Anticipatory Thinking in Cognitive Architectures with Event Cognition Mechanisms

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Abstract

There is no comprehensive theory for how anticipatory thinking capabilities emerge from cognitive processes. Event cognition describes some human anticipatory thinking capabilities, but is not integrated with general theories of cognition. We use Event Segmentation Theory to motivate a theoretical account for how the Soar cognitive architecture and the Common Model of Cognition can be extended to support event cognition, and in turn account for anticipatory thinking processes and reasoning. Current cognitive architectures appear to require additional mechanisms to create computational models implementing this theoretical account.

Anticipatory thinking (AT) is an emergent cognitive functionality. AT has been described as the ability to proactively guide attention and take preparatory action (Klein, Snowden, and Pin 2011). We propose the development of a cognitive theory of human AT functionality based on the combination of event cognition research and research on cognitive architecture. A general cognitive theory of human AT could predict how human AT changes as a result of specific training, experience, environments, and/or access to different kinds of knowledge. Additionally, with a theory of how AT is realized in human cognition, AT can be implemented in artificial systems with similar computational structure.

Event cognition research studies the human ability to perceive, understand, and remember everyday events (Radvansky and Zacks 2014). This research has the potential to provide insight into how AT is realized in human cognition. Event cognition research hypothesizes that humans simultaneously perceive and predict events to guide attention in real-time and also use the same mental representations both for guiding action and comprehending the actions of others (Richmond and Zacks 2017). We propose that these properties of human event cognition are also core aspects of AT.

While there is a neuro-physiological account for some aspects of event cognition (Franklin et al. 2019), event cognition is not currently integrated with a general theory of cognition. Such an integration would allow an understanding of how additional cognitive processes enable the decision making and response preparation necessary for functional AT.

Including mechanisms for human-like event cognition in cognitive architectures can provide such an integration to better understand how human AT functionality emerges from cognitive processes. Cognitive architectures are theories for the fixed computational mechanisms that underlie cognition. While many architectures initially made different and conflicting assumptions or described isolated aspects of cognition, over time a consensus has emerged. This consensus is formalized through the Common Model of Cognition, which is a theoretical specification of the computational processes underlying cognition (Laird, Lebiere, and Rosenbloom 2017). Extending the Common Model to include event cognition provides a model for how AT is realized in human-like cognition.

Event Segmentation Theory

With support from observations of human behavior (Eisenberg, Zacks, and Flores 2018), memory (Sargent et al. 2013), and brain activity (Baldassano et al. 2017), Event Segmentation Theory (EST) has become the dominant theory for event cognition. It provides the process model depicted in Figure 1. The theory is that humans understand their experience in terms of discrete segments of experience called events (Zacks and Swallow 2007). Similarly to AT as a form of sense making, the segmentation of experience into events is considered part of ongoing comprehension.

The theory proposes that humans use *mental models* for events. These models are divided into *event models* describing specific situations and *event schemas* describing the

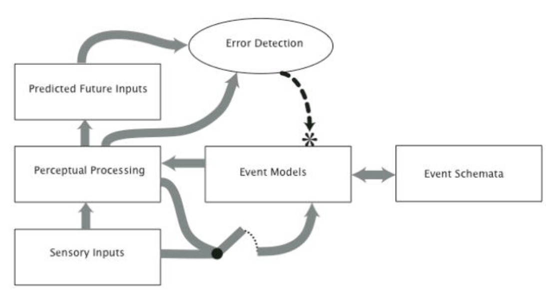

Figure 1: The structure of the Event Segmentation Theory process model. (Reproduced from (Zacks et al. 2007).)

commonalities for a given type or class of event (Radvansky and Zacks 2011). A mental model is an abstract representation of a situation used for reasoning. It is composed of individual elements (such as entities and relations) that can be rearranged and that are grounded to perceptual representations. An example of a mental model is representation of an animal in terms of an arrangement of body parts. An event model is a mental model for a specific event. Event models are entities and relations describing a particular span of space and time, but usually in a single location. Event models include labels, spatial relations, and relations that convey a temporal ordering. An event schema is a mental model for a class of event models, where multiple event model instances belong to the same event schema. As an example, a specific memory for having watched a film is an event model while an understanding for how a visit to the theater generally proceeds is an event schema. Event models are created by specializing event schemas to a set of observations. Both representations contain causal relations between changes.

During everyday tasks, event models predict changes to the current situation and guide perceptual processing (Zacks et al. 2007). For example, predictive-looking describes the human behavior of looking to where changes are expected to occur. This ability is diminished near the boundaries between events (Eisenberg, Zacks, and Flores 2018). We use the term *working event model* to refer to event models used to describe the current situation (Radvansky 2012).[1] As shown in Figure 1, when a prediction fails, a prediction error is detected and signals that the working event model does not match the situation. In this case, humans create a new event model to interpret the situation by retrieving an event schema that matches to recent sensory input and creating new expectations.

The EST process model focuses on descriptions of ongoing perception for a directly-experienced event. Anticipatory thinking appears to require reasoning that includes expectations for future events beyond short-term expectations for the currently-experienced event, which motivates our account of event cognition using a cognitive architecture.

Event Cognition in Soar

Cognitive architectures are computational models for the fixed mechanisms and processes that underlie cognition. These architectures act as theories for the functionality provided by different memory systems and cognitive processes. They also can be used to implement artificial cognitive systems. However, these architectures do not currently exhibit the event cognition functionality found in humans.

EST specifies representations of events, but does not describe how (together with other mental models) they are encoded, stored, or retrieved from memory systems, nor the reasoning processes that use them. Cognitive architectures can extend event cognition theory by including the memory systems and reasoning that EST lacks. An intriguing possibility is to explore the integration of EST with the Common Model of Cognition. Unfortunately, due to its abstract nature, the Common Model does not provide the level of detail necessary for implementation of running computational models. Instead, we use Soar, an architecture consistent with the Common Model, as a model for how cognitive architectures (and, more abstractly, the Common Model) can realize event cognition functionality.

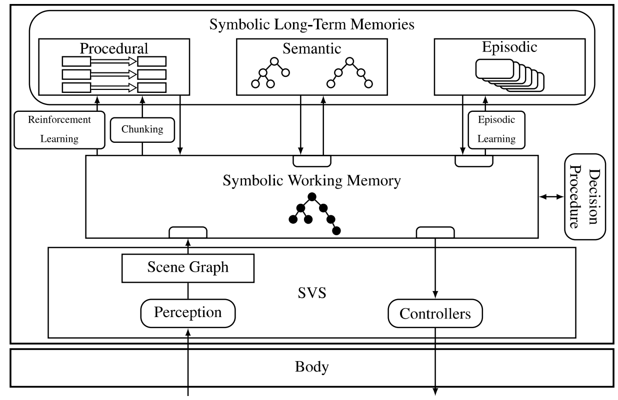

Figure 2: The structure of the Soar Cognitive Architecture.

Soar models cognition as a series of deliberate actions that perform reasoning steps, retrievals from long-term memories (episodic or semantic), or motor actions (Laird 2012). The actions are initiated by knowledge retrieved from procedural memory, based on the contents of working memory. Working memory contains a symbolic representation of the current situation (derived from perception and internal reasoning), current goals, and intended actions. A cognitive cycle, which consists of processing input, a deliberate decision, and output to the motor system, maps onto approximately 50 ms of human behavior. This low-latency perception and action cycle provides reactivity to both changes in perception and knowledge retrieved from long-term memory. Complex behavior arises from a sequence of cognitive cycles. Figure 2 shows Soar's structure.

To theoretically model event cognition phenomena using Soar, we map the different mental representations specified by EST to Soar's memory systems. Both event schemas and event models contain relational information and lack perceptual detail. They contain entities and relations for describing an event, which are directly supported by the memory systems of Soar. We assume that event schemas and models have relations depicting changes over time, allowing for representation of future state using these relations. The association of event schemas and event models to the memory systems of Soar is depicted in Figure 3.

The working event model is grounded to ongoing action and perception. It is also used in reasoning about the current situation. To provide this functionality, it must be composed of working memory structures and also representations of perception and action. Figure 3 depicts the working event model within working memory, but specifically as including the representations for perception and control.

[1] In EST, event models are hierarchical. Thus, a single working event model describes the current situation, but it can contain nested sub-events that are event models for smaller space and/or shorter segments of time.

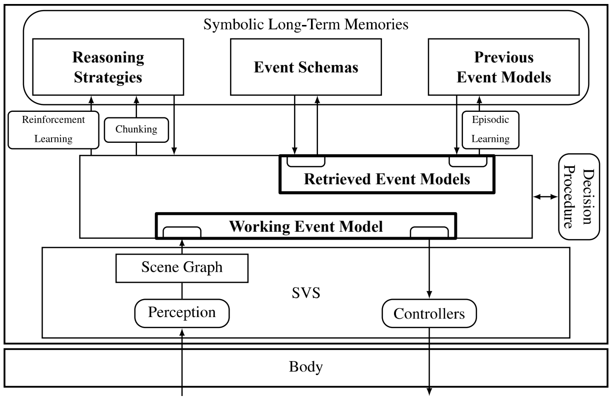

Figure 3: Soar's memory systems populated with event cognition knowledge.

In contrast, event models representing prior situations and event schemas require long-term storage and need to be stored within the long-term declarative memory systems in Soar. Event models have been hypothesized as the episodes of episodic memory in humans (Ezzyat and Davachi 2011). In Soar, they naturally belong in episodic memory as a result of automatic storage of working event models in working memory. In Soar, semantic memory provides a means to knowledge independent of the exact situation in which it was learned, and thus, as shown in Figure 3, is where event schemas are stored. To be used in reasoning, these stored event schema and model representations must be retrieved into working memory.

By assigning the mental representations described by EST to the memory systems of Soar, we can replicate the EST process model using the mechanisms available in Soar. Perception feeds into working memory and cues for retrieval of an event schema from semantic memory. This event schema can then be grounded to perception and action to form a working event model that is compared to perception. Then, the ways in which event models within working memory can be used for reasoning depends on the reasoning strategies within procedural memory.

The contribution of this model is that reasoning is not limited to only performing the EST process model loop of maintaining a working event model to describe the present. In situations where an agent performs long-term planning (representing and reasoning about the future beyond the current event), additional event models that represent expected distant future states are retrieved into working memory to be used in reasoning. Also, previous event models can be retrieved for comparison of a specific previous situation to the present for case-based reasoning. These additional reasoning capabilities arise from the general cognitive mechanisms available for using and manipulating stored event knowledge.

Cognitive Modelling of Anticipatory Thinking

The cognitive mechanisms available for manipulating event representations in Soar's memory systems enable modelling of AT processes. Anticipatory thinking is associated with three distinct processes. These processes are "*recognition* of a situation based on current cues derived from previous experience, *extrapolation* of a system state to a different state, and *construction* of a mental model of the system based on variable evidence" (Geden et al. 2019). These processes have also been referred to as "pattern matching," "trajectory tracking," and "convergence," respectively (Klein, Snowden, and Pin 2011). To explain how the proposed model supports these processes, consider the following scenario:

> You observe someone else printing papers. You recognize that they are likely creating exam packets. You infer that they will need to staple these papers together. You observe that they do not have a stapler. You fetch a stapler to help them achieve their goal.

The process of *recognition* uses cues from the present situation to retrieve knowledge for similar situations from the past. An example of pattern matching is the recognition of someone in the act of creating exam packets by observing them in the copy room printing papers. In our model of event cognition, there are two forms of recognition. When there is knowledge for a type of event that generalizes multiple specific events, this is stored as an event schema in semantic memory. Recognition can take the form of retrieval of an event schema from semantic memory based on the cue that someone is printing papers. However, if such knowledge is not available, there can also be knowledge of a specific similar event from the past. Recognition can thus also result from retrieval of an event model from episodic memory.

The process of *extrapolation* involves not only predicting future states, but also guides action in conjunction with predictions to realize a desired future state. An example is catching a ball, but extrapolation also refers to narrative understanding and prediction (Klein, Snowden, and Pin 2011), not only to the ongoing real-time prediction of perception performed by working event models. An example of such extrapolation is creating the expectation that someone will need a stapler. They may not currently need a stapler to proceed, but they are doing a task which involves later use of a stapler. In human event cognition, event models are also used to simulate future events consistent with episodic future thinking (Richmond and Zacks 2017; Szpunar, Spreng, and Schacter 2014). Additionally, event models can be used to understand indirectly experienced narratives and situations (Radvansky and Zacks 2011). Using this as inspiration, in our model extrapolation results from the structure and contents of the retrieved schema. When the schema for creating exam packets is retrieved, this knowledge includes causal relations and expected future state. Because this future state is currently retrieved to working memory, it is available for reasoning despite this state not yet having occurred. This ability to use a representation of future state in current reasoning provides AT extrapolation.

Construction is the ability to reason about and create mental models for a situation. We model this as reasoning about the conditions and connections between events. When recognizing that someone is involved in a task which will require a stapler in the future, we have the ability to integrate an event model for delivery of that stapler with an event model for someone else's future use of the stapler, allowing us to coherently model both our delivery and the satisfaction of their task. This ability to evaluate how our planned actions will impact external events in the future is an example of conditional AT which uses causal relations between event models. Soar supports construction through relations in working memory that link different event models. The model associated with preparing exams and the model for fetching a stapler can be combined to form a composite mental model within working memory.

These processes do not directly map to individual mechanisms in the architecture, but are supported by existing mechanisms and representations. In combination, these processes enable different types of AT reasoning.

Types of Reasoning for Anticipatory Thinking

In EST, event models are updated following misprediction. However, events often proceed as expected with little additional reasoning required to guide action. During these periods, proactive reasoning can be performed to prepare for future events without jeopardizing reactivity in the present. This is one case in which it is possible to perform AT.

Alternatively, an agent may have a goal, but does not have sufficient event schema knowledge for how to realize its goal. (The knowledge may not exist as an event schema in semantic memory or it may be difficult to cue for retrieval.) In this case, an agent needs additional knowledge to proceed.

In either of these cases, an agent can perform additional types of reasoning beyond the default EST behavior of retrieving a single event schema to update the current working event model. Soar provides mechanisms to account for these types of additional reasoning.

In Soar, agents can detect when their knowledge for the current situation is insufficient to select additional actions. These situations are architecturally-recognized as *impasses*. Note that this is distinct from misprediction. An agent could have a good model of the environment, but not have the knowledge for how to act or how the currently available actions will impact goal achievement. To resolve these impasses, additional knowledge is brought into working memory to guide action. These moments during which it is unclear which actions to perform (either in the present or in preparation for the future) provide opportunities for AT.

Geden et al. describe three types of anticipatory thinking that depend on the aforementioned AT processes: *prospective branching*, *backcasting*, and *retrospective branching*. Using our model of event cognition, these types of anticipatory thinking emerge from general cognitive processes in Soar (and potentially in other cognitive architectures) that support search-based planning and means-ends analysis.

Prospective branching refers to imagining potential future states, given the current state. Search-based planning is an analogous form of reasoning in which an agent imagines potential futures by simulating actions using action models. When an agent has a goal, but the agent does not have knowledge for which actions will accomplish this goal, an agent performs search-based planning to simulate how available actions would change the situation.

Backcasting is reasoning that finds ways or paths to a particular future state. Means-ends analysis performs similar reasoning in Soar. In order to determine a path to a future state, reasoning proceeds backwards from the future state, attempting to create a plan of actions that can achieve the future state, while recursively attempting to achieve the preconditions of those actions until a path is found with preconditions that are satisfied in the current state.

Retrospective branching also involves determination of the preconditions for achieving a given state. It can be implemented with means-ends analysis, but using the present state as the initial cue for retrieval instead of a future state.

Traditionally, these forms of reasoning leverage action-model knowledge stored in procedural memory. Action models feature preconditions and causally-related effects. However, AT includes reasoning for distant or indirectly-experienced states while action models describe local experience. Using event schemas and event models generalizes the aforementioned forms of reasoning to perform AT[2].

With each of these methods, the same underlying architecture is used and reactivity to the current situation is maintained by incremental processing. As in human AT, if an action must be taken in the moment, this reasoning may be interrupted or forgotten. Additionally, as in human AT, this reasoning can fail if there is simply insufficient knowledge available in memory. The main distinction between existing reasoning methods and the provision of AT functionality is the use of event models as the knowledge for simulating the environment. Thus, the main challenge in implementing AT in this model is learning and encoding event schema knowledge that includes causal relations and preconditions.

Future Work and Implementation

So far, we have only considered a theoretical specification. Soar, and potentially other cognitive architectures, implement the forms of reasoning described above. However, cognitive architectures do not generally contain the necessary mechanisms to implement event cognition. A full implementation of event cognition includes, but is not limited to: automatic learning of event schemas, event model misprediction or surprise detection, memory for the past in terms of event models, and mechanisms for retrieving event models and event schemas based on their contents (Franklin et al. 2019). A full account of event cognition also describes how event models and schemas are used for reasoning and not just the constraints placed on memory systems.

Other cognitive architectures besides Soar have included mechanisms that partially support event cognition. These architectures include Sigma, ACT-R/e, and Icarus.

Sigma has mechanisms for detecting surprise (Rosenbloom, Gratch, and Ustun 2015) and misprediction (Rosenblooma, Demskia, and Ustuna 2017). Each can be used as a measure for detecting when to use a new event model to characterize the current situation. Sigma also includes some episodic memory functionality (Rosenbloom 2014).

[2]This is similar to the approach taken by Cardona-Rivera et al. that used a planning-based knowledge representation for narratives.

ACT-R/e has been used to model some aspects of event cognition explicitly (Khemlani, Harrison, and Trafton 2015). The ACT-R/e implementation of event boundary encoding supports aspects of segmentation-based retrieval.

Icarus supports event cognition with a dedicated episodic memory store (Ménager and Choi 2016) and a measure of expectation violation explicitly presented as providing event segmentation (Ménager et al. 2018). Icarus has been evaluated for its ability to model human memory for events (Ménager, Choi, and Robins 2019).

These architectures motivate extending the specification of the Common Model to provide a formal account for event cognition and anticipatory reasoning. Limitations to the Common Model include insufficient specification of how query mechanisms retrieve event models and event schemas, no event schema learning, little evaluation of error detection or misprediction mechanisms for event models, no delineation between episodic and semantic memory, and no direct specification for what generally constitutes event cognition functionality. A specification of event cognition functionality in general (including reasoning, memory, and learning) could motivate further implementation and evaluation among architectures.

Additional support for event cognition in cognitive architectures will allow for computational models of human anticipatory thinking performance. This modelling depends on integrating event representations with existing agent reasoning for achieving goals. Pursuing this specification and implementation will provide further constraint into which architectural mechanisms and agent knowledge are useful – both for modelling humans and for implementing AT functionality in artificial systems.

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