In Danilo Fum, Fabio del Missier, Andrea Stocco (Eds.), Proceedings of the 7th International Conference on Cognitive Modeling, Trieste (ICCM 2006), pp. 50–55. Edizioni Goliardiche, Trieste. 2006.

Computational Modeling of Reasoning with Mental Images: Basic Requirements[*]

Sven Bertel[1], Thomas Barkowsky[1], Dominik Engel[2], and Christian Freksa[1]
({bertel, barkowsky}@sfbtr8.uni-bremen.de, dengel@cosy.sbg.ac.at, freksa@sfbtr8.uni-bremen.de)

[1] SFB/TR 8 Spatial Cognition
University of Bremen, Germany

[2] Department of Scientific Computing
University of Salzburg, Austria

Abstract

The interest in the cognitive phenomena linked to mental imagery and to reasoning with mental images has sparked the development of numerous conceptual and computational models from different scientific backgrounds. These models serve to explain cognitive processes or to improve technical reasoning models. Our aim in this paper is to identify a number of requirements that are essential for any computational model of mental imagery. This stocktaking of requirements is useful for the critical assessment of existing models of mental imagery as well as for improving future models. We assess three prevalent computational imagery models and conclude with an outlook on a next generation of imagery models that will implement the set of requirements.

Introduction

Mental imagery is more relevant for cognitive science today than ever, in research as in applications: we have started to understand the mental principles that make aspects about the world selectively explicit while maintaining other aspects implicitly. On the other hand, employing these principles in application systems (such as in assistance or tutoring contexts) can allow reasoning processes to be more to the point and more efficient.

As a collection of psychological phenomena, mental imagery has long held the interest of the scientific community. The topic of the format of mental images has sparked a vivid debate (cf. Tye, 1991): what are mental images and how can images help us understand the world outside the mind?

Different types of models of imagery processes have been developed: artificial intelligence (AI) implementations focusing on the use of spatial structures for reasoning; neuropsychological models describing insights about human memory structures and processes; and models that attempt to close the gap between empirical insights and technological realization. The philosophical debate has been replaced by a discussion on specific mechanisms for dealing with imagery-related aspects of the represented world to enable reasoning. In robotics as well as in cognitive systems design, *embodied cognition* plays an increasingly significant role (Wilson, 2002): here, the direct functional coupling between the world and its representation provides necessary cognitive shortcuts to understanding the environment and offloads part of the reasoning to it. For example, in architectural or product design, creative discoveries are provoked by way of reasoning loops which iterate through mental images and external diagrams (Goldschmidt, 1991). In diagrammatic reasoning, spatial structures are exploited for reasoning about the world (e.g., Khenkhar, 1991).

Computational imagery models have emerged from a broad background: There are numerous approaches to better explain the phenomena or to use the insights from prior models and psychological experiments in technical systems. Our aim in this paper is to identify, without the claim of completeness, a number of requirements that are essential for any computational model of mental imagery. The contribution of our work in this respect is not to put forward an individual new model, but rather to take stock of the requirements that can be formulated to a) critically assess and evaluate existing computational models of mental imagery and to b) improve future models by providing a checklist.

This paper is organized as follows: next, we will sum up some basic work on mental imagery; then, we will formulate the requirements that should be reflected in computational mental imagery modeling; third, we will use the criteria to critically assess three existing models of different types; finally, we will evaluate the requirements and outline how they can be applied, improved, and expanded in future work.

Mental Imagery. Mental imagery can be defined as “the mental invention or recreation of an experience that in at least some respects resembles the experience of actually perceiving an object or an event” (Finke, 1989; cf. also Tye, 1991). The term designates imagery phenomena in the presence of actual visual perception and those evoked solely on the basis of knowledge retrieved from memory. In both cases, imagery results from an interplay of distinct functional subsystems (cf. Kosslyn, 1994). Visual mental imagery and visual perception rely to some extent on the same cognitive mechanisms across subsystems; there is neuropsychological evidence that cortical areas active in visual perception are often activated in mental imagery as well (cf. the extensive cross-study analysis by Kosslyn & Thompson, 2003). Michelon and Zacks (2003) review a number of studies that show similarities between imagery and perception, on the behavioral, on the neuro-psychological, as well as on the neurological level.

Semantic effects have been shown to interfere with mental image reinterpretation (Chambers & Reisberg, 1992),

---

[*] We gratefully acknowledge support by the German Research Foundation (DFG) for the project R1-[ImageSpace] of the Transregional Collaborative Research Center SFB/TR 8 Spatial Cognition. We also thank Holger Schultheis and two anonymous reviewers for constructive comments.

In Danilo Fum, Fabio del Missier, Andrea Stocco (Eds.), Proceedings of the 7th International Conference on Cognitive Modeling, Trieste (ICCM 2006), pp. 50–55. Edizioni Goliardiche, Trieste. 2006.

and mental structural reconfiguration is generally hard (Verstijnen et. al., 1998), perhaps because of an organization by visual chunks (cf. Kosslyn & Pomerantz, 1977). Hierarchical organization of long-term memory (LTM) contents (Stevens & Coupe, 1978) may be reflected in the structure of the chunks. Images often represent systematically distorted spatial relations that are reconstructed from fragmentary or incomplete knowledge (Tversky, 1993).

Requirements for Models of Mental Imagery

Content and Structure

Representation is an important aspect of computation. In a large majority of current computational models of cognition, knowledge is represented in propositional structures. This has clear advantages to using many other structures as the format is simple, content may be compared across cognitive subsystems, and standard description and reasoning frameworks can be used. However, a uniform sentential mental representation format is not in line with a host of empirical findings (e.g., Kosslyn & Thompson, 2003). We will make the case for hybrid representation formats in modeling mental image-based reasoning: propositional structures form a basis from which integrated, increasingly analogical structures are dynamically constructed, when needed.

Leaving Representational Schisms Behind. The representational format of mental images has long been the issue of vivid discussions: the dominating question of whether images are like pictures (cf. Kosslyn, 1980; 1994) or like propositions (Pylyshyn, 1973) reflects the assumptions that knowledge is encoded in only one of these formats.. More recent analyses suggest that neither format may be adequate (e.g., Pylyshyn, 2003) and that, rather, some tasks that in the past have been described as imagery tasks have visual traits (such as the inspection of details, or tasks that involve shape knowledge; Kosslyn & Thompson, 2003) while others are solved *non-visually* (e.g., tasks in which spatial relations have to be mentally dealt with; cf. Knauff & Johnson-Laird, 2002). The bottom line is this: there seems to be more than the visual part to a mental image and it is likely that non-visual mental reasoning operates on more than just propositions.

Visual mental images are mental models in the sense of Johnson-Laird (1983), as they integrate knowledge fragments into a coherent scheme; they are special mental models in that they may comprise visual information (e.g., shape information). The visual information gets partially (re-)instantiated in a functional subsystem (the *visual buffer* in Kosslyn's model, 1994; here, 'visual' should be used metaphorically, see above) where it is subject to processes similar to those that operate on visual percepts. It is here where parallels to pictorial formats lie. In addition, non-visual information forms part of a mental image, for example knowledge regarding the structure and organization into constituting parts, or regarding the interpretation associated with the content of an image. These are aspects dissimilar to pictures and visual percepts (e.g., Verstijnen et al., 1998).

Given the evidence that mental images should be conceived of as hybrid, exhibiting both visual and propositional traits, and also given the evidence on functional subsystem architectures and cognitive control as a distributed process (see below), two main modeling alternatives arise: (a) mental imagery is a process that draws on several functional subsystems that differ in their representational formats; in their interplay across tasks, notions of the formats are more or less dominant; or, (b) mental imagery is a process that draws on an integrated cross-modal representation format; depending on the task, it is scalable in several representational aspects. A third option (c) is possible, of course: a heterogeneous system that in parts is more like (a), in others more like (b), depending on the imagery task at hand.

For the moment, there is no clear evidence from experimental research in favor of one of the options. Consequently, a modeling decision for (a), (b), or (c) has to be taken on other grounds, such as based on general (e.g. computational) processing principles. Hopefully, future integrated research cycles with computational imagery models, model-based predictions, and empirical evaluation will help closing this gap in our knowledge about functional subsystem structure and dependencies.

Composite Structure of Knowledge in Mental Imagery. Mental images are constructed from pieces of knowledge that are retrieved from memory (Denis & Kosslyn, 1999). These *knowledge fragments* are either elementary (for instance, an elementary knowledge fragment may be modeled as consisting of some *n*-ary relation along with *n* entities for which the relation holds) or they may be further structured like memory chunks and consist of an aggregation of a (small) number of elementary knowledge fragments.

Complementation and Integration of Knowledge in Imagery. Knowledge from memory is often under-constrained with respect to what is needed for image construction: it can be incomplete, scarce, or lean (e.g., Barkowsky, 2002). During mental image construction, mental processes need to dynamically add knowledge fragments to *increase specificity*. Declarative default knowledge in fragment integration and procedural defaults in image construction are two types of such additional knowledge.

Mental representations of spatial knowledge are frequently distorted or even partly conflicting. Visual mental images, however, are specific and coherent, at least locally and with respect to certain aspects (like mental models in the sense of Johnson-Laird, 1983). Therefore, processes that either precede the actual image construction or that are a part of it must resolve conflicts at least locally in order to achieve the necessary level of knowledge integrity. Relevant mechanisms for conflict resolution include prioritizing certain fragments, which may lead to an effective reduction in informational content.

Processing and Control

As is the case with representation structures, computational abstractions of cognitive processes are simplifications; they serve to describe very dynamic settings. One has to keep in

In Danilo Fum, Fabio del Missier, Andrea Stocco (Eds.), Proceedings of the 7th International Conference on Cognitive Modeling, Trieste (ICCM 2006), pp. 50–55. Edizioni Goliardiche, Trieste. 2006.

mind that representation and process abstractions both arise from using computation to describe cognition; it does not make sense to design or use one without the other, and ultimately, their differentiation may well only exist in the modeling domain. With that in mind, for reasoning with mental images, we argue for multi-directional, distributed processes, as will be explained below. Across functional subsystems, simple common processing mechanisms exist, which are mutually comparable although their individual instances may differ. On a higher abstraction level, we argue that the subsystems are linked by processing pathways. A combined bottom-up / top-down perspective of cognitive control such as advocated here is only one of several alternatives. However, in our view, it has the advantage of combining distribution and emergence with models whose processes are transparent to the modeler.

The Top-Down Abstraction View: Knowledge Processing Follows Major Pathways. In terms of system abstraction, mental knowledge processing is performed in working memory (WM): here, mental images are constructed and processed. With respect to knowledge fragments in mental imagery, there exist three major conceptual ways by which knowledge can enter WM (cf. the discussion in Barkowsky, to appear), and these ways need to be reflected in mental imagery modeling: knowledge fragments can be retrieved from LTM, they can be the product of a WM operation itself, including mental image inspection, or they can originate from mental processing of perceptual input. Given the evidence for overlapping, coupled, or shared functional subsystems in mental imagery and (higher) visual perception (e.g., Ishai & Sagi, 1995), mental processes involved in the inspection of a mental image and a visual percept can be expected to be equally entangled.

Once knowledge is part of WM, it has to be kept activated or it will fade out over time. Content in WM can be modeled as consisting of activated LTM structures, of representations in dedicated WM buffers, and of short-term buffers, such as the visual buffer. Knowledge fragments resulting from construction and inspection processes in WM can be stored in LTM for later use.

The Inter-Level View: WM Processes Are Multi-Directional. Operation in WM includes the integration of knowledge fragments and with it, the construction of mental models that are specific enough to allow for an actual mental visualization of their contents (i.e., the construction of a visual mental image). The various functional processes involved (e.g., in knowledge retrieval or knowledge integration) have traditionally been conceived as a sequential processing stream (i.e., knowledge fragments have to be retrieved from LTM before an integration can occur). As Allport (1993) points out, in many traditional theories, mental processing is taken as a "linearly ordered, unidirectional sequence from sensory input to overt output". However, information also flows the other way as higher-level processes frequently do have an influence on lower-level ones.

For example, the integration of knowledge fragments can cause the retrieval of further fragments from LTM. Thus, control of processing should be modeled on a multitude of functional levels, comprising local and super-local phenomena (i.e. phenomena situated within a functional subsystem or those that are spread across subsystems). Such a multi-level assumption of control is well in line with proposals regarding the functional structure of WM that suggest that resources (e.g., of attention and storage) are associated with subsidiary systems as well as with central control mechanisms (Baddeley, 2002).

The Bottom-Up Abstraction View: Cognitive Control is a Distributed Process. Recent evidence, both on the functional and on the neural level, suggests that flow of control should be conceived of as an emergent phenomenon of the interplay between autonomous subsystems (Allport, 1993; Hommel et al., 2004; Ishai et al., 2000; Nobre et al., 2004; Schultheis, 2005). Furthermore, the traditional view that linked control mainly to attentional selectivity in the context of limited cognitive resources (e.g., Norman, 1968) has to be expanded to include management, scheduling, and communication tasks (cf. Kieras et al., 2000).

These conceptions should be reflected in modeling: for problem solving from a functional point of view, in the collaboration of autonomous subsystems, each subsystem aims at achieving a local goal (e.g., the image construction subsystem works towards a representation that is suitable for visualization in the visual buffer), and collaboratively furthering the convergence of the system towards a global goal derived from an initial problem representation. The global flow of control thus should emerge from the gradated composition of local goals on different granularities. For spatial reasoning, for example, Engel et al. (2005) argue for a set of simple mechanisms, *grouping* and *chunking*, *scanning* and *sequentialization* which implement control on the finest granularity level. On coarser levels, the goals gradually assume a more global character, up to the goal of solving the initial problem. Such a bottom-up conception is desirable: for example, Hommel et al. (2004) argue for a highly distributed view of executive control of human behavior and with respect to the processes involved they conclude that "most if not all of these processes may turn out to be disappointingly common and it may be their concert that creates the emergent property of being 'executive'". In a similar vein, Cowan (1999) proposes a set of basic mechanisms of activation and attention in his embedded-process model of WM.

A distributed conception of cognitive control has advantages for computational modeling over more centralistic conceptions: the aim to achieve locally defined goals results in collaboration between (functionally) neighboring subsystems (i.e., interacting subsystems), based on a set of basic mechanisms. This can facilitate the construction of collaborative networks in which processes, capacities, and resources from different subsystems are joined. Different situations lead to the formation of different constellations, e.g., access, construction, and conversion subsystems could collaborate in solving a spatial linearization problem with only little involvement of other (e.g., visual) subsystems (this view incorporates into the model findings which report missing neural activation in visual cortex for such problems; e.g., Knauff & Johnson-Laird, 2002). Correspondingly,

In Danilo Fum, Fabio del Missier, Andrea Stocco (Eds.), Proceedings of the 7th International Conference on Cognitive Modeling, Trieste (ICCM 2006), pp. 50–55. Edizioni Goliardiche, Trieste. 2006.

other super-local phenomena, such as memory spans and processing capacities are mainly associated with local subsystems (e.g., the visual buffer).

Similarly, cognitive selectivity and resource management can be mapped to a cognitive model: global resource management emerges from local optimization strategies, balancing two (sometimes conflicting) requirements: allocating resources for the achievement of a local goal and saving resources for the whole system. These strategies can be traced on different granularity levels: the multi-level organization of control eventually allows that on the coarser scales resource management is targeted at the global problem at hand (or divided among target problems, e.g., in the case of dual-task configurations). Finer scales are oblivious to the global problem and optimize the use of resources available to them to achieve their local goals.

Reasoning

Goal-directed processes in mental imagery (and processes associated with them) can be conceptually differentiated from other processes. For adequate computational modeling, a consolidation between distributed data-driven and goal-driven components has to be found.

Sequential Reasoning Emerges from Multi-Directional Processing. Reasoning with mental images is in some ways similar to reasoning with ordinary mental models, while differing in others. On a problem-solving level, reasoning with analogous, quasi-pictorial content involves sequences of mental image construction and inspection in which information from other WM systems enters into an integrated quasi-visual format, and conversely, in which information is read off the image and passed on to other systems, including LTM. On lower abstraction levels, however, to account for phenomena reported from dual task experiments, some of these activation and processing sequences need be conceived of as being instantiated by parallel, underlying processes (which is compatible to models with more distributed resources in WM; e.g., Baddeley, 2002) and as multi-directional. One possibility is that high-level, goal-directed processes initiate sequences of parallel processing steps. An interesting question is how synchronization can be modeled where intermediate results from different processes and subsystems are needed for further processing. While the conception of cognitive control as a distributed phenomenon based on common simple processing mechanisms across subsystems should facilitate modeling of the integration of parallel processing and synchronization, many open issues still exist, regarding computation and regarding findings from empirical and behavioral research.

Parallels to Visual and Diagrammatic Reasoning. In addition to purely mental reasoning, the close coupling and sharing of functional subsystems in mental imagery and visual perception enable reasoning loops in which mental image content is externalized (through drawing a diagram), the diagram inspected, and the inspection results again used for mental image construction. The significance of such reasoning loops that comprise mental representations and processes and external representations has been frequently acknowledged (e.g., Goldschmidt, 1991 for design tasks) and should be a core aspect for computational modeling of reasoning with mental imagery. On an aside, it is this integration of mental and external reasoning in imagery that holds particularly promising perspectives for applications built around computational cognitive models (e.g., for assistance or tutoring contexts; cf. Bertel, 2005).

The coupling of processes and representations is important here (cf. Palmer, 1978). In psychological accounts, either one of these two is often given precedence in consideration over the other, especially in the context of mental imagery, where the traditional discussion has predominantly focused on the representational format, and the processes involved have been explored *given* a specific representational format. It has been put forward by Engel et al. (2005) that an approach to imagery that views processes and images, and their mutual influence on each other, on an equitable level, is advantageous in terms of explanatory power.

Image Inspection Leads to Partial Image Construction. On a higher-abstraction reasoning level, the construction of a visual mental image is a sequential process that can involve a causal chain of events. For example, the retrieval of a specific knowledge fragment from LTM may be initiated by prior retrievals or by the composition of specific representational parts or aspects. Items may be added to an image or items that are present may be detailed in image parts to which attentional resources are allocated. Where these resources are absent, image parts fade or lose representational detail. As a result, mental image inspection can be seen as partial construction processes with shifting foci of attention, and mechanisms for image inspection are likely to draw on those for image construction.

In a similar vein, mental reasoning in the presence of an external diagram (e.g., a geographic map) involves successive partial inspections of the diagram. The inspection steps will likely not be random. For example, they may be determined by factors that lie in the structure of the image content or in the purpose of the inspection (cf. the structured decomposition of a mechanical system by the causal chain of events, Hegarty, 1992, and the organizing function of eye movements, Brandt & Stark, 1997). Thus, any given inspection step will to some extent depend on inspection steps that preceded it. Regarding the modeling of spatial reasoning, both the scanning and sequentialization principles argued for by Engel et al. (2005) exploit such chains of events.

Prevalent Computational Imagery Models

Results of mental imagery research have led to various attempts to model processes, functions, and formats, both on conceptual and implementation levels. We will now briefly discuss some of the presented aspects in representation, processing, and reasoning with respect to three of the more prevalent models; the computational imagery system by Glasgow and Papadias (1992), the comprehensive functional model by Kosslyn (1994), and the computational model MIRAGE by Barkowsky (2002).

Computational Imagery and the Format of Images. The *computational imagery* system by Glasgow and Papadias

In Danilo Fum, Fabio del Missier, Andrea Stocco (Eds.), Proceedings of the 7th International Conference on Cognitive Modeling, Trieste (ICCM 2006), pp. 50–55. Edizioni Goliardiche, Trieste. 2006.

(1992) employs results from mental imagery research in a technical AI system capable of dealing with spatio-visual problems. With respect to a hybrid representation format, their model rightfully distinguishes between different formats of the knowledge contained. However, the distinction into ‘spatial’ and ‘visual’ types assumed in their model is likely ill-set as some highly visual aspects of topological relations (such as the containment of figural representations) are not placed within the ‘visual’ type. In contrast, we argue that some information contained in mental images can be adequately described as visual (i.e., it gets instantiated in the visual buffer), while other is non-visual (i.e., it is processed in different WM subsystems). The inclusion of spatial knowledge fragments in mental image construction can lead to visual or non-visual models, depending on the specific knowledge, the task to be solved, and the reasoning strategy chosen. It seems that some of the distinctions made by the Glasgow and Papadias model contrast visual and non-visual rather than visual and spatial problem solving. The model offers an interesting perspective on reasoning as a number of imagery routines (e.g. rotation) exist for visual and spatial subsystems, only differing in their actual implementations.

A Functional Imagery Model. Kosslyn’s 1994 model is conceptual. While it has not been implemented as a computer program, it nevertheless offers a comprehensive description of the functional interactions between the diverse mental components involved in image processing and incorporates neuropsychological findings about high-level visual perception. The most prominent components of the model are the *associative memory* subsystem with diverse *lookup* and *pattern activation* systems and the *visual buffer* with the *attention window* and *attention shifting* facilities.

The Kosslyn model does not distinguish between mental representation structures and processes; rather, it identifies and describes functional mental imagery components that serve specific tasks, as well as the interactions among them. By focusing on the components, a static account of imagery is provided which, on a higher level of abstraction, identifies major processing pathways and gives snapshot-like views of representation and formats at different times and points in the processing. While allowing for very useful systematic abstractions, the model ultimately cannot account for how the general processing and control emerge from distributed processes across components

The Computational Model MIRAGE. The model by Barkowsky (2002) is a computational approach that describes mental reasoning processes about spatial relations in geographic space. It is composed of a hierarchical LTM structure and a WM for processing spatial knowledge.

The model describes the construction of mental images to answer specific questions about spatial relationships, for example concerning topological or orientation relations between geographic locations. Based on the entities and relations involved, additional *spatial knowledge fragments* are sequentially provided from LTM. Underdeterminacy is a central assumption, i.e., spatial relations required for image construction may be missing or available only in a too coarse form. To still allow for image construction, available knowledge fragments are complemented in WM by default components prior to visualization in the *visual buffer*. During *visualization*, the qualitative spatial relations used in the construction of the WM representation are replaced by specific geometric descriptions.

While being completely implemented as a demonstrator system, MIRAGE focuses mainly on high-level and goal-directed processing. As is the case with Kosslyn’s 1994 model, this model does not fully explain how processing and control emerge from an underlying set of subsystems, including the interplay of goal-directed (i.e., top-down) and distributed, parallel (i.e., bottom-up) processing that has been proposed above. With respect to formats of representation, both models shape their images pictorially, thus differing in their approach from the hybrid representation format proposed above.

MIRAGE and Kosslyn’s model focus on mental imagery as occurring in the absence of external stimuli. With respect to the discussion of how mental image-based and diagrammatic reasoning are intimately intertwined, it seems absolutely necessary that mental/external reasoning loops be among the central aspects considered for future computational models of imagery.

Discussion

Computational modeling of reasoning with mental images takes place on theoretical grounds that have many pitfalls: one must avoid taking the propositional and pictorial format metaphors too literally that have long haunted the imagery debate, but one must also not loose the specific representational aspects that make up imagery, and that distinguish it from other phenomena of mental reasoning. We have tried to lay out an undogmatic way by seeing images as special kinds of mental models, thus, letting them share most if not all properties with ordinary-type mental models, with a few additional, (quasi-)visual properties.

With respect to procedural issues, multi-directionality on lower abstraction levels along with major processing pathways on higher ones seem to be viable functional generalizations that can be made based on current neuropsychological and behavioral findings. Regarding cognitive control, the state of the art seems to suggest a distributed account of executive faculties where the global resources, including storage, attention, communication, scheduling, and management, emerge from an interplay of local subsystems, and global goals emerge from the conjunction of local ones across multiple, structured levels.

Getting a thorough understanding of how such goal emergence happens is important for understanding image-based reasoning as a whole. This is especially true for reasoning with mental images: how do goal-directed and seemingly sequential characteristics synchronize with underlying parallel, data-driven (i.e., perceptual) processes? Here, additional empirical, behavioral, and computational research seems to be required.

While the prevalent imagery models (such as Kosslyn, 1994) identify a number of functional components that serve specific tasks, and describe the components’ interrelations on an abstract processing level, it is important that the next

In Danilo Fum, Fabio del Missier, Andrea Stocco (Eds.), Proceedings of the 7th International Conference on Cognitive Modeling, Trieste (ICCM 2006), pp. 50–55. Edizioni Goliardiche, Trieste. 2006.

generation of models concentrate *en detail* on describing the mechanisms that operate in the individual subsystem and on how these trigger mechanisms in other subsystems. Coordination across systems to produce overall goal-directed behavior is clearly an important issue. The approach put forth by Engel et al. (2005) of a simple set of mechanism that are shared across subsystems on an abstract level but differ in their instantiation can be seen as a first step towards such detailed descriptions of interrelations.

This contribution has proposed one possible coherent set of requirements that are essential for a computational model of imagery and that can be used to evaluate existing models. As the knowledge of imagery structures and processes grows and as modeling techniques develop, our set will evolve and increase in size.

References

Allport, A. (1993). Attention and control: have we been asking the wrong questions? A critical review of twenty-five years. Meyer, D. E. and Kornblum, S. M. (Eds.), *Synergies in experimental psychology, artificial intelligence, and cognitive neuroscience*. Cambr.: MIT Press.

Baddeley, A. (2002). Fractioning the central executive. In D. T. Stuss & R. T. Knight (Eds), *Principles of frontal lobe function*. NY: Oxford Univ. Press.

Barkowsky, T. (2002). Mental representation and processing of geographic knowledge - A computational approach. Berlin: Springer.

Barkowsky, T. (to appear). Modeling mental spatial knowledge processing: An AI perspective. In F. Mast & L. Jäncke (Eds), Spatial processing in navigation, imagery, and perception. Springer, Berlin.

Bertel, S. (2005). Show me how you act on a diagram and I'll tell you what you think. In Papers of 2005 AAAI Spring Symposium (SS-05-06). Menlo Park, CA: AAAI.

Brandt, S.A., & Stark, L.W. (1997). Spontaneous eye movements during visual imagery reflect the content of the visual scene. *J. Cogn. Neuroscience, 9*, 27–38.

Chambers, D., & Reisberg, D. (1992). What an image depicts depends on what an image means. *Cognitive Psychology, 24*, 145-174.

Cowan, N. (1999). An embedded-process model of working memory. P. Shah, & A. Miyake (Eds.), *Models of WM: Mechanisms of Active Maintenance and Executive Control*. NY: Cambridge University Press.

Denis, M. & Kosslyn, S.M. (1999). Scanning visual mental images: a window on the mind. *Cahiers Psychologiques Cognitives, 18*, 409-465.

Engel, D., Bertel, S., & Barkowsky, T. (2005). Spatial Principles in Control of Focus in Reasoning with Mental Representations, Images, and Diagrams. C. Freksa et al. (Eds.), *Spatial Cognition IV.* Springer, Berlin.

Finke, R. (1989). *Principles of mental imagery*. MIT-Press.

Glasgow, J., & Papadias, D. (1992). Computational imagery. *Cognitive Science*, 16, 355–394.

Goldschmidt, G. (1991). The dialectics of sketching. *Design Studies*, *4*:123-143.

Hegarty, M. (1992). Mental animation: inferring motion from static displays of mechanical systems. *JEP: Learning, Memory, and Cognition, 18* (5), 1084-1102.

Hommel, B., Daum, I., & Kluwe, R.H. (2004). Exorcizing the homunculus, phase two: Editors' introduction. *Acta Psychologica*, 115, 99–104.

Ishai, A., & Sagi, D. (1995). Common mechanisms of visual imagery and perception. *Science, 268*, 1772-1774.

Ishai, A., Ungerleider, L.G., & Haxby, J.V. (2000). Distributed neural systems for the generation of visual images. *Neuron*, 28, 979–990.

Johnson-Laird, P.N. (1983). *Mental models*. Cambridge, MA: Harvard University Press.

Khenkhar, M. (1991). Object-oriented representation of depictions on the basis of cell-matrices. In Herzog & Rollinger, *Text understanding in LILOG*. Berlin: Springer.

Kieras, D.E., Meyer, D.E., et al. (2000). Modern computational perspectives on executive mental processes and cognitive control. S. Monsell, & J. Driver, (Eds.), *Control of Cognitive Processes*. MIT Press.

Knauff, M., & Johnson-Laird, P.N. (2002). Visual imagery can impede reasoning. *Memory & Cogn, 30*, 363-371.

Kosslyn, S. M. (1980). Image and mind. Cambridge, MA: Harvard University Press.

Kosslyn, S.M. (1994). Image and brain - The resolution of the imagery debate. Cambridge, MA: MIT Press.

Kosslyn, S.M., & Pomerantz, J.P. (1977). Imagery, propositions and the form of internal representations. *Cognitive Science, 9*, 52-76.

Kosslyn, S.M., & Thompson, W.M. (2003). When is early visual cortex activated during visual mental imagery?. *Psychological Bulletin, 129* (5), 723-746.

Michelon, P., & Zacks, J.M. (2003). What is primed in priming from imagery? *Psych. Research, 67*, 71-79.

Nobre, A.C., Coull, J.T., Maquet, P., Frith, C.D., Vandenberghe, R., & Mesulam, M.M. (2004). Orienting attention to locations in perceptual versus mental representations. *J. Cogn. Neuroscience*, 16 (3), 363–373.

Norman, D.A. (1968). Toward a theory of memory and attention. *Psychological Review, 75,* 522-536.

Palmer, S.E. (1978). Fundamental aspects of cognitive representation. In E. Rosch & B. B. Lloyd, *Cognition and categorization*. Hillsdale, NJ: Lawrence Erlbaum.

Pylyshyn, Z. (1973). What the mind's eye tells the mind's brain..*Psychological Bulletin, 80*, 1-24.

Pylyshyn, Z. W. (2003). Return of the mental image: Are there really pictures in the brain? *Trends in Cognitive Sciences, 7*, 113-118.

Schultheis, H. (2005). Distribution and association: Modeling two fundamental principles in cognitive control. In K. Opwis & I.-K. Penner, *Proc KogWis05*. Basel: Schwabe.

Stevens, A., & Coupe. P. (1978). Distortions in judged spatial relations. *Cognitive Psychology, 10*, 422-437.

Tversky, B. (1993). Cognitive maps, cognitive collages, and spatial mental models. In A. Frank & I. Campari (Eds), *Spatial information theory*. Berlin: Springer.

Tye, M. (1991). *The imagery debate*. Cam., MA: MIT Press.

Verstijnen, I.M., van Leeuwen, C., Goldschmidt, G., Hamel, R., & Hennessey, J.M.. (1998). Creative discovery in imagery and perception: Combining is relatively easy, restructuring takes a sketch. *Acta Psych, 99*, 177-200.

Wilson, M. (2002). Six views of embodied cognition, *Psychonomic Bulletin and Review*, *9*, 625–636.