Functional Embodied Imagination and Episodic Memory

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Abstract
The phenomenon of episodic memory has been studied for over thirty years, but it is only recently that its constructive nature has been shown to be closely linked to the processes underpinning imagination. This paper builds on recent work by the authors in developing architectures for a form of imagination suitable for use in artifacts, and considers how these architectures might be extended to provide a form of episodic memory.

Introduction
Episodic memory – the ability to recall particular events – is universally accepted as one of the key elements of human conscious experience, closely linked to the construction of the self, and to the sense of a continuing personal identity (Dere et al. 2008). Its identification by Tulving (e.g. Tulving 1972, 1984) gave rise to a range of studies by psychologists, most of which concentrated on the relationship between episodic memory and other forms of memory. However, recent work in neuropsychology has shown that episodic memory is more closely related to the phenomenon of imagination than to other forms of memory (e.g. Addis et al. 2007), and the idea that in evolutionary terms it probably followed imagination, and re-used many of the structural elements supporting imagination, is now being actively discussed. In particular, episodic memory, like imagination, is constructive; this idea forms the core of the constructive episodic simulation hypothesis (Schacter and Addis 2007).

The imagination of possible or likely future events has also been linked to episodic memory within the concept of mental time travel (Suddendorf and Corballis 1997, 2007), an approach which claimed (at least initially) that mental time travel was unique to humans. However, there is strong behavioral evidence that forms of episodic memory may exist in some mammals, such as meadow voles (Ferkin et al. 2008), and in some birds, particularly food-caching species such as Western scrub-jays (Clayton and Dickinson 1998; Clayton et al. 2001; Clayton et al. 2003; Clayton et al. 2007; Clayton and Russell 2009). Traditional approaches to episodic memory place conscious awareness at the centre of the process; since this is not a feasible approach when discussing animals, Clayton has introduced the idea of episodic-like memory, which emphasizes the inferences that can be made from observing the functional effects on behavior of previous events, particularly the questions of 'what, where, and when' associated with the individual events. More recently, Clayton has observed that Tulving's original minimalist formulation (Tulving 1972) was perfectly compatible with her approach, and has argued for its re-adoption as a baseline applicable to animals, young children, and adults.

This paper builds on our previous work in developing and demonstrating architectures for functional embodied imagination (Marques and Holland, 2009; Marques 2009), and discusses what must be added to an artificial system capable of imagination in order to give it the ability to support forms of episodic-like memory. In this context, Clayton's proposal for a minimalist formulation is extremely apposite. The focus of our work is on the structure and nature of the necessary architectures and component processes; this is in contrast to the existing approaches to episodic memory in artifacts, most of which have concentrated on the benefits for an agent or robot of having episodic memory (see Kawamura et al. 2008 for an excellent example of this approach). Of course, when considering a possible evolutionary pathway from imagination to episodic memory, each step along the way should be accompanied by some possible or actual increase in utility, so we will also consider what useful purposes the simplest forms of episodic memory might serve. (We can ignore for the moment the requirement that the increased utility should not be bought at too high a cost). A further problem is that our model systems are even more intellectually under-equipped than Clayton's birds, and we cannot assume any but the simplest form of information extraction from the recall/construction of a particular episode. This may be a disadvantage from the point of

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view of obtaining utility from recalled episodes, but it is certainly potentially useful in terms of testing the extension of Clayton's minimalist formulation to artificial agents.

**Biological Inspiration**

Our work on functional embodied imagination considered the problem from an abstract functional perspective, rather than in an explicitly biological context. Having developed a number of working examples, and having tested them on both simulated and real agents, we were then able to examine the architectures, components, and behavior to identify some parallels with the architectures, components, and behavior of the nervous system.

The ease of episodic memory is rather different in at least two important ways. First, the utility of imagination for both natural and artificial systems is immediately obvious, whereas the utility of the recall of episodic memories in the absence of a well developed capacity for higher cognition is unclear, to say the least. Second, it can be argued that the concept of imagination is only contingently connected with subjectivity, whereas episodic memory, in humans at any rate, seems intimately bound to consciousness and a persisting sense of self.

What these points have in common is the questionable value of the (apparent) re-experiencing of the perceptions, actions, and other accompaniments of a situation that was first experienced at some previous time. Although it is known to occur in some biological systems, it does not appear to have any intrinsic utility. It is therefore difficult to structure an examination of episodic memory within an abstract framework similar to the one we adopted for imagination precisely because the core phenomenon lacks intrinsic utility. Crudely put, if episodic memory did not exist in (some) biological systems, would it be necessary to invent it? Could the questions of what, where, and when be answered without anything analogous to the apparent recall, replay, or re-experiencing of the original situation?

In fact, this is the territory being explored by the critics of Clayton's approach, who attribute the abilities of the Western scrub-jay and other food-caching species to semantic rather than episodic memory, thereby preserving the human uniqueness of episodic memory. Although Clayton has reported experiments that seem to answer these criticisms, they do not answer the broader question of whether some form of episodic memory is necessary for some non-subjective functionality. Fortunately, our situation means that we do not have to confront these issues, because our starting point is a system equipped with the machinery necessary for imagination, and so the question is not about whether episodic memory is the only solution to the problem, but is rather about whether episodic memory is the most economical solution to the problem, given that the system already has the resources to support imagination. The biological inspiration for our approach is therefore the observation that imagination and episodic memory (in humans at least) appear to be closely related, and that imagination is hypothesized to have evolved first.

**Functional Embodied Imagination**

In Marques and Holland (2009), we defined functional imagination in the context of artificial embodied agents as a mechanism that allows an agent to simulate its own actions and behaviours, predict their sensory-based consequences, and extract behavioural benefit from doing so. By behavioural benefit we mean an increase in net reward or utility obtained; this would normally be defined in relation to objective factors, such as energy intake, but there is no reason why it should not be extended to internal factors such as the average value of some affective variable.

In our analysis, we first proposed a set of five necessary and sufficient conditions for implementing a system capable of functional imagination in an embodied agent. We then developed a taxonomy of simple possible architectures, and then identified the necessary components required for the construction of those architectures. Finally, we tested a subset of the architectures using both simulated and real agents. It will be useful to reprise these steps here in a form condensed from the original paper.

**Necessary and Sufficient Conditions**

**Representation of alternative sensory states.** In the course of functional imagination, an agent must be able to represent a sensory state different from that due to its current context.

**Sensory state based prediction.** An agent must be able to predict the consequences of its actions in terms of sensory state. This condition implies the presence of sensory and motor mechanisms (provided by default in an embodied agent) as well as a mechanism for predicting the sensory consequences of a motor action. Predictive mechanisms of this type are generally referred to as forward models: in control theory, a forward model is a mechanism that predicts the next state of a general system (the plant) given its current state and the action executed.

In the context of functional imagination we can distinguish two types of forward model. The first and most widely used is a shallow computation, typically connectionist, which accepts the state and action variables as input, and delivers the predicted state variables as output. Most current work uses relatively small and simple feedforward or recurrent neural networks for this. A second type, exemplified by Vaughan and Zuluaga (2007), uses a complex simulation in which the outputs are determined through the mediation of some kind of explicit self-model interacting step by step with a simulated world. We call the first type of forward model unmediated, and
the second type mediated. Our work used the second type, and, as will be seen, it is this type that has the potential for enabling episodic memory.

**Goals.** An agent must be able to execute behaviour in relation to goals, that is, it must have the ability to generate motor commands in a given external state as a function of some internal state which is capable of being changed in some way as a result of the behaviour of the agent. For functional imagination to be possible, the goal is not necessarily required to be represented explicitly in the way required by a goal-directed system (McFarland 1989). However, it is essential that the agent is able to recognise a goal once it is arrived at, which means that the agent must be able to perform either goal-directed or goal-achieving behaviour (McFarland 1989). The reason for this is that the usefulness of internal simulation must be measured, and this measurement must be in terms of progress towards or away from a unitary or compound goal. Without the presence of a goal, implicit or explicit, internal simulation loses its functional value because there is no way of determining whether it arrived at a useful result or not.

**Evaluation.** In order to select a relatively good series of real actions, an agent must be able to evaluate the final sensor state based outcome of the corresponding series of simulated actions. Such an evaluation may take a number of forms. For an objective evaluation, it should at least possess the capacity to determine whether a goal has been fulfilled or not; as noted above, this is a minimum requirement of any agent capable of either goal-directed or goal-achieving behaviour. If possible, it might in addition assign to the outcome some figure indicating the degree of satisfaction of the goal according to some measure (say, net energy expenditure, or speed); this would distinguish between states in which a goal had been achieved.

**Action selection.** All animals have a number of different goals that must be fulfilled in order for them to survive and reproduce. In order to deal with these goals, they are capable of producing a variety of different behaviours, and so mechanisms of action selection are required to ensure that only one behaviour is produced at any time, and that (if possible) it is appropriate. However, an agent with functional imagination must also be able to select actions for internal simulation.

**A Taxonomy of Architectures**

**Economical vs. duplicated**

One important aspect of biological imagination is the question of the activation of sensory and motor structures during imagination. However, it is not yet clear whether exactly the same neurons are involved during overt and covert behaviours or whether there is some sort of co-located duplication of sensory and motor structures with one set being used for overt behaviour and the other set being used for covert behaviour. We therefore differentiate between possible architectures that reuse the sensory and motor structures for covert behaviour – economical architectures – and architectures which use duplicated structures – duplicated architectures.

**Reactive vs. rational**

When using functional imagination there are at least two ways for deciding what to do: simply performing the first successful solution found — a reactive architecture — or continuing simulating to find a better solution within the available time frame — a rational architecture.

**Single-step vs. multi-step**

A basic characteristic of any functional imagination system is the number of steps ahead that it is able to simulate. The minimum is obviously one step; the maximum will be limited by the available computational resources, but the utility of lookahead may be limited by other factors such as noise. The architectural requirements for simulating a single step ahead will clearly be much simpler than those for architectures that consider more than one step ahead.

**Memoryless vs. memorising**

Another simple computational distinction is whether an agent stores successful solutions for the problems it encounters, or whether it simply keeps simulating afresh every time, even when it faces a familiar problem. Although this distinction received little attention in Marques and Holland (2009), architectures of both types were examined in Marques (2009). As will be seen, this aspect is of crucial importance for the development of episodic memory.

**Architectural Components**

Six of the components used in our architectures are implicit in the five necessary and sufficient conditions outlined above. They are the sensor system, the motor system, the forward model (for sensory state based prediction), evaluation, a goal buffer, and an action selection mechanism. A small number of additional components turn out to be necessary for managing the flow of information and control: various simple forms of short-term memory (STM), simple forms of long-term memory (in some architectures), and switches. The memory elements require no introduction, beyond remarking that some may include extra infrastructure for managing the selection, storage, and retrieval of the contents. However, some explanation of the nature and role of switches is required. An agent endowed with functional imagination needs to generate both sensory and motor states. If the structures in which these states are generated are those used in overt behavior (i.e. if the architecture is economical rather than duplicated), then the normal channels of sensory input to, and motor output from, these structures
must be inhibited during internal simulation, and enabled during overt behavior. Whatever their implementation, the mechanisms responsible for this inhibition and enabling are referred to as switches.

**Designing and Testing the Architectures**

A small subset of architectures was designed, implemented, and tested in Marques and Holland (2009); a larger subset was investigated in Marques (2009). The design process proceeded as follows: we began with the simplest architecture (reactive, economical, single-step, memoryless), and produced what we believed to be the simplest implementation of it, using the minimum number of components and connections. We then successively constructed the more complex designs by adding components and connections to the previous design. Designs were first expressed diagrammatically in terms of the information and control flow between components, and were then implemented in software. They were then tested, either on a very complex humanoid robot (CRONOS), or on a simulated version of the same robot (SIMNOS). Where appropriate, noise was added to the internal processes and to the simulations. We found that it was possible to produce functioning architectures of all the possible basic types by this incremental process.

**Migrating to Episodic Memory**

The key to episodic memory lies in one component: the forward model. Rather than using a shallow unmediated forward model, we had chosen to use a mediated forward model – a step-by-step simulation of the agent carrying out the action in a simulated world with the appropriate initial state. An important reason behind our choice was that we wished to avoid producing a solution that would only work in some oversimplified toy world. Our robot was one of the most complex ever constructed, an elastically actuated humanoid torso with 42 degrees of freedom. In order to be able to produce a forward model with general predictive validity, we were then forced to resort to the physics-based dynamic modeling of both the robot and the world – there was simply no available way of simplifying the problem down to the level of a toy problem, and certainly no way of predicting the consequences of the robot's actions in the world using an unmediated model. We speculate that the same is true of the human body, which is even more complex than our robot. However, we do not mean to imply that the brain contains an accurate physics-based simulator along the lines of the one we built, but rather that the brain's simulator will necessarily be of the mediated type, regardless of its underlying principles.

The starting point for our investigation of functional embodied imagination was the simplest possible type of architecture: economical, reactive, single step, and memoryless. Whenever a goal (defined in sensory terms) was presented to it, it would first test the current sensory input to see if the goal was satisfied. If it was not, it would operate the switch to decouple the sensory and motor outputs from the real world, and then simulate possible actions in the current sensory state, testing each simulated resultant state; when the resultant state satisfied the goal, it would execute the most recently simulated action (stored in a buffer) by restoring the switch. Possible actions were specified in terms of an action type (e.g. grasp, throw, or hit) and an action target (e.g. red stick, blue stick); the simulated movement was then synthesized from this information, taking into consideration the perceived location of the targets and the starting position for the movement. The same sensory and motor structures were used for perception and action in both simulation and reality; this required the rendering of the simulated view of the world by the robot, a trivial task in comparison to the physics-based computations.

This most basic of systems was unable to store any information about the outcomes of previous actions, and so whenever a goal was presented that was not immediately satisfied, the imagination process had to be invoked. We can begin our investigation of episodic memory simply by considering the simplest way in which the outcomes of previous actions in previous states might be stored in a way that would benefit this basic system. The most obvious suggestion is to suppose that a previous action in a state identical to the current state had been successful in achieving the current goal. In that case, simply repeating the action should again achieve the goal. What information would be needed to retrieve the stored information? The answer is the current state and the goal, both of which would be available. What would need to be retrieved? The target and the action type. What would have to be done with the retrieved information? It would have to be transferred to the appropriate buffers before the switch was released. None of this would be difficult to arrange – and nothing in the operation of such a system would correspond to episodic memory.

So what would correspond to episodic memory? One possible answer is very simple: if the retrieved information were used to load the target and action type for a simulation cycle, the synthesized execution of the corresponding movement would constitute a constructive replay of the original event that had led to the information being stored in the first place. Why might this be preferred over the direct overt execution of the movement? It is not difficult to think of possible reasons. The retrieved information may have been degraded by noise – a simulation cycle would then act as a filter for potentially bad movements. Or since, by definition, a movement can be synthesized from an action type and a target, it may be that a rehearsal might lead to a faster or more accurate execution, through some form of motor priming, or perhaps the formation of motor plans that could be preloaded for execution.
If we accept for the moment that the retrieved information is used to initiate a simulation cycle, can we see any other features that align well with episodic memory? The classic formula connecting a memory to a specific event involves the issues of what, where, and when. (It should be noted that the importance of time has been queried by some, giving rise to the claim that where and when are merely two aspects of a more general characteristic of context.) From the point of view of the system, ‘what’ is surely defined by the outcome of an action taken in a particular initial state. This is exactly the same as the information used in retrieval, except that what was previously thought of as the goal is now expressed as the outcome. Similarly, ‘where’, and perhaps at least some of the contextual aspects of ‘when’, simply corresponds to certain features of the initial state.

We can take these thoughts further in a number of different ways. For example, suppose that the recalled (or reconstructed) action is successful in simulation, and is also successful in overt execution. How might this affect what is stored? (This is an aspect of what is known as memory reconsolidation; see Dudai (2006) for a recent review from the perspective of memory in general.) In the context of episodic memory, there are a number of possible answers. It might not affect it at all; it might replace the previous memory by overwriting and erasing it; alternatively, since the actual sensory state at the start of execution will certainly differ from the corresponding state at the start of the original event, it may form a new memory indexed by the new and slightly different initial state. Of these possibilities, the last two are compatible with what is known of biological episodic memory. And if the memories degrade in accuracy with time, overwriting will correct this, incidentally connecting the memory to the most recent corresponding event and thus giving an element of temporal specificity.

An interesting question, and one that also cropped up in our investigation of imagination, is whether the original stored memory should be affected by the outcome of a simulation as well as by the outcome of an action. If the original event, the recalled or reconstructed event, and the executed action are all identical, then the question is an empty one, but if the reconstructed event does not produce an outcome that satisfies the goal against which the memory was indexed, then this information, which has incurred a metabolic cost and an opportunity cost, should be used to increase future utility.

A simulation can fail for a number of reasons: (a) the retrieved information may have been degraded by noise, as noted previously; (b) the original event may have been a fluke, or may have depended upon some hidden state; or (c) the simulator itself may not match reality. In situations (a) and (b), updating the memory according to the outcome of the simulation will lead to increased utility. In situation (c), it will replace a correct prediction based on a real outcome with an incorrect prediction based on a defective simulation, and this would be expected to reduce utility. Whether the balance favors updating the memory following an unsuccessful simulation depends on the distribution of the different types of errors, and also on whether any means is available for correcting errors in the simulation system. Interestingly, there are now strong indications from both psychology and from neuroscience that a recalled (or reconstructed) episodic memory may affect the original memory trace in a number of ways (e.g. Hupbach et al. 2007).

We should also note here that simulations are not performed solely at the prompting of stored memories; they are also generated through the exercise of functional imagination. Again, there may be new information in the results of such a simulation, and if the simulator is accurate, the storage and subsequent use of the relevant data might then increase utility. If the memory components and contents are the same as those used for the storage of the states and outcomes of overt actions, there will be no functional difference between the effects of recalling an imagined and a real action. This has parallels in the developmental psychology of episodic memory, where young children do not appear to differentiate between their memories of imagined and real actions (e.g. Ceci 1997).

Of course, in any of the above cases, if the granularity of the representation is sufficiently fine, it is very unlikely that a given initial state will recur exactly. This may apply independently to both the sensory state and the goal specification. Other things being equal, the closer the current sensory state and goal pair are to a sensory state and outcome pair in the memory, the greater the probability that the stored action type and target will yield a successful simulation and action. An associative content-addressable memory would be a logical choice for implementation. The utility of using the stored data as the starting point for a simulation is that the probability of the simulation being successful should be greater than that associated with a purely imaginative simulation. There should therefore be some cut-off level of similarity between the state/goal couple and the stored state/outcome couple; the simulation should only be primed from the memory when this level is greater than that expected to produce net positive utility.

**Future Work**

We believe that this initial conceptual analysis justifies a work program following the same strategy as our previous investigation into functional imagination. Instead of the original CRONOS robot and its physics-based software model SIMNOS, we will use the similar but better engineered ECCE series of robots being developed under the European Commission's ECCEROBOT project, together with the associated physics-based model ECCEOS. Our aim will be to develop successively more sophisticated types of episodic memory through an
incremental process starting with the basic level outlined in this brief paper. Of course, these systems will implement imagination as well as episodic memory, and we hope to be able to examine such issues as the possible existence of an analogue of mental time travel in robots in order to shed light on the ongoing discussions about time travel in humans and animals.

We also hope to be able to contribute to two additional perspectives, one very old, and one very new. The old one, from Kant (1781), concerns the nature of our experience of objects; it has recently been revived by Clayton and Russell (2009) in the context of episodic memory, and we refer the reader to their paper. We believe that our use of physics-based modeling as a substrate provides an a priori embedding in time and space, and that our robot may serve as an example of a system that exactly fits Kant’s analysis. The new one is machine consciousness; our work on imagination had its origin in a theory of (machine) consciousness (Holland 2007) and we will extend our work on episodic memory into the same framework.

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