Freksa & Röhrig, 1993; Cohn, 1997; Vieu, 1997) and diagrammatic reasoning (DR) (Glasgow et al., 1995).

Qualitative spatial reasoning investigates processing of spatial knowledge without relying on exact metric measurements. Humans usually deal with their spatial environment using qualitative rather than quantitative information (even though precise metric information may be available and is also utilized in reasoning tasks, cf. Montello, 1998). In qualitative spatial reasoning all types of spatial knowledge like topological information, orientation knowledge (directions), comparative distance information, and combinations of them are investigated. Besides the type of spatial relationships QSR also focuses on the ontological type of entities involved in spatial reasoning (e.g., whether entities are conceptualized as point-like or as spatially extended objects).

Diagrammatic reasoning uses spatio-analogical representation structures to make use of the medium's properties for reasoning. These structures may be positional or relational (which refers to the conception of representing space per se versus representing objects in space, respectively). The core idea is that the properties of the spatial representation medium can be employed in reasoning: The spatial properties of the medium restrict the possible relationships between entities which may reduce reasoning to just representing (i.e., mapping to the spatial medium).

A diagrammatic reasoning approach that explicitly refers to mental imagery is the computational imagery system by Glasgow and Papadias (1992). It distinguishes between a deep representation structure (related to long-term memory), a spatial and a visual representation structure (related to working memory and short-term representations, respectively).

3 The MIRAGE[2] Model

This section presents the MIRAGE model that utilizes pieces of geographic knowledge for the construction of image-like representations. In doing so, it compensates for missing pieces of information by employing default knowledge for spatial properties and relations. The overall structure of the model is depicted in Fig. 1. MIRAGE is structured according to three memory substructures: *non-activated long-term memory*, *activated long-term memory*, and *short-term memory*[3]. Working memory is constituted by activated long-term memory and short-term memory.

In Fig. 1 three subsystems of the model are identified: the *long-term memory activation* subsystem, the *image construction* subsystem, and the *image inspection* subsystem. All three systems operate in parallel. Thus further pieces of knowledge can be retrieved while an image is under construction on the basis of previously retrieved knowledge; or an image can be explored by the image inspection subsystem while the image is still being constructed or refined. The components of the three subsystems are described in the following.

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[2] MIRAGE stands for Mental Images in Reasoning About Geographic Entities.

[3] As retrieval from long-term memory is conceived of as being done by activation (cf. Section 2.2) two long-term memory systems are distinguished. This is done for functional reasons in the model and does not imply a physical information transfer. In the brain, information in long-term memory may be activated or not, thus belonging to one of the two systems distinguished in the model.

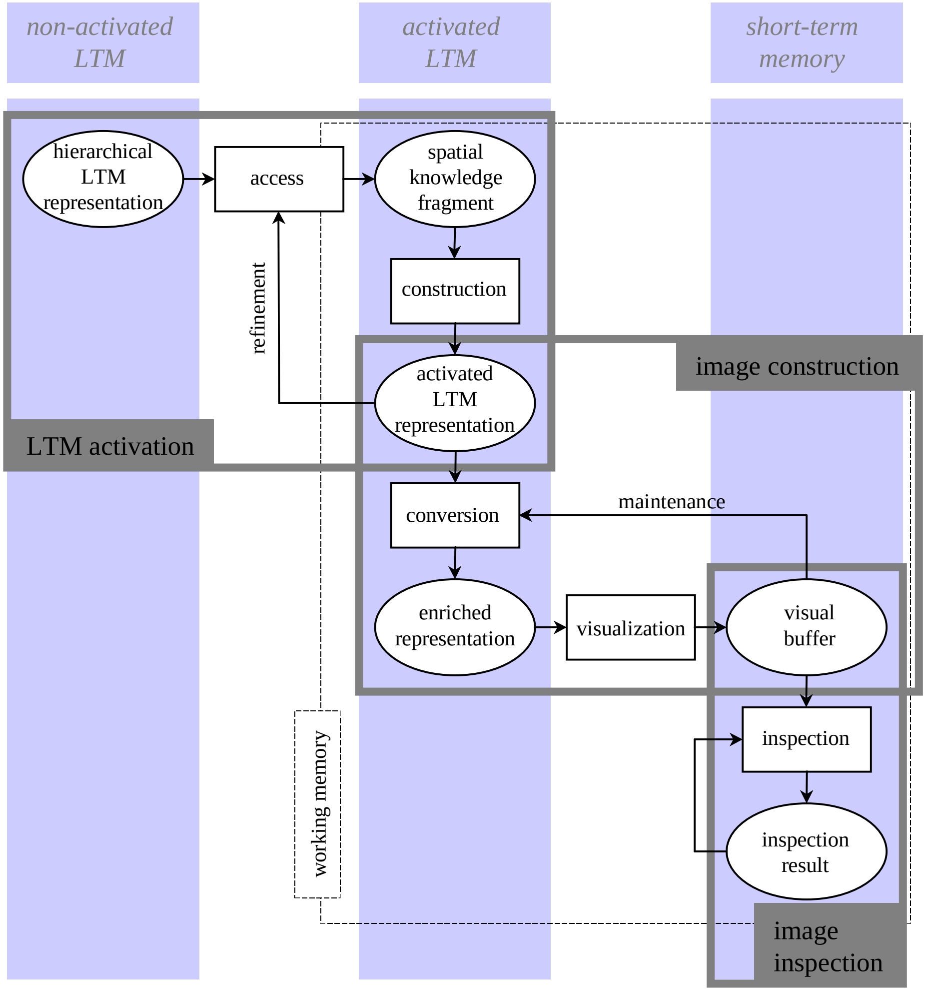

Fig. 1. Overview of the MIRAGE model with its three subsystems *long-term memory* (*LTM) activation*, *image construction*, and *image inspection*. The model is structured according to the three memory structures of non-activated LTM, activated LTM, and short-term memory (see text). The latter two constitute the working memory.

3.1 Long-term Memory Activation

The long-term memory activation subsystem comprises the underlying hierarchical long-term memory representation in non-activated long-term memory, which is utilized by an access process to obtain a spatial knowledge fragment. Spatial knowledge fragments are further processed by a construction process that builds up the activated long-term memory representation in working memory. The activated long-term memory representation forms the basic representation for the image construction process (see Section 3.2).

Spatial knowledge fragments are represented by n-ary spatial relations between geographic entities that are uniquely identified. The relation is annotated by the type of spatial information and its degree of resolution. Currently, topological and orientation information (cardinal directions, cf. Frank, 1992) are represented as propositional knowledge, whereas shape information of extended objects is represented in pictorial form. Both knowledge types can be represented at different stages of resolution.

The hierarchical long-term memory representation is a directed graph structure whose nodes are formed by identifiers of geographic entities and whose edges are the relations that hold between the respective entities. The edges encode the information represented in the spatial knowledge fragments. A visualization of an exemplary hierarchical long-term memory representation is given in Fig. 2a.

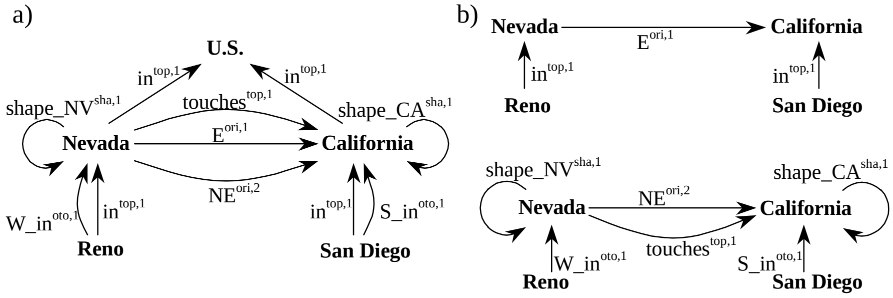

Fig. 2. Example of a hierarchical long-term memory representation (a) and two stages of corresponding activated long-term memory representations (b). Compared with the hierarchical LTM representation the activated memory representation only contains geographic relations relevant for the task to be solved (i.e., to determine the position of Reno with respect to San Diego). In the example, geographic entities are connected by topological and orientation relations.

The access procedure is modeled as a graph search procedure driven by (i) the type of relation wanted, (ii) the entities involved, and (iii) the hierarchical structure that is encoded in the long-term memory representation. So the access procedure tests the structure for a path between the entities in question that delivers that wanted type of relation. The spatial knowledge fragments encoded in this path are returned and passed to the construction process that builds the activated long-term memory representation.

The activated long-term memory representation is defined like the hierarchical long-term memory representation with the following restrictions: The activated long-term memory representation only contains information relevant to the question at hand due to the access procedure; between two geographic entities there are no spatial relations of the same type at different levels of granularity. Figure 2b shows two stages of activated long-term memory representations corresponding to the hierarchical long-term memory representation shown in Fig. 2a. The activated long-term memory representation forms the basis for the image construction subsystem described in Section 3.2.

The construction process builds an activated long-term memory representation from spatial knowledge fragments provided by the access process. To meet the specification of the activated long-term memory representation it checks for granularity conflicts between relations of the same type between a given set of geographic entities.

3.2 Image Construction and Image Inspection

The image construction subsystem starts with the activated long-term memory representation. It comprises a conversion procedure that yields the enriched representation. The enriched representation is the preliminary stage to the image generation proper. The image is generated in the visual buffer by the visualization process. The visual buffer is inspected by the inspection process to yield the inspection result.

The enriched representation complements missing information in the activated long-term memory representation prior to visualization. It is defined like the activated long-term memory representation with the following additions: (i) Every spatially extended entity is assigned a specific shape; (ii) all spatial relations are complemented to enable an immediate visualization in the subsequent visualization process (see below). In the enriched representation no annotations of relational type or granularity are required.

The conversion procedure builds the enriched representation from the activated long-term memory representation. First, for every spatial entity that does not come with a specific shape from long-term memory, an ontological type is assigned. To ease further processing, point-like entities are used as far as possible. Finally, further spatial relations are assigned for visualization. These relations are qualitative, i.e., no specific values are determined so far. Figure 3 shows two resulting enriched representations that correspond to the examples in Fig. 2b.

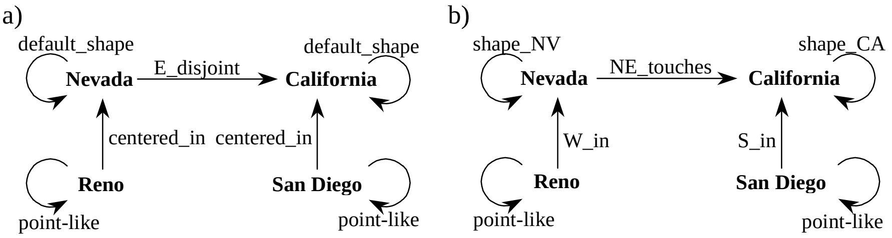

Fig. 3. Two resulting enriched representations corresponding to the activated LTM representations shown in Fig. 2b. In both cases it has been determined whether geographic entities are point-like or extended. In (a) default shapes have been assigned to extended objects whereas in (b) shapes retrieved from LTM are employed. The relations that hold between the entities have been made determinate with respect to orientation and topology.

The visual buffer models the quasi-pictorial medium that contains the image proper. In the model it is realized as an image representation in vector format. This format appears suitable to describe visuo-spatial working memory that exhibits behavior observed in humans; however, it is not intended to model structural properties of the visual buffer in the brain. The visual buffer forms the basis for the subsequent inspection process.

The visualization procedure transforms the representation in the enriched representation and maps it into the visual buffer. This is done in a two step manner. First, specific (metric) values are assigned to the entities and the relations between them (image specification). This is done to prepare the subsequent second step of the visualization. In the second step the image is mapped into the visual buffer (image mapping). For this purpose, clipping and scaling must be performed on the representation generated in the first step. This is done because the visual buffer is restricted both in spatial extension and in resolution (Kosslyn, 1980; 1994). So to map the information of interest as suitable as possible for inspecting the information wanted an appropriate positioning and zooming has to be performed. When it cannot be computed in advance which parts of the image must be focused on in the visual buffer, the visualization process may be necessary to be performed in an iterated manner.

Figure 4 shows two examples of the two steps of the visualization procedure (cf. Fig. 3a and b). In Fig. 4a and b default shapes (squares) are assigned to the extended entities; Fig. 4c and d show the two visualization steps with the proper shapes retrieved from long-term memory.

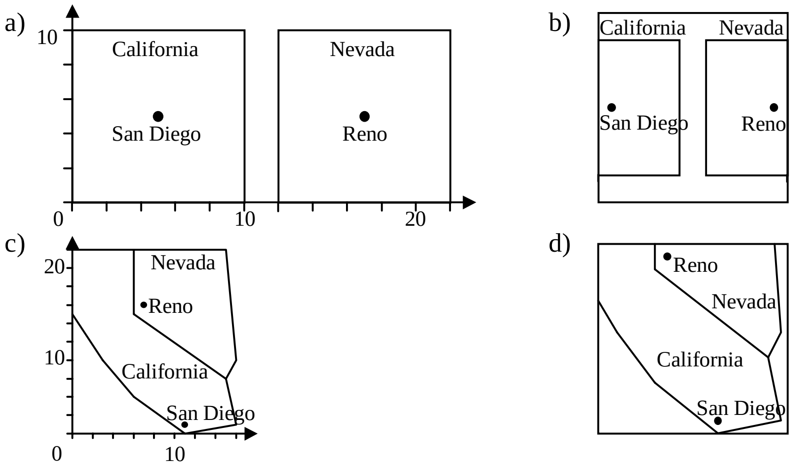

Fig. 4. Two examples of the two subsequent steps (image specification and image mapping) of the visualization procedure. In (a) squares are assigned as default shapes, whereas in (c) proper shapes are employed. In both cases the objects' positions have been specified metrically. Figures (b) and (d) show the results of the image mapping step corresponding to (a) and (c), respectively, that generate the image in the visual buffer focusing on the entities Reno and San Diego.

The image inspection process interprets the image representation in the visual buffer to yield the spatial relation wanted. For this purpose the graphical relations of objects in the visual buffer are translated to qualitative spatial relations. This is done in an iterated manner such that modifications in the visual buffer immediately result in a updated inspection result.

3.3 Dealing with Conflicting Situations in Mental Image Construction

Visualization is not always as straightforward as demonstrated in the example. Figure 5 shows a more complicated scenario. In Fig. 5a the given activated LTM representation is depicted. In this example the orientation relation between the two cities Nice (France) and Geneva (Switzerland) is wanted. As can be observed, the representation structure is a cyclic graph structure, i.e., each spatial entity is restricted by spatial relations to two other entities.

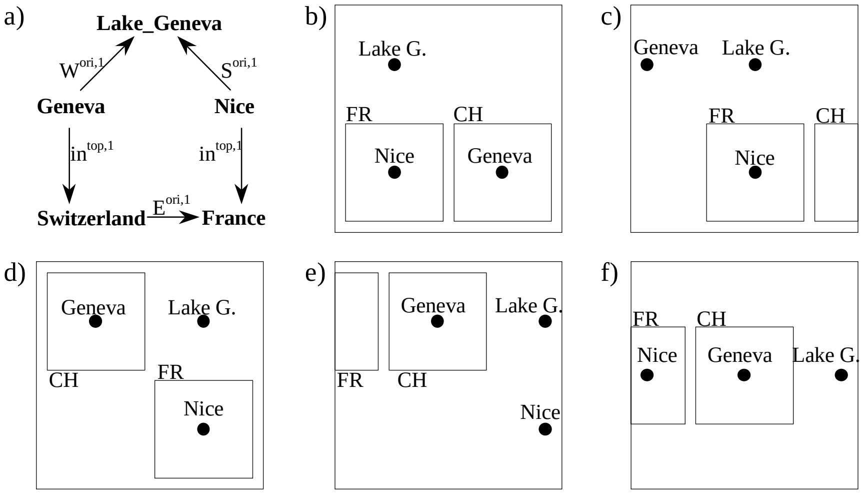

Fig. 5. A more complicated activated LTM representation (a) and five possible images (b-f) constructed according to the strategies described. None of them visualizes all five relations represented in the underlying representation.

When trying to visualize this scenario in a straightforward way as demonstrated in the previous section, we can see that no consistent visualization is possible. Depending on the order in which the entities and the relations between them is dealt with, five possible images can be constructed (Fig. 5b-f). None of them allows for integrating all relations represented in the underlying working memory representation.

What are the consequences for answering the question using mental imagery? Three types of consequences are conceivable: (i) The image may be unstable; (ii) conflicting facts may have to be ignored and omitted from the image; or (iii) the preceding image generation steps have to be revised.

An ***unstable image*** occurs when in a subsequent visualization step an object already contained in the image must be placed elsewhere due to additional spatial constraints. As image maintenance is performed by repeatedly updating entities depicted in the image (cf. Section 4.1) this would lead to an object being moved to another location. This behavior can be compared to the interpretation of 'impossible figures' used in empirical investigations in cognitive psychology (e.g., Schacter et al., 1991).

When a spatial relation causes a conflict with already visualized entities the relation may be ***omitted.*** In this case the image remains incomplete and it cannot be detected which parts of the information cause conflicts and whether another solution might allow for the integration of all facts. However, under resource restrictions the strategy of omitting facts may be helpful.

The ***revision*** of previous image generation steps is the most difficult but most promising option when a complicated situation needs to be solved. Modifications in the image generation strategies can be made both in the conversion procedure and in the image specification step of the visualization process. In any case this option is resource consuming and it is not clear in advance whether a solution (i.e. an adequate image) can be found at all.

For each of the cases the following problems must be addressed: First, it must be *detected* that a complication has occurred in the image. Second, the cause of this complication must be *assessed* and options for solving the complication must be evaluated. Third, when having decided for a revision of the visualization strategies, the main difficulty is how the available resources in working memory can be efficiently utilized. The efficient use of chunking and intermediate storage facilities is known to be one of the crucial factors in efficiently employing visual mental imagery in complex situations (Kosslyn, 1994; Hegarty, 2000).

4 Conclusion and Outlook

The MIRAGE model is designed to mimic the characteristics of the construction of geographic knowledge representations in mind. This section reviews the model's features and relates it to principles in human mind that have been addressed in cognitive science research. We will point to open research questions and to potential further applications of the system.

4.1 Discussion

The hierarchical LTM representation models a *lean* knowledge structure. Many relations between geographic entities are not represented. Since spatial knowledge usually is not acquired systematically, most pieces of geographic information needed in a specific situation are not stored explicitly in mind. Often spatial facts must be inferred from related information that is available. Fortunately, spatial facts and relations have a strong interdependence on various levels that makes the derivation of useful information from less suitable information possible.

Nevertheless, also redundant knowledge is represented in the hierarchical LTM representation. For example, orientation information may be available at different levels of granularity. As the cognitive collage and atlas metaphors for mental spatial knowledge suggest, spatial knowledge may be available at different stages of accuracy and on different levels of resolution.

The hierarchical LTM representation is built from *spatial knowledge fragments*, which form the elementary units of spatial knowledge in the model. They encode both geographic properties and spatial relations that hold between one, two, or more geographic entities. Knowledge for geographic entities is known to be fragmented in memory rather than globally coherent.

The LTM representation in the model is organized in a *hierarchical* manner imposed by the type of relation encoded and the degree of resolution. From results in cognitive psychology it is known that facts stored in memory always are structured by some sort of hierarchy, be it imposed by a given superordinate structure (e.g., Hirtle & Jonides, 1985), be it constructed by the person according to some idiosyncratic principle (McNamara et al., 1989). The hierarchical organization enables retrieval processes that provide semantically related pieces of knowledge. In the model, retrieval is done by the access process that utilizes the hierarchical structure with respect to the problem to be solved.

In MIRAGE's image construction subsystem spatial relations held in the activated LTM representation are complemented using default knowledge to obtain the required information from the underlying lean knowledge. This together with the image specification step in the visualization process relates to the categorial-to-coordinate conversion subsystems claimed in mental imagery (Kosslyn, 1994), which convert *types* of entities to *exemplars* for visualization.

Compared to the underlying lean LTM representation the image representation in the visual buffer is fully instantiated. This relates to mental models (Johnson-Laird, 1983) in which humans for decision taking purposes instantiate just one potential solution rather than considering all possible solutions (cf., preferred mental models, Schlieder, 1999).

Mental images require periodical rehearsal to prevent them from fading out. In the model, image maintenance is realized by iterated image constructions based on the activated LTM representation. The activated LTM representation is more persistent than the image (Kosslyn, 1994); so modifications in the underlying working memory representation cause the image to be updated in the next visualization step.

In MIRAGE, the three subsystems LTM activation, image construction and image inspection - though they rely on each other - operate independently of each other and in parallel. Inside each of these systems operations are performed sequentially. This construction principle leads to an *anytime* characteristic of the model: An image represented in the visual buffer can already be used at an early stage of image construction, while the underlying image representation in working memory is still being updated and refined.

4.2 Further Research Questions

The architecture of MIRAGE has been devised as a modeling framework for describing imagery processes for mental reasoning about geographic configurations. Its conception for the use of mental images for constructing spatial representations exhibits a number of degrees of freedom that leave room for experimentation and that raise further research questions. The model presented does not provide answers to these questions, but it can be used to point out and further elaborate issues that may lead to a more accurate modeling conception. Most of the answers needed require further empirical investigations.

Focusing on the image construction the following questions are of interest:

- How is missing specificity compensated for in working memory prior to image construction? Especially, which shapes are employed when reasoning about extended entities, and how are qualitatively represented relationships specified to be mapped into the mental image?
- When straightforward strategies fail, how are parameters modified and constraints relaxed, which alternative strategies can be employed, and how is the respective situation assessed to come up with alternative control strategies in the image construction processes?
- What are the feedback structures that enable tuning between the interacting subcomponents for efficient strategies in complex image generation tasks?
- What are the strategies that compensate for the resource restrictions in working memory when alternative images have to be compared, or when complex situations require more and more pieces of knowledge being included in the image?

4.3 Further Application Perspectives

MIRAGE's primary objective is in basic research in spatial cognition. However, there are also further application perspectives. Visual thinking in mental images can be improved using suitable external pictorial media. For example, people use paper and pencil to draw sketches for extending visual thinking processes in mind in the external medium. In the same way intelligent technical assistance systems can support and complement the processes of spatial reasoning with mental images. Capacity limits and other resource restrictions in working memory can be compensated for by external systems that assist reasoning processes involving visual mental images.

Modeling imagery processes for reasoning about problems in large-scale space may serve as a first step in externally extending the internal pictorial space together with the intermediate reasoning processes involved. Application perspectives can be seen in the interactive presentation of geographic information provided by geographic information systems (e.g. for planning tasks), in interactive design systems, or in the cognitively adequate presentation of environmental information in spatial assistance systems (e.g. in tutorial systems or in wayfinding assistance).

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