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Cognitive Architectures: Valid Control Mechanisms for Spatial Information Processing

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Abstract

In this paper, we address the issue of how to identify appropriate mechanisms for cognitive control in a system that incorporates complex, spatial information processing to represent human-level competence. Our solution to this difficult issue is to use a cognitive architecture, which contains well-validated mechanisms for many aspects of human cognition, including cognitive control. This approach allows us to focus on developing theoretically motivated mechanisms for spatial competence that can be integrated into the existing architecture. The result is a more detailed and comprehensive theory, which includes a specification of how other cognitive capacities interact with spatial information processing mechanisms to generate human performance.

Introduction

Accounting for human performance in complex, dynamic environments requires a thorough understanding of the computational mechanisms in the human information processing system. Accurately identifying computational mechanisms underlying human cognition is the primary goal of research using cognitive architectures, like 4CAPS, ACT-R, EPIC, and Soar (Anderson et al., 2004; Just, Carpenter & Varna, 1999; Kieras & Meyer, 1997; Laird, Newell & Rosenbloom, 1987). Cognitive architectures instantiate 'unified theories of cognition' consisting of implementations of theories of the mechanisms utilized by humans in processing information. Since Newell articulated the goal of Unified Theories of Cognition in his seminal book (Newell, 1990), a number of cognitive architectures have been developed, with varying degrees of both depth and breadth of coverage (see Pew & Mavor, 1998 for a review). However, none of these theories provide a serious treatment of human spatial competence.

There is a similar situation with regard to research in the area of spatial knowledge processing. A multitude of theories have been proposed to account for how humans perceive, represent, store, process, and use spatial knowledge in a variety of tasks and situations (O'Nuallain, 1998). These theories also vary in detail, and some of these have been implemented as simulations that can exhibit human-like performance in particular task domains. These theories, however, are typically not implemented as a component of a more comprehensive theory of human cognition.

This, of course, is the very point made by the organizers of this symposium. There are sophisticated theories of the human cognitive architecture, as well as theories of how humans process spatial information to solve particular problems. There remains, however, a significant question regarding how these two areas of research in cognitive science can be linked to provide a powerful means of explaining human cognition and performance across a wide range of tasks and domains where spatial information processing interacts with other components of cognition.

Our research group has taken up the challenge of linking theories of the human cognitive architecture with a broad theory of human spatial competence. We have conducted detailed empirical and theoretical research investigating multiple aspects of human spatial ability (e.g., Gunzelmann & Anderson, 2005; 2006; Lyon, Gunzelmann, & Gluck, 2005), and we have developed computational cognitive models using a cognitive architecture to instantiate explanations for our findings (Gunzelmann, 2006; Gunzelmann, Anderson, & Douglass, 2004; Gunzelmann & Lyon, 2006; Lyon, Gunzelmann & Gluck, 2006). We have used our experience to develop a theory of human spatial competence that is integrated into a cognitive architecture (Gunzelmann & Lyon, in press). In the next two sections, we describe our rationale for using a cognitive architecture, followed by a description of how we have leveraged multiple constraints in considering how to implement mechanisms for spatial information processing within a general theory of human cognition.

Cognitive Control Mechanisms

As we noted above, we address the challenge of integrating cognitive control mechanisms with mechanisms for spatial competence by using a cognitive architecture to represent human cognitive processes, and embedding mechanisms for spatial competence into that architecture. There are two critical questions to be answered with regard to this decision. The first is clear: why use a cognitive architecture? The second question becomes important once the decision has been made to use a cognitive architecture: which cognitive architecture to use?

Why Use a Cognitive Architecture?

The goal of our research, and cognitive science research more generally, is to develop accounts for human cognition and performance that accurately reflect the processes and outcomes observed in human behavior. Cognitive architectures represent an attempt to address these issues in a detailed, quantitative manner. They instantiate comprehensive theories of human cognition and performance that can be utilized to generate quantitative predictions. These predictions can be compared directly to data from human participants.

The real value in cognitive architectures stems from the extensive validation that they undergo and the close match that they provide to human performance data across a range of tasks and domains (e.g., Anderson et al., 2004; Anderson & Lebiere, 1998; Kieras & Meyer, 1997; Just et al., 1999; Newell, 1990). This provides confidence that the mechanisms in those architectures are really instantiating important capabilities of the human cognitive system to encode, process, and store information. The conclusion that we have drawn from this is that cognitive architectures offer the best opportunity to capture important mechanisms and computational properties of human cognition, including cognitive control, that operate in conjunction with mechanisms for spatial information processing when individuals solve spatial tasks.

There are additional advantages to this approach. Besides providing important functionality, cognitive architectures include a variety of assumptions and theoretical commitments that provide important constraints on theory development. These include the timing of information processing activities, what processes are available, and how information is represented. These constraints help to limit the degrees of freedom in developing mechanisms for new cognitive abilities, like spatial information processing, and force consideration of how they will integrate and interact with the rest of the cognitive system.

Which Cognitive Architecture to Use?

There are a number of cognitive architectures that have been developed over the last 10 to 25 years, with different theoretical commitments and varying degrees of support from the experimental literature (see e.g., Pew & Mavor, 1998, for a review). We are using the Adaptive Control of Thought – Rational (ACT-R) cognitive architecture in our research efforts. We find that there are a number of advantages to ACT-R that make it a good choice for pursuing our goals.

ACT-R contains extensively validated subsymbolic mechanisms, which accurately capture the characteristics of human performance by providing for graded variations and stochasticity in human cognition. Its perceptual and motor mechanisms also incorporate decades of research on human visual attention and simple motor actions. In addition, mechanisms in ACT-R have been linked to brain regions, providing converging evidence to support the theory (Anderson et al., 2004). But perhaps the biggest advantage, for purposes of this paper, is ACT-R's separation between declarative knowledge (represented as frame-like 'chunks') and central control processes (represented as productions). This division allows us to precisely define the role of control processes in an ACT-R model of a cognitive task. This is illustrated in more detail below, as we consider how our work on spatial competence ties in with features of the current ACT-R architecture.

Mechanisms for Spatial Competence

Spatial competence comprises a vast literature spanning a variety of particular capacities and mechanisms in human information processing. Therefore, an account of human spatial abilities must be able to address a range of specific abilities within the context of overall cognitive functioning. In addition to breadth, however, accounts of human spatial competence must also be detailed enough to provide explanations for the complex array of abilities and limitations shown by human participants across tasks. These challenging issues require integrating a large research literature. While we do not claim that our account of spatial competence addresses every phenomenon in the experimental and neuropsychological literature, we do provide broad coverage of human spatial abilities.

We have developed our account to be consistent with current understandings of the mechanisms humans utilize to process spatial information combined with representations that support that processing. We incorporate evidence from a variety of sources to constrain our theory. In this section, we describe the major components of our theory by discussing how they have emerged from constraints supplied by the ACT-R cognitive architecture, relevant psychological theory, and neuropsychological evidence.

Architectural Constraints

Cognitive architectures present a theory of the mechanisms of human cognition, which impose important high-level constraints on the types of representations and processes that can be used in implementing new capabilities. ACT-R contains specialized processing modules that operate in parallel to perform the processing involved in different components of human cognition. These modules interact with central cognition through buffers, which hold a single item and make the results of processing in the modules available to the serial production system that lies at the center of ACT-R's representation of cognitive processing.

Importantly, modules in ACT-R represent other crucial aspects of human cognition that are relevant for understanding spatial information processing, like vision, motor action, and declarative memory. These capabilities provide a solid foundation on which to develop a detailed theory of human spatial abilities. To fully integrate our account into this framework, we implement spatial information processing mechanisms as a new module in ACT-R, which represents a specialized processing subsystem in the architecture. The module follows ACT-R convention by incorporating a buffer to allow interaction and communication with the central production system.

ACT-R includes prescriptions for central control of cognition in the form of a serial production system, and specifies how the system interacts with the specialized modules. There is a particular set of requests that can be passed to the modules from the production system, and the output of the modules must be in the form of a chunk that is placed in the corresponding buffer. We adhere to these principles in our account. In fact, these mechanisms play an important role in supporting mental imagery beyond their role in processing abstract spatial information. Creating and transforming mental images is handled through these central control mechanisms in our account.

Though we do not address, in this paper, the timing of operations for the proposed mechanisms, it is interesting to note that ACT-R imposes important constraints on the timing of cognitive actions. The pace of human cognition is prescribed in ACT-R through the 50 ms cognitive cycle time (production cycle time) that has been established through extensive research. This will provide an important constraint as we implement the mechanisms, since the operations must match human performance times while adhering to the architectural constraints regarding the speed of various processing activities.

Finally, while we take architectural constraints seriously, it is sometimes necessary to posit some modifications to accommodate available evidence. In the current version of ACT-R, there are no direct links between modules that allow processing requests to be initiated or for information to be shared directly between modules. This is not the case in our account. We propose that the spatial module has direct connections with at least the motor and vision modules, for planning and executing motor movements (including eye movements) and for extracting spatial information from visual perception. This provides a form of cognitive control that operates outside the central production system and represents an important contribution of this work beyond adding to our understanding of human spatial competence. This also illustrates how adding new competencies to a cognitive architecture can have implications for the architecture itself.

Psychological Theory

Our theory of spatial competence draws heavily on existing psychological evidence. We posit three primary representations of external space: (1) a space centered on the current point of gaze (retinotopic space); (2) a space centered on the body and its orientation (egocentric space); and (3) a space defined by a particular frame of reference or landmark external to the body (environmental space). There is extensive empirical data establishing the psychological reality of multiple representations of space such as these (e.g., Mou & McNamara, 2002; Previc, 1998; Tversky, 2003). In addition, we propose a theory of visuospatial mental imagery that is similar to that of Kosslyn (1994) in that it uses many of the same mechanisms and brain structures as vision.

Our focus in this paper is on the control processes that we propose for translating between these spatial representations. As noted above, a principal advantage of implementing the theory in an empirically validated cognitive architecture such as ACT-R is that many of these control processes have already been developed and tested. For example, a retinotopic representation of space (the visual icon), and processes for selecting and processing information from this space, already exist in ACT-R. We propose to augment these with mechanisms to estimate egocentric locations and to select prominent frames of reference and landmarks to support the representation of location within environmental space. Other processes will tie together the representations of these different spaces and place the result in an 'episodic buffer' that indexes the other buffers and represents an integrated percept. When percepts leave the buffer, they will be stored in a declarative memory with validated mechanisms for learning and forgetting. These design decisions are tied to ACT-R, but their importance and relevance derive from the psychological evidence that has been accumulated to support the functional capabilities they provide.

In our theory, ACT-R's attention control processes are also needed to build new spatial representations, including the kinds of allocentric representations that are sometimes called 'cognitive maps' (e.g., O'Keefe & Nadel, 1978; Tolman, 1948). We strongly disagree with the contention that allocentric cognitive maps are created automatically. There is evidence that the extraction of spatial relationships between objects in an allocentric framework requires attention and cognitive effort. Moreover, attention control processes are not the only control processes required for extracting spatial information. Once the objects in question have been attended, cognitive processes are required to extract inter-object distances and bearings. We propose a spatial module to provide this functionality, which is analogous to current ACT-R modules. Psychological theory will drive the details in these mechanisms, such as error/bias and timing.

Our proposed spatial module contains other control processes as well. For example, there are processes to compare spatial information such as directions and extents. Some processes will do fast qualitative comparisons, while others will be specialized for conducting slower but more precise metric comparisons (cf. Kosslyn, 1994). A particularly important set of control processes in the spatial module are those that perform spatial transformations. Initially we will focus on ‘primitive’ transformations such as translation, rotation, and zooming. Such transformations are vital for solving spatial problems.

Finally, our theory contains control processes for generating and accessing visuospatial images, including processes for reading and writing to the visual icon. In order to account for the transitory nature of visual images, we will extend the activation decay component of ACT-R to the icon itself. We will also introduce a new process – spatial interference – to the representation of visual images. We have found strong evidence for spatial interference in imagery in studies of path visualization (Lyon et al., 2006).

Neuropsychological Evidence

Neuropsychological evidence provides additional support for the account we have developed, but also serves to constrain many of the mechanisms. As noted above, these neuropsychological constraints interact with architectural constraints in determining precisely how the processes account for human performance. These complementary sources of evidence add to the plausibility of the proposal.

Perhaps most important is the research by Kosslyn (e.g., Kosslyn, 1994), which exposes the extensive overlap between vision and visual mental imagery in terms of the cortical areas involved. These findings suggest that many of the same cognitive mechanisms and structures are involved in visual perception and in visual mental imagery. We have developed our account of visual mental imagery with appreciation of these findings. This is illustrated by the lack of a module or a buffer devoted to mental imagery. Instead, the same mechanisms that control visual attention and encoding are used in mental imagery. This includes mechanisms in the vision module, with intense interaction with the spatial module to perform transformations. Neuropsychological evidence drives these hypotheses. For instance, we propose that the mechanisms that perform transformations to visual mental images are situated in the superior parietal lobule, which has been associated with visuospatial working memory operations (Jonides, & Smith, 1997; Smith, Jonides, & Koeppe, 1996; Zago & Tzourio-Mazoyer, 2002).

Another point in our account that was informed heavily by neuropsychological evidence is the set of mechanisms proposed for different portions of the parietal cortex. Multiple proposals have been made regarding the particular functions in this part of the cortex. For instance, proposals for the role of the supramarginal gyrus include directing spatial attention (e.g., Perry & Zeki, 2000), mental imagery (e.g., Knauff et al., 2000), and motor preparation (Decety et al., 1992). All of these functions fit well with the role attributed to this area in our account, which is to estimate spatial values like distance and bearing. This representation of location this enables (following Ungerleider & Mishkin, 1982) is important in supporting action in the environment (as suggested by Milner & Goodale, 1993). Thus, our proposal can serve to unify some seemingly conflicting ideas concerning the role of the dorsal visual processing stream in human cognition.

We also provide an integrative view of the role of the angular gyrus, in the ventrolateral portion of the posterior parietal cortex. The angular gyrus is active in spatial tasks (Baciu et al., 1999; Ardila, Concha, & Roselli, 2000) and in tasks requiring calculations, particularly mathematics (Dehaene et al., 2005; Duffau et al., 2002). We view the role of this part of the cortex as performing ‘magnitude computations,’ which involve combining quantitative information across multiple existing representations. This general function supports some kinds of spatial reasoning as well as mathematical operations.

Finally, the precise role of the hippocampus in our account has been influenced by consideration of the neuropsychological evidence reviewed by Kosslyn (1994). Specifically, in our view the hippocampus has the role of encoding episodic information about visual experience (although it is plausible, even likely, that this incorporates other sensory modalities as well). The representation we posit lines up closely with the description provided by Kosslyn (1994). He states, “…the hippocampus may set up the neural equivalent of ’pointers‘, linking representations that are stored in different loci…” (p. 223).

We believe that the mapping of mechanisms in our proposal to particular portions of the human cortex provides two main advantages. Firstly, we use existing neuropsychological research that speaks to human spatial information processing abilities to inform our account. In this section we have attempted to illustrate some of the ways this has occurred. Secondly, these mappings will provide an important avenue for validating and refining our account. Already, researchers using ACT-R have provided accurate predictions of fMRI data based upon mapping existing components of the architecture to brain regions (Anderson et al., 2003; 2004; Fincham et al., 2002). We hope to utilize this approach, in conjunction with other kinds of empirical data and theoretical evidence to provide converging support for the account we have developed. Next we describe what we think are some of the major benefits associated with this approach, for both cognitive architectures and for theories of spatial competence.

The Benefits

For Cognitive Architectures

Adding spatial competence to cognitive architectures will greatly increase the breadth of tasks to which models built within them can be applied. Historically, cognitive architectures, including ACT-R, have been applied to typical experimental psychology tasks involving verbal or propositional reasoning, simple visual search, or memory paradigms. To the extent that spatial representations are required at all, they tend to be 2D, retinotopic representations. Enriching the variety and power of spatial representations within these architectures is necessary for extending the architectures very far into the domain of spatiomotor tasks. These kinds of tasks are becoming more common domains of application of computational cognitive modeling.

Beyond tasks with obvious spatial requirements, human performance in other tasks and domains often relies on spatial imagery. This capability is currently absent in the major cognitive architectures. Thus, adding mechanisms of spatial competence to a cognitive architecture offers the opportunity to both expand the breadth of coverage, as well as provide more detailed and accurate accounts of human performance in existing areas of emphasis. For example, Fincham et al. (2002) provide a demonstration of how spatial processes may be utilized in solving a favorite task in the cognitive architecture community, the Tower of Hanoi. This model did not provide a thorough treatment of the spatial reasoning involved in this task, but it does help to illustrate that variety of ways that spatial information processing mechanisms are used to facilitate problem solving and planning.

For Theories of Spatial Competence

A theory of spatial competence that consists only of an analysis of the various kinds of spatial representations that people use is, unfortunately, not a complete theory at all. What is missing is a specification of the cognitive mechanisms that construct, coordinate, transform, and use the various spatial representations to perform tasks and how they interact with other cognitive mechanisms. As we have argued, cognitive architectures like ACT-R contain empirically validated control structures that can provide the basis for such a theory. ACT-R's central production system instantiates a theory of central control, and is augmented by control mechanisms for interacting with specialized processing modules. This provides a framework for understanding how mechanism for spatial competence can be integrated with other aspects of cognition. By creating a theory that includes an account of this relationship, one can construct a model that is able to perform tasks of interest. This assures that the theory is sufficient to generate behavior, and greatly enhances the argument that the theory is a plausible representation of human cognition.

Conclusion

Understanding human spatial ability requires consideration of the mechanisms that are responsible for overall control of information processing. In our research we use a cognitive architecture to represent those control mechanisms, and to provide validated and theoretically motivated representations of other critical aspects of human cognition. The ACT-R architecture provides high-level constraints and well-validated mechanisms that establish a foundation for the development of a theory of human spatial competence.

We have only briefly described the theory in this paper, focusing instead on how our decision to use ACT-R has influenced the theory and the mechanisms. A more thorough description of our account is available elsewhere (Gunzelmann & Lyon, in press). In many ways, this account is dependent upon the existing ACT-R architecture and the conceptualization it embodies concerning the structure of human cognition. As we implement our account, we will look to this view of human cognition for inspiration and constraint, just as we will look to empirical and neuropsychological findings in refining the mechanisms we propose. Through this process, we hope to arrive at a cognitively, psychologically, and neurologically valid account of human spatial competence, implemented in the context of a broad theory of human cognition.

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