EPIC Lessons for the Proposed Standard Model of the Mind

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Abstract

EPIC is a computational cognitive architecture developed for modeling human cognition and high-speed performance; on the whole, it is consistent with the proposed standard model. However, lessons learned from using EPIC to account for fundamental phenomena in the empirical psychological literature suggest that the standard model includes unnecessary constraints, in particular, the cognitive seriality and attentional bottlenecks. These standard model constraints are unjustified. They should be relaxed so that the standard model subsumes a broader class of more-plausible cognitive architectures. Two additional lessons learned from EPIC concern plausible characteristics of working-memory and functional relations between cognition, perception, and action. The proposed standard model does not take a position on these issues, and should not until the psychological theory and data are much better developed.

Introduction

The proposed standard model of the mind promises to provide an umbrella framework for many individual computational cognitive architectures, summarizing and synthesizing what they have in common. The prospect of consensus, coherence, and future progress in this space is exciting, but making good progress requires a careful, thorough, scholarly approach.

EPIC was perhaps the first computational cognitive architecture to combine a 50-ms cognitive processing cycle with detailed perceptual and motor processors, and so has much to contribute to this effort. But the standard model does not incorporate some important lessons learned from work with EPIC regarding two major theoretical issues, and also needs to recognize some cautions regarding two additional issues.

In what follows, these four issues will be discussed, and a proposal about future elaboration of the standard model will be provided for each issue. The description of the standard model used in the following discussion is that provided in Laird, Lebiere, and Rosenbloom (in press).

Background on EPIC

The EPIC cognitive architecture is about the *human* mind; it was developed to support modeling of skilled human cognition and performance. Human performance is the area of experimental psychology concerned with how humans can and do perform simple and complex high-speed tasks. It generally overlaps with the study of processes such as skill acquisition, perception, attention, multitasking, and motor control. It generally excludes complex learning, problem solving, natural language processing, and long-term memory. Some classic examples of human-performance phenomena are Hick's Law, Fitts' Law, patterns of between-task interference in multitasking, the psychological refractory period, the cocktail party effect, effects of color-coding in visual search, and many other robust empirical regularities that involve human perception, basic levels of cognition, and action. Correspondingly, EPIC is a system for modeling high-speed skilled human performance; to date, it has incorporated no mechanisms for learning per se.

In terms of Newell's (1990) analysis, the tasks addressed by EPIC are at the middle and lower end of the "cognitive band," where limitations imposed by the underlying architecture would be more apparent than for higher-level tasks.

As discussed more extensively by Meyer and Kieras (1997a, 1997b, 1999; Kieras, 2016), because perceptual/motor constraints and strategy-related task demands are easier to identify and characterize than are the relatively hidden characteristics of cognition, explanations of processing limitations based on these constraints and demands should be given first priority. Correspondingly, EPIC discourages assuming, *a priori*, that central cognitive limitations are the principal source of apparent performance limitations. In accounting for many well-established human-performance phenomena, this principled theoretical approach has allowed us to explore new, parsimonious, and more plausible explanations that are radically simpler and quantitatively more precise than the "conventional theoretical wisdom" about human cognition and performance that was developed in the era of verbal, rather than computational, theorizing in psychology. The lessons learned from our work with EPIC bear directly on steps that should be taken toward further developing the standard model.

Issue 1. What should be Assumed about the Cognitive Serial Bottleneck?

The proposed standard model makes a *cognitive serial bottleneck* assumption that on each ~50 ms cycle only *one deliberate action* can be executed. The assumption that a cognitive processing cycle takes, on average, approximately 50 ms is justified on several complementary empirical and theoretical bases (Kieras and Meyer 1995, 1997; Meyer and Kieras 1992, 1997a, b, 1999; Meyer et al, 1995). However, in the psychological literature, the phrase *cognitive serial bottleneck* implies that only one mental action can be taken at a time; this assumption needs critical examination.

What is a Deliberate Action?

As described, the serial bottleneck and single deliberate actions specification seems to mean that, on each cycle, a fixed package of one or more state changes is made in system components (e.g. working memory and/or motor processors) as a compound response to the current state of the system; only one such package of changes can be selected and applied on each cycle. Yet exactly what the contents of these state-change packages may be, and what mechanisms underlie their selection, remains unspecified at this time.

In EPIC, the procedural memory consists of production rules that are simple condition-action list pairs. On each cycle, all production rules whose conditions are currently satisfied are fired and all of their actions are executed. Furthermore, if there are multiple instantiations of a rule's conditions, the rule actions are executed for each instantiation. The actions can modify the production system working memory (PSWM) or send commands to the motor processors to execute movements. The implementation is very simple; the Parsimonious Production System (PPS) used in EPIC is probably the simplest production system engine in use. Thus, while many rules can execute and modify the system state on the same cycle, allowing *cognitive parallelism*, the rate of firing is limited by the cycle time. Of course, the rules must meet a serial constraint if the actions in a task must be done in a certain order.

EPIC actually conforms to the above definition of a deliberate action: on each cycle, the current state matches some set of rule conditions, and the actions for this set of rules make up the package of state changes. The twist is that individual production rules, being independent of each other, may fire together on some cycles, but not on others, so the actual packages of state changes are "dynamic" combinations of individual-rule packages.

A set of EPIC production rules could be rewritten into a one-rule-at-a-time system simply by starting with the same rules, and then including additional rules that contain the conditions and actions for all combination of rules that in EPIC might fire on the same cycle, and finally modifying the original rules so that that the new ones take precedence when required. This would result in the same state change packages being applied in the same states in both systems. The difference is that the EPIC-style rules would be simpler and fewer in number than the equivalent strictly serial rules. Therefore, EPIC's parallel rule firing is not really a fundamental departure from the standard model, but just a variation on the cognitive cycle theme. This makes it clear that the real point of this assumption is that the system is limited in the *rate* at which state changes can occur: only one change per 50 ms.

Humans do not have a Cognitive Bottleneck

There is a long-standing conventional idea in psychology that humans can only think or do one thing at a time, often described as a *response-selection bottleneck* (e.g. Pashler 1984). But EPIC models can, and sometimes do, select and initiate responses simultaneously for two or more motor modalities in multitasking contexts. In their exhaustive review of the psychological literature, Meyer and Kieras (1997a) argued that there never was a good empirical or theoretical case for a fundamental central cognitive bottleneck; many of the apparent manifestations of a bottleneck are actually due to task constraints, memory or sensory/motor constraints, or especially instructions that encourage subjects to opt for serial processing even though parallel processing is possible (see Meyer and Kieras 1992, 1997a, b, 1999). With proper task design, instructions, and training, subjects can perform simultaneous tasks with no interference (e.g. Schumacher et al. 2001).

By abandoning the conventional bottleneck assumption, and taking advantage of EPIC's cognitive parallelism together with its lack of a hard-wired goal stack, we were able to construct simple and elegant models for high-speed and multiple task performance. In particular, it is simple to represent *executive control processes* as just sets of production rules that interactively supervise and coordinate the execution of specific task production-rule sets (hence the acronym **EPIC** for **E**xecutive **P**rocess - **I**nteractive **C**ontrol). Because executive-process production rules can, when needed, execute simultaneously with those of the specific tasks, which in turn can fire simultaneously, cognitive parallelism allows a straightforward representation of multitasking similar to multi-threaded computer programs. As a result, EPIC provides parsimonious accurate accounts of human performance in a variety of dual-task paradigms (Meyer and

Kieras 1997a, b, 1999; Kieras et al. 2000; Kieras 2007; Kieras and Meyer 1995).

Proposal 1

The misleading *cognitive serial bottleneck* terminology should be discarded and the single-deliberate-act per cycle in the proposed standard model should be specified more precisely as: State changes can only occur at the cycle-time rate. However, various architectures may differ in the definition of how state changes are accomplished, such as in whether single or multiple production rules and their state changes are allowed to apply on a single cycle.

Issue 2. Should the Standard Model Require an Attention Bottleneck in Perception?

The proposed standard model assumes that there should be attentional bottlenecks in perception that constrain the amount of information that can be transmitted by the model's perceptual (e.g. visual) processors to working memory. Also, accompanying this constraint, it is assumed that perception can be influenced "top-down" through information stored in working memory. This specification seems to be based on traditional psychological theory: this attentional bottleneck is similar to the traditional *early selective attention* or "filter" concept in the psychological literature (cf. Norman, 1976) wherein some mechanism limits the perceptual information available to cognitive processing.

Should the initial standard model assume such attentional bottlenecks in perception? At least for now, the answer based on previous work with EPIC is "no". The reasons why are simple and compelling.

There is no doubt that there is a phenomenon of "paying attention" in that humans are capable of controlling their internal processing and behavior based on some aspects of the current environment and not others. Yet this phenomenon can be explained without additional mechanisms for early selective attention. In EPIC, we have succeeded instead with two alternative assumptions: (1) *all* of the current products of the perceptual processors are delivered to working memory, limited only by the peripheral sensory mechanisms, e.g., the retina; (2) production rules for cognition can operate on all available perceptual products currently in working memory. The production rules are then responsible for selecting what aspects of those products to use for selecting responses or other processing. Thus, in the parlance of traditional theories of attention, EPIC's approach could be called a *very late selection* concept. Unlike the present standard model, EPIC has and needs no attentional bottleneck that limits what information from its perceptual processors is available to cognition.

Why doesn't this approach result in a vast information overload on cognition? The answer is that the sensory and perceptual mechanisms have their own limitations, unrelated to "attention" per se, so even if they supply all of their products directly to cognition, the amount of such information is already strongly limited: enough so that it is reasonable for cognition to have access to all of it. Note that the perceptual contents of PSWM consists of all of the *current* products of perception; if an object disappears from the external visual scene, its information is removed from PSWM.

The significance of this analysis for modeling of human performance is that "attention" has proved to be a very slippery concept to nail down empirically and theoretically. By not presupposing a perceptual attentional bottleneck, EPIC replaces an ill-defined concept with very straightforward well-justified explanations based on known sensory and perceptual capabilities. This can be illustrated by EPIC modeling in the domains of audition and vision.

Modeling the cocktail party effect in audition

The early selection model of attention was first introduced to account for results from studies of the *cocktail party effect*, which occurs in two-channel listening tasks where people hear two simultaneous speech messages but must respond to only one of them. Such tasks have been studied for decades since Cherry's (1953) pioneering experiments and many phenomena have been described (e.g. see Yost 1997).

In recent work with Gregory Wakefield, EPIC models were developed using the very-late-selection principle (Wakefield et al. 2014; Kieras et al. 2016a; Kieras et al. 2016b) to account for important effects in two-channel listening tasks. The auditory perceptual system must segregate the two streams of input, associate portions of the input to each stream, and recognize the words in the input. The simultaneous presentation of the speech messages causes interference (termed *energetic* and *informational* masking in the psychoacoustics literature) that in our models, results in representations of the input that may have missing content and incorrect associations of word content to streams. All of the available information is presented to cognition, where production rules may be able to infer some of the missing information and decide how best to respond to satisfy the task demands. Our current models account for almost all of the variance in very detailed data involving manipulation of speaker voice characteristics, relative loudness, and spatial location, all without any attentional selection of the input supplied to cognition.

Modeling visual search

A second thread of development of attention theory is in the context of vision, in particular, visual search. Perhaps the most influential study was Treisman and Gelade (1980) who claimed that simple single-feature searches could be done with pre-attentive parallel mechanisms that are both fast and only slightly affected by the number of objects. In contrast, search for the conjunction of two visual features required the serial application of attention to "bind" the separate features together into an object representation. This serial selective attention mechanism resulted in search times that steeply increase with the number of items. However, this appealing hypothesis was thoroughly refuted in the subsequent flood of experiments that demonstrated many cases of parallel-speed conjunctive searches (e.g., Wolfe, Cave, and Franzel 1989), undermining the original claim of a serial attentional bottleneck in such tasks.

The remarkable thing about this branch of the visual search literature is its long-lasting insistence that there was no involvement of eye movements and early vision limitations such as limited peripheral resolution. Note that moving the eyes was not the original intended meaning of top-down control and early attentional selection, which are supposed to be purely cognitive influences on perception. In contrast, the current state of the empirical literature is that the various effects on visual search rates are due to a combination of whether eye movements are required and early-vision perceptual limitations such as limited peripheral resolution or crowding effects (e.g. Carrasco et al. 1995; Findlay and Gilcrest 2003; Wertheim et al. 2006; Rosenholz 2016; Poder 2017; Hulleman and Olivers 2017).

The EPIC models for visual search (Kieras and Marshall, 2006; Kieras 2009a, 2016; Kieras and Hornof 2014) make a simple assumption: All of the products of the visual perceptual system are represented in PSWM, but the amount of the information is limited by the early-vision mechanisms. The production rule strategy for performing the task use the available information to decide where to move the eyes next, which results in additional information about the objects becoming available. The information necessary to complete the task eventually appears in PSWM, and other production rules can make the necessary response.

Thus, in EPIC, there is no selective attention bottleneck; there are only perceptual limitations and the cognitive strategy for working around these limitations to complete the task.

Proposal 2

The attentional bottleneck terminology should be discarded as misleading. The traditional bottleneck assumption, and the claim that the contents of the perceptual buffer depend on some kind of cognitively-controlled attention mechanism, may actually interfere with attempts to understand perception because it obscures the importance of sensory/perceptual limitations. It should be replaced with language such as: Cognition has access to perceptual products from the perception modules; different architectures will have different specifications of how much and what types of information are represented there, and the conditions under which it is present.

Issue 3. Should Working Memory be Psychological Working Memory?

A central component in the proposed standard model is *short-term working memory*. Although no constraints are currently specified, again the terminology adopted in the standard model implies similarities with conventional psychological concepts. However, making this similarity more explicit would be a mistake.

We have taken care that EPIC's production system working memory (PSWM) is not identified with the concept of *working memory* as used in cognitive psychology. Our rationale is that in fact, the term has been extremely broad and vague. For example, the Miyake and Shah (1999) symposium volume on working memory contains numerous diverse, and sometimes contradictory, concepts of working memory that have few features in common other than being temporary.

Rather than oversimplify the situation, we argued that the production rule strategies for tasks require a variety of types of information to be kept in some kind of quickly accessible and temporary store (Kieras et al. 1999). We allowed different kinds of PSWM information to have different properties developed from modeling tasks in which relevant perceptual and motor mechanisms were taken into account. For example, we modeled verbal working memory by implementing the classic phonological loop in terms of auditory memory and covert speech with a strategy that attempts to maintain a rehearsal chain; we showed how the capacity limits observed in memory span tasks followed from these constraints (Kieras et al. 1999). Meanwhile, our models for visual search assume a visual working memory with very different properties (Kieras 2006, 2009a; Kieras and Hornof 2014). Thus, PSWM in EPIC does not correspond to a particular concept of psychological working memory.

Proposal 3

Constraints should not be added to the standard model about characteristics of working memory that are based on current psychological concepts of working memory. The psychological theory of working memory is still under development, and different kinds of information may have very different properties.

Issue 4. How should the Standard Model deal with Spatiality in Perception, Cognition, and Motor Control?

The proposed standard model specifies that the motor modules accept commands and carry out movements, but imposes very few constraints, which is wise because motor control continues to be seriously under-developed in psychology. However, some of the details of movement planning, initiation, and execution make a substantial difference in how tasks are performed, and how movements are controlled at the cognitive level. For example, originally EPIC implemented the concept from Rosenbaum (1991) that movements are specified in terms of elementary features that take time to program; cognition can program motor processors with features in advance to prepare movements for faster initiation. However, this uniform concept in EPIC had to be modified when spatial stimulus-response compatibility effects and the properties of visually-aimed spatial movements were taken into account (Kieras 2009b). Apparently, aimed movements, both manual and ocular, could be made directly to visual targets without the previously assumed feature preparation. This suggests that when spatial location is involved, there is a privileged connection between some motor systems and the visual system.

An additional example of spatial factors in cognition and action is the very strong effects on learning and performance of the spatial location of response effectors in choice reaction tasks (Alegria and Bertelson 1970; Welford 1971; Lacey et al. 2004). Note that most studies average over individual S-R pairs, thus hiding this remarkably strong effect.

Finally, at the top level, the human mind contains the *action system* described by Milner and Goodale (1995) and Rossetti and Pisella (2002), which is the primitive, partly autonomous subcognitive system in the brain that supports navigating and interacting in spatial environments. The basic phenomena are that visually-guided spatial movements can be made without real-time cognitive control or cognitive processing of the visual information. This means that a great deal of spatial visual-motor computation has been offloaded from cognition into a separate system.

Kieras (2016) suggests that the action system is a complex system in its own right, essentially a "noncognitive" processor roughly as powerful as how we normally think of the cognitive processor. A complete architecture for the human mind will need to have the action system represented in addition to the usual cognitive architecture components.

Proposal 4

At least for architectures that support modeling of human performance, it will be important to develop a coherent and comprehensive treatment of how spatiality is represented and used in the architecture. Meanwhile, the standard model should not set premature constraints on how movement is specified or represented in learning, nor insist that all of the work of planning and executing movements in space be performed by cognition. Rather it should allow possible future major additions in the form of an integrated perception-action subsystem.

Conclusion

The lower levels of the cognitive band are likely to be a stronger source of constraints on the details of a cognitive architecture than the higher levels. The success of EPIC models at these lower levels justifies its fundamental assumptions that differ from traditional psychological theory that developed in the era of verbal theorizing. These assumptions contradict some key constraints in the proposed standard model, and warn against adding constraints in other areas. Thus, the lessons learned from EPIC should be included to provide wider possibilities in the further development of the standard model of the mind.

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