Design of an Architecture for Reasoning with Mental Images

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Mental reasoning about spatial environments often uses spatio-analogical or quasi-pictorial representation structures. As human working memory for spatio-analogical knowledge processing is severely restricted in capacity, mental processes dynamically construct and explore task-sensitive representations to obtain desired spatial information.

Visual mental images can be conceived of as mental models (in their Johnson-Lairdian sense, 1983) which involve both spatial and visual information (Kosslyn, 1980; 1994; Finke, 1989). Mental images are working memory constructions which are closely related to visual perception. The term is used to designate either imagery phenomena in the presence of actual visual perception, or those that are evoked solely on the basis of knowledge retrieved from long-term memory. Visual mental imagery and visual perception seem to rely on the same cognitive mechanisms to some extent; see the contribution of Mast (this workshop) for an overview of how both phenomena are related.

Work on conceptual and computational models of human mental imagery includes approaches by Kosslyn (1980; 1994), Glasgow and Papadias (1992), and Barkowsky (2002). Although the second Kosslyn model is so far the most elaborate system of mental information processing with visual mental images, it remains purely conceptual for most of its parts. In contrast, the computational model by Glasgow and Papadias does not aim at psychological validity in the modeling itself, but rather at employing cognitive principles in the context of a technical diagrammatic reasoning system. There is no computational architecture yet that describes mental image-based knowledge processing of spatial environments as a whole. However, for the processing of knowledge about geographic spaces, the MIRAGE model proposed by Barkowsky (2002) offers a computational modeling framework for the construction and inspection of visual mental images. Based on this framework, we present the draft of a conceptual architecture of mental imagery processing that involves long-term memory, working memory, and short-term memory components, as well as an interface to external diagrams, for instance to sketches or maps (cf. Fig. 1). This conceptual model serves as an input for a detailed model specification, which will subsequently be implemented to form an executable computational architecture.

In a simplified layout, the model consists of five main subsystems:

(1) *Long-term memory activation:*
Based on a pre-processed representation of a (propositionally stated) problem – for example to decide upon the spatial orientation of two geographic locations with respect to each other – long-term memory representations are accessed. This leads to the activation of spatial knowledge fragments from long-term memory, which through this activation become part of working memory.

(2) *Image construction:*
The activated fragments are then output to a construction process that links them into an activated representation structure. As the knowledge contained in this structure is

usually underdetermined (i.e., it is incomplete and too coarse for an immediate instantiation of an image), the structure is enriched in a conversion process. Specifically, this process assigns ontological types to spatial entities in the structure and completes relations where necessary. For instance, default mechanisms are employed that may be induced by hierarchical properties of representations in memory.

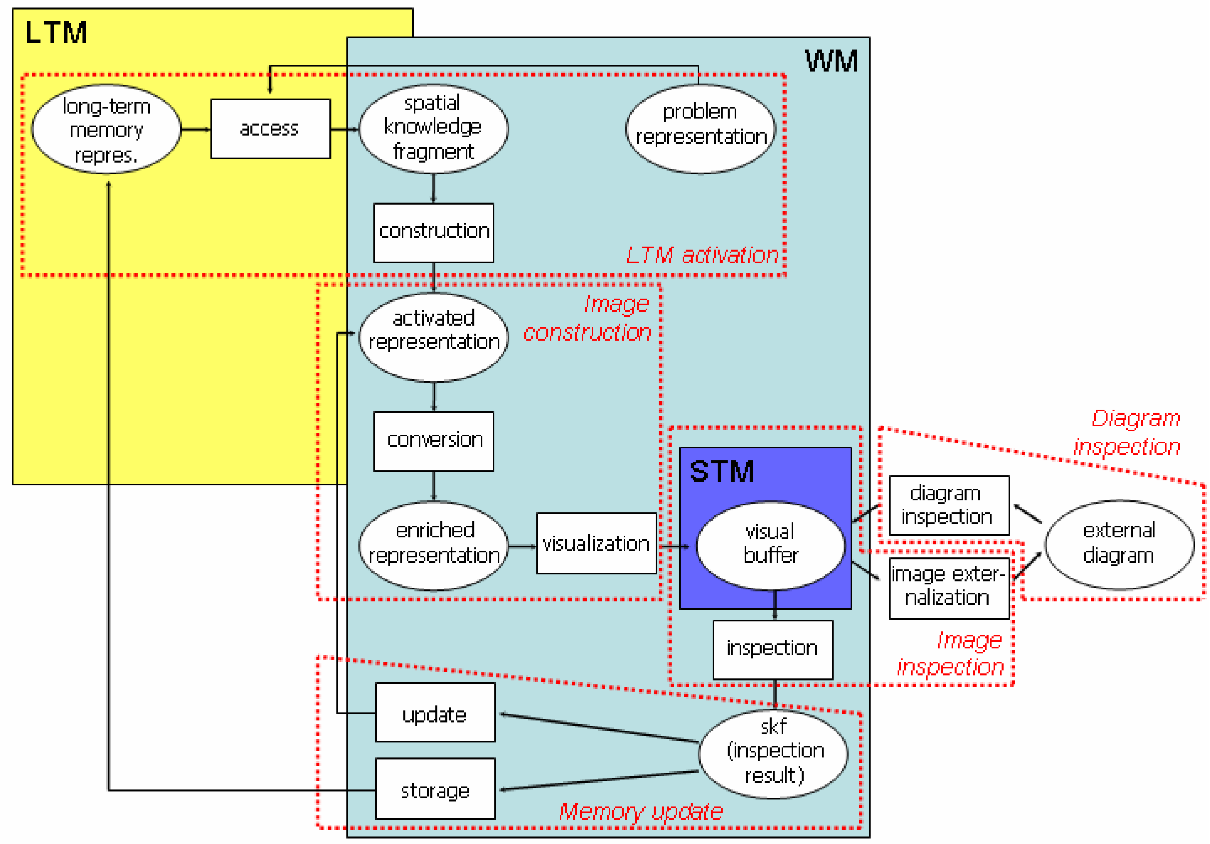

Figure 1. Conceptual model consisting of diagram inspection, long-term memory activation, image construction, image inspection, and memory update as principal subsystems.

(3) *Image inspection:*
A visualization process takes over and leads to the construction of a spatio-analogical representation (i.e., a mental image) in the visual buffer (a short-term memory system). This representation is then inspected. Individual spatial knowledge fragments may be read off and input to the memory update subsystem, or knowledge contained in the image may be fed into an image externalization process, leading to the construction of an external diagram.

(4) *(External) diagram inspection:*
As the visual buffer is situated between memory and perception systems (or is even seen as a part of either one of them), it receives input through both the constructive memory and the perception channels. Functional aspects of the latter are captured through the external diagram inspection subsystem.

(5) *Memory update:*
The result of a mental image inspection is again re-represented as a spatial knowledge fragment. This fragment can serve as an input to memory update processes in working memory and long-term memory, where long-memory update is conceptualized as 'storage'. The inspection result may also be externalized in terms of propositions (the corresponding subsystem is not shown in Fig. 1).

Naturally, the processing cycle described here is a highly idealized one as it emphasizes the forward mechanisms and abstracts from interactions between neighboring functional components. For example, the image inspection process and the result of the inspection supposedly influence parameters in the visualization process directly, without going through the entire update-conversion-visualization loop. Also, super-local phenomena of attention, span, and processing capacities clearly exist, although these aspects are mainly associated with local components (for example the visual buffer). Third, all four processes associated with the visual buffer – visualization, (image) inspection, diagram inspection, and image externalization – probably draw on a common set of elementary faculties to significant extents. Still, we may want to conceptualize them separately for functional reasons.

For the purposes of the workshop, we would like to address three main issues:

1. *The role of visual and spatial components in mental reasoning.*
   The visual impedance hypothesis (Knauff, 2002) suggests that classes of spatial problems exist (e.g. in deductive reasoning) for which performance is poorer when mental images are formed during a solution process as compared to solution processes that avoid imagery. It sensibly can be assumed that spatial problems classes can be found for which the situation is reversed, i.e. non-visual strategies will impede reasoning (for example due to the problem's complexity). According to the model proposed here, non-visual and visual reasoning strategies are based on two types of representations in working memory, where contents in visual working memory can be constructed based on non-visual mental representation structures.

2. *The relation between visual perception and visual mental imagery.*
   Visual perception and visual mental imagery seem to largely rely on the same or similar cognitive mechanisms. If mental images are employed in reasoning about abstract concepts, what is the residue of visual perception mechanisms in such abstractions? Can mental activities involved in reasoning processes about spatial problems and about abstract concepts be distinguished by neuroimaging techniques (see the discussion by Mast, this workshop). Since abstract (i.e. non-spatial) knowledge can be conveyed by external diagrams and since mental constructions in visual mental images can by externalized during reasoning tasks, abstract problems can be assumed to be dealt with by the same or similar mental mechanisms as visuo-spatial problems.

3. *The role of pictorial space for spatial reasoning.*
   Gattis (this workshop) points out that processes involved in reasoning about small-scale and large-scale spaces might be fundamentally the same. Where spatial representations form the basis for inferences, the original absolute scale of a domain does not seem to matter much. The same argument holds for reasoning with mental images: whether humans form a mental image from spatial knowledge fragments that designate entities on a geographical or a table-top scale matters only insofar as concepts and/or their designators vary between domains (for example, one would not refer to a keyboard being *north* of a computer screen in a table-top scenario). With respect to

topological, ordinal, and metrical properties, however, domains from different scales seem to be widely analogous. As it may be convenient to define an origin for cross-scale mappings, pictorial space can be regarded as such a medium through which we access spatial representations of scenarios on various scales.

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