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# Neural modeling of sequential inferences and learning over episodic memory

Budhitama Subagdja *, Ah-Hwee Tan

*School of Computer Engineering, Nanyang Technological University, Singapore*

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ABSTRACT

Episodic memory is a significant part of cognition for reasoning and decision making. Retrieval in episodic memory depends on the order relationships of memory items which provides flexibility in reasoning and inferences regarding sequential relations for spatio-temporal domain. However, it is still unclear how they are encoded and how they differ from representations in other types of memory like semantic or procedural memory. This paper presents a neural model of sequential representation and inferences on episodic memory. It contrasts with the common views on sequential representation in neural networks that instead of maintaining transitions between events to represent sequences, they are represented as patterns of activation profiles wherein similarity matching operations support inferences and reasoning. Using an extension of multi-channel multi-layered adaptive resonance theory (ART) network, it is shown how episodic memory can be formed and learnt so that the memory performance becomes dependent on the order and the interchange of memory cues. We present experiments as a proof of concepts to show that the model contrasts sequential representations in semantic memory with those in episodic memory and the model can exhibit transitive inferences consistent with human and animals data.



## 1. Introduction

Episodic memory is a particular type of long-term declarative memory that stores specific past experiences. In contrast, the other type of declarative long-term memory is semantic memory which stores general facts, concepts, or rules. Episodic memory plays a key role in binding many aspects of human everyday lives. It provides the extension of perceptions beyond momentary perceptual ranges by providing past relevant episodes. Studies in neuropsychology have shown that damages in episodic memory caused by lesions in hippocampal areas in human and animals impair significant cognitive capacities [1–3]. Most of these studies agreed that episodic memory and hippocampus deal with declarative retrieval of the past specific experienced events apart from other non-declarative memory. Without the episodic memory, a situation cannot be properly referred to in its past context. This kind of cognitive deficit resulting from episodic memory impairment indicates the main feature of hippocampus or episodic memory for rapidly storing and binding daily events for latter use [4].

Various computational models have been developed to explore different aspects of episodic memory. Many contemporary models suggest that the hippocampus works as conjunctions of specific patterns coming from different stimuli [5–8] before they are recalled for latter use or consolidated to more permanent forms. Various architectures and approaches have been proposed to model the sequential representation for episodic memory using statistical models (e.g. [9]), connectionist architectures (e.g. [10,11,5]), symbolic models (e.g. [12–14]), and probabilistic matching (e.g. [15]). These models have demonstrated that sequential structure of episodes can be represented, stored, and recollected later based on memory cues. Most of these models assume a standard functionality of episodic memory that a sequence of events can be learnt rapidly at once and recalled later based on a memory cue consisting of a subsequent presentation of events partially of the original sequence. This assumption implies that hippocampus, as the main part of episodic memory in the brain, only performs pattern completion to recollect or predict the complete episode based on the first few subsequent steps of the episode. It has been suggested that hippocampus should interact with its surrounding cortical areas in order to realize the complete functionality of episodic memory [8].

However, beyond memory recalls, there are evidences showing that hippocampus handles different temporal contexts of memory tasks, cues, and entries supporting further processes of decision making, reasoning, and learning in general. The accuracy of retrieval

* Corresponding author.
*E-mail addresses:* budhitama@ntu.edu.sg (B. Subagdja), asahtan@ntu.edu.sg (A.-H. Tan).

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incidentally depends on the relative position of cues, lags between memory items, and the context from previous operations [16–21] allowing it to construct novel patterns and handle noisy, corrupted, or low fidelity memory cues.

Understanding how does episodic memory work, the structure of information stored, its distinctions and relationships with other types of memory (e.g. semantic or procedural memory) can provide useful insight for building an intelligent computational agent that autonomously explore and learn from the environment. Aside from its value to gain more knowledge about human memory, the model of inference and reasoning with episodic memory may guide the design towards more efficient reasoning and decision making of an intelligent agent architecture.

In this paper, a model of episodic memory emphasizing its support in inferences and decision making is presented. The model comprises the long-term memory buffer resembling hippocampal systems. In contrast to other more realistic models of episodic memory, the proposed model simplifies the neural structure of hippocampus but caters different memory functionalities supporting inferences and learning. The model is made as a multi-layered and multi-channel Adaptive Resonance Theory (ART) neural network. However, to handle temporal or sequential order, it relies on a special encoding wherein temporal events are captured as analog patterns both in neural activations and synaptic weights. This emphasizes that a memory item is stored with a magnitude level reflecting its order relative to other items in the sequence. This allows event instances, memory cues, and sequential constraints to be expressed and manipulated through pattern matching and completion operations. This special neural network model also supports dynamic adjustment of matching parameters enabling explicit indications of its recognition level and similarity of the retrieved item. Moreover, the model inherently supports incremental learning in which neural codes for events and episodes can be dynamically allocated on demand based on the novelty in the incoming memory entries. This last feature provides advantage over other sequential memory models based on sequential chaining inference models like those with probabilistic or recurrent auto-associative methods.

This paper provides theoretical accounts of the structure of episodic memory and its supported operations. The characteristics of sequential representation and processing in hippocampus are contrasted with the ones in other kinds of memory like semantic and procedural that may rely on probabilistic chaining mechanisms. Case studies are shown to confirm the characteristics of episodic memory to support inferences in comparison to semantic/procedural memory. The case studies investigate the use of episodic memory for transitive inferences and temporal context formation for learning and reasoning. The results show that the characteristics of the proposed model are consistent with human and animal data.

The rest of the paper is structured as follows. The next section provides an overview of studies on episodic memory and hippocampus. The next section reviews related works of modelling episodic memory. Section 3 describes the proposed episodic memory model. Section 4 describes the implementation and case studies of the proposed model to investigate the transitive inference and contextual alternation learning capabilities.

## 2. Related work

Studies with computational models have revealed particular roles of episodic memory in supporting cognitive functions. The models are made to study different aspects of memory according to the interests and research objectives. Different aspects of memory like scalability [10], performance [11,22], and similarity with human memory performance in weighing memory traces [23–25,9] have been the main concerns.

In the context of computational agents in virtual environment, the survivability of a situated agent can be improved since a wide range of cognitive functions from sensing, reasoning, and learning is supported by episodic memory [12,13]. The incorporation of episodic memory may also add the realism of an artificial character. As a source of autobiographical record, episodic memory provides the necessary information about past experiences that can be useful to interact with the environment and communicate with other agents [26–28].

However, most of the aforementioned models still assume a limited set of memory operations. The common process consists of reconstructing the complete memorized episode, given a cue as a partial representation of a state or an event snapshot. The recalled sequence may be produced as a series of readout starting from the first cue presentation. For example, the episodic memory extension of SOAR cognitive architecture [13] uses a simple cue-based retrieval to recollect an episode and the complete sequence can be reconstructed by retrieving the next (or previous) element of the episode one after another in a subsequent order.

Other works on computational model have looked at possible neural structures wherein episodic memory is resided in the brain. Gluck and Myers suggest the neural network structure of episodic memory and more-permanent semantic memory showing how both interact to robustly learn and store information [29]. A similar but more complete model covers the memory consolidation process from episodic memory to more permanent abstract form in semantic memory [6]. The model suggests that episodic and semantic memory work complementarily side by side and learn independently in different rates. Episodic memory captures specific patterns rapidly in a single pass while semantic memory learns general facts and abstract knowledge in a slow and gradual manner. The model explains how complex and abstract knowledge can be formed in semantic memory based on the specific experiences captured in episodic memory.

Similarly, O'Reilly and Rudy argue that the episodic memory functionality can be supported by the interaction between hippocampus and some surrounding cortical areas [8]. They suggest that solving conjunctive learning tasks does not totally require hippocampus but can be partially supported by some cortical areas. The complementary model of cortical/hippocampal memory system puts aside the idea of hippocampus as a part of declarative memory and suggests that the hippocampus is only important for incidental tasks. Although the model considers the contextual relations to be substantiated as recurrent connections in the hippocampal CA3 area, it is still assumed that the sequential relations in cognitive tasks are provided explicitly as additional inputs to hippocampus.

The cortical/hippocampal interaction model can explain the associative distance effects [17] in which the performance of accurately retrieving the correct memory entries depends on the lags between cue items wherein other monolithic neural architectures still fail to explain this phenomena. It is suggested that the distance effect is actually influenced by the cortical parts of the memory system that learn to select the stimulus presented as the input to the hippocampus. Another work look at the sequential relations between items and contexts for retrieval in hippocampus. Based on probabilistic model called TRBM (Temporal Restricted Boltzman Machine), hippocampus is modeled consisting of different components according to its anatomical structure in the brain [30]. The current state of the world is represented as a unitary form in the symmetric auto-associative network. The unitary representation enables complex description of momentary condition in a single state. To represent the sequential structure, explicit transitions link states that occur subsequently. This model