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Mental Time Travel? A Neurocognitive Model of Event Simulation

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Abstract

Mental time travel (MTT) is defined as projecting the self into the past and the future. Despite growing evidence of the similarities of remembering past and imagining future events, dominant theories conceive of these as distinct capacities. I propose that memory and imagination are fundamentally the same process – constructive episodic simulation – and demonstrate that the 'simulation system' meets the three criteria of a neurocognitive system. Irrespective of whether one is remembering or imagining, the simulation system: (1) acts on the same information, drawing on elements of experience ranging from fine-grained perceptual details to coarser-grained conceptual information and schemas about the world; (2) is governed by the same rules of operation, including associative processes that facilitate construction of a schematic scaffold, the event representation itself, and the dynamic interplay between the two (cf. predictive coding); and (3) is subserved by the same brain system. I also propose that by forming associations between schemas, the simulation system constructs multi-dimensional cognitive spaces, within which any given simulation is mapped by the hippocampus. Finally, I suggest that simulation is a general capacity that underpins other domains of cognition, such as the perception of ongoing experience. This proposal has some important implications for the construct of 'MTT', suggesting that 'time' and 'travel' may not be defining, or even essential, features. Rather, it is the 'mental' rendering of experience that is the most fundamental function of this domain-general simulation system enabling humans to re-experience the past, pre-experience the future, and also comprehend the complexities of the present.

Keywords Autobiographical memory · Default mode network · Episodic memory · Future thinking · Hippocampus · Imagination · Medial prefrontal cortex · Prospection · Schema · Semantic memory

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1 Introduction

Janus, the Ancient Roman god of beginnings, transitions and endings, links the past with the future. He is represented in art as doubled-faced, capable of looking to both the past and the future. This ability is known in contemporary psychology and philosophy as mental time travel (MTT; Tulving 1985). Although Janus is the god of time and travel, MTT is a capacity not only in possession of the gods; (most) mortals also possess the capacity to remember the past and imagine the future. Janus embodies the close linkage of past and future – that *one* mind/brain can look both forwards and backwards in time, though his two faces suggest these might be distinct processes. For millennia, humans have debated whether memory and imagination are the same or distinct capacities – viewpoints known as continuism and discontinuism, respectively. Within modern psychology and cognitive neuroscience, the intertwinement of past and future thinking has been emphasized, most influentially by Tulving (1985), but nevertheless are usually conceived of as distinct capacities. However, it is becoming increasingly apparent that the brain's default mode network (DMN) is not only involved in MTT into the past and future but also engaged by other forms of MTT such as counterfactual thinking (De Brigard et al. 2013), as well as other forms of cognition, including creativity (Roberts and Addis 2018), theory of mind (Frith and Frith 2003), narrative comprehension (Mar 2004) and event perception (Baldassano et al. 2017). Thus, I suggest that underpinning MTT as well as these other 'non-MTT' forms of cognition is *simulation* – the mental rendering of experience.

I begin this paper with a brief discussion of relevant theoretical perspectives on memory and imagination (Section 2) and continuism and discontinuism (Section 3). Next, I present a continuist proposal that MTT into the past and future are instantiations of one 'simulation system' (Section 4). In support of this view, I outline how the simulation process draws on the same information, is governed by the same processes, and is underpinned by the same brain system irrespective of whether the simulated event is remembered or imagined. I also propose that this 'simulation system' supports the construction of multi-dimensional cognitive spaces, within which any given simulation can be mapped by the hippocampus (Section 5). Finally, I will suggest that simulation may be a general cognitive capacity underpinning other forms of cognition, including perception (Section 6).

This view has some important implications for how we understand MTT, suggesting that 'time' and 'travel' may not be defining characteristics. Although this simulation system can be co-opted to mentally traverse time and space, it is the 'mental' rendering of experience that is the key function of this system and crucial to many aspects of higher cognition. It is hoped that this continuist reconceptualization of simulation as a single neurocognitive system will yield testable hypotheses and ultimately advance our understanding of the ways in which simulation is utilized in forms of cognition, including MTT and beyond.

2 Theoretical Underpinnings

2.1 MTT into the Past: Episodic and Semantic Memory

The collection of essays on the *Science of Memory: Concepts* (Roediger et al. 2007) captured an important snapshot of the dominant conceptualization(s) of 'memory' from the leading memory scientists of the day. As is clear from that volume, most of these scientists conceive of memory as a distinct form of cognition – a natural kind, separate from other cognitive faculties – that can be carved further into multiple independent memory systems. Specifically, the most accepted taxonomy of memory (Schacter and Tulving 1994) divides memory into multiple systems falling under two umbrellas: declarative and non-declarative. Relevant here, declarative memory is composed of memory for facts (semantic memory) and memory for events (episodic memory), a widely-accepted distinction introduced by Tulving (1972). The defining differences between episodic and semantic memory are related to: (1) contextual specificity, where an episodic memory is localized to a specific time and place while a semantic fact is not; and (2) the conscious experience of recollection, whereby an episodic memory is associated with autonoetic consciousness (i.e., "I am re-experiencing an event I experienced in the past") and semantic memory with noetic (knowing) consciousness (i.e., "I know this fact").

By this framework, Tulving (1985) posited that MTT into the past and the future was supported primarily by episodic memory. Therefore, initial theories regarding the role of simulation in past and future MTT (e.g., scene construction theory, Hassabis and Maguire 2007; constructive episodic simulation hypothesis, Schacter and Addis 2007) focused on the role of episodic memory in imagining episodic future events, but not to the exclusion of semantic contributions, such as, *"the source of knowledge about the general properties of events, and … to guide the construction of future scenarios in line with these known event properties*" (Schacter et al. 2007, p. 660). Indeed, it is increasingly apparent that simulation involves – perhaps critically – semantic forms of memory (Irish and Piguet 2013), including concepts and categories (categories are networks of associated concepts, that in turn are a set of defining features), gist (abstract representation of the essential aspects and/or theme of an event), narratives (abstract representation of a sequence of events), and schemas (high-level knowledge structures that organize lower-level forms of memory; Ghosh and Gilboa 2014; Gilboa and Marlatte 2017).

Episodic memory is primarily conceived of as a constructive process. Since the seminal work of Bartlett (1932), numerous cognitive studies have demonstrated that memories may be missing elements and/or may contain new information (information that is schema-relevant and/or was newly encountered since the original experience; Schacter et al. 1998). Such distortions are a normal 'by-product' of a constructive memory system in which event representations encoded during the original experience are pieced back together, providing opportunities for the omission and/or the erroneous inclusion of content. Furthermore, neuroimaging has provided evidence that, for instance, episodic retrieval involves synchronous reactivation of activation patterns in the cortical areas that initially processed the elements of the original experience, thereby *reconstructing* the originally-encoded representation of the experience (Fuster 1997; Schacter et al. 1998). Because episodic retrieval involves reactivating the elements of a past experience, the exact brain regions involved in a given memory will vary depending on the representational content.

2.2 MTT into the Future: Constructive Episodic Simulation

The notion that episodic memory is linked to future thinking has gained increasing traction over the past 15 years. Building on Tulving's (1985) earlier observation that densely amnesic patient KC could not imagine events in his future, recent studies have demonstrated parallel deficits in various populations with varying degrees of memory loss, ranging from dense amnesia (e.g., Hassabis et al. 2007; but see Squire et al. 2010) and Alzheimer's disease (Irish et al. 2012a) through to the comparatively mild changes in memory in depression (Addis et al. 2016) and healthy aging (Addis et al. 2008). Psychological research has demonstrated that episodic memory and imagination emerge at similar times during childhood (Atance and O'Neill 2001), and that in adulthood, individual differences in emotion regulation and mental imagery abilities are correlated similarly with past and future events (D'Argembeau and van der Linden 2006). Neuroimaging has revealed that memory and imagination engage the same brain networks, including the DMN (Addis et al. 2007; Okuda et al. 2003; Szpunar et al. 2007; see Fig. 1).

The central tenet of the constructive episodic simulation hypothesis is that although the constructive nature of episodic memory results in relatively frequent distortions during retrieval, thereby reducing the veracity of memory, it is nevertheless an adaptive 'design feature' that facilitates the flexible simulation of future events (Schacter and Addis 2007). There is, however, an asymmetry inherent in this account, in that the neurocognitive overlap between past and future events reflects a *unidirectional contributory* relationship whereby episodic memory supports future simulation, but not the reverse. Episodic memory provides the raw materials for future imagination, and the distributed storage of episodic memories as elements heightens the accessibility of episodic details. The episodic memory system supports the cognitive processes that are utilized during future simulation: episodic retrieval to reactivate details and relational processing to integrate details into a novel event representation.

Framing the relationship between past and future MTT as unidirectional has two implications. First, it promotes a reconceptualization of the function of episodic memory as prospective rather than retrospective, given that its constructive nature compromises the accuracy of recall but facilitates predictive forms of thinking (Bar 2009; Schacter et al. 2007). This is not to say that episodic memory is never accurate; nor is it to argue that the accuracy of episodic memory is not useful. It acknowledges the *adaptive* benefits of episodic memory are conferred when used in prospection, including enhancing well-being (Taylor and Schneider 1989) and problem solving

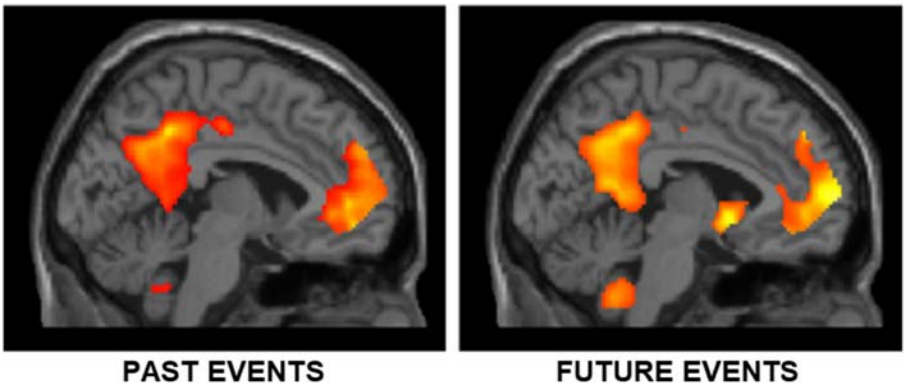

Fig. 1 Brain activity primarily in the default mode network during the simulation of past and future events relative to a control task. Adapted from Addis et al. (2007)

(Sheldon et al. 2011). Second, a unidirectional contributory framework positions memory and imagination as fundamentally distinct processes. Despite considerable evidence of overlap between past and future events, these findings have been interpreted as reflecting the contribution of episodic memory *to* future simulation. Even the use of the term 'overlap' signals an inherent distinction between the two processes. In other words, the dominant perspective does not go so far as to conclude that memory *is* imagination. It is likely that this reluctance is because there are some differences between episodic memory and future simulation, such as differential activity thought to reflect future-specific processes such as intentional thinking, novelty, and the recombination of episodic details (Addis et al. 2007; Okuda et al. 2003; Szpunar et al. 2007). Additionally, differential deficits in future thinking have been reported in various disorders (de Vito et al. 2012b; Irish et al. 2012a). Although these findings are difficult to explain within current theories of episodic memory, a theoretical framework that views memory and imagination as the *same* process removes this difficulty.

3 Memory and Imagination: One and the Same?

3.1 Discontinuist Views

While conceiving of memory and imagination as entirely distinct faculties is a fairly strong form of discontinuism, more moderate discontinuism argues for the involvement of different sub-processes. A common argument is that unlike imaginings, memories are associated with a sense of pastness or a consciousness indicating that the event happened before (i.e., autonoesis; e.g., Tulving 1985), a meta-cognition reflecting the intention to recall (Urmson 1967), a meta-representation that the event happened in reality (Mahr and Csibra 2017), and/or a direct causal link to the original experience (Perrin 2016; Robins 2016). In addition, Robins (this issue; in press) argues that imagination is accompanied by an explicit awareness that one is imagining and not remembering, but that people struggle to distinguish between whether they actually remember or whether they are only 'seeming to remember'. In other words, there is a certainty when one imagines, perhaps due to the cognitive effort required, that is not experienced when one remembers. Others locate the key difference in the phenomenological quality of the representation. For instance, the Source/Reality Monitoring Framework specifies that relative to imagined events, memories comprise more external sensory and less internally-generated content, are more plausible, more consistent with pre-existing knowledge, and easier to construct (Johnson et al. 1993; Johnson and Raye 1981).

Most cognitive neuroscience theories sit somewhere between moderate discontinuism to moderate continuism. As discussed in Section 2.1, most contemporary researchers appear to consider memory as a cognitive faculty distinct from other cognitive domains. Even though it is now widely acknowledged within cognitive neuroscience and psychology that memory and imagination are related processes, I think very few memory scientists would comfortably reject the notion that memory is distinct, or put another way, accept that memory *is* imagination. Memory scientists have, by-and-large, focused on the ability to remember the ground truth of experience, thus emphasizing a direct causal link to the past that imagined events cannot possess. Indeed, as memory scientists we described our findings that imagining engages the same brain network as remembering as “striking”, “remarkable” and “unexpected” (Addis et al. 2007), and in our constructive episodic simulation hypothesis we qualified this overlap by emphasizing the differences between past and future events (Schacter and Addis 2007). While philosophers such as Perrin (2016) describe theories such as the constructive episodic simulation hypothesis as moderately continuist, most psychologists and cognitive neuroscientists likely hold views that are at least somewhat discontinuist in that similar theoretical weight is given to both the similarities of, and the differences between, past and future thinking.

3.2 Continuist Views

A clear demonstration of the fluidity between past and future representations, and of memory and imagination, is the ability to mentally rework past events to have different outcomes, usually with a view to increasing future success (i.e., counterfactual thinking). Taking a moderately continuist perspective, Michaelian (2011, 2016a) posits that memory and imagination are both forms of imagination. Specifically, he argues that both are constructions comprising elements of real experience augmented with internally-generated (imagined) content. If people actually retain as few details about their experiences as suggested by the results of a recent study (Misra et al. 2018), then it is not surprising that remembered past events involve some degee of imagination, such as filling in missing details with internally-generated content including details from related experiences, conceptual information that fleshes out aspects of the memory, and scripts and schema that aid in the reconstruction process (Bartlett 1932; Rubin and Umanath 2015). Michaelian argues that this imaginative process is likely gist-based, while others suggest it involves interpolation of the most likely values for missing details on the basis of available information (Dannenberg et al. 2018). Summarizing his view, Michaelian states that “to remember simply *is* to imagine the past” (Perrin and Michaelian 2017, p. 233). However, the imagined content must meet a reliability condition, that is, it must be “mostly accurate”; if it strays too far from what is realistic or plausible, the event becomes a confabulation (Michaelian 2016b). According to this view, because past and future representations themselves do not differ in structure or content, it is hypothesized that it is the fluency of the constructive process – an attribute of both memory and imagination – that indicates whether or not a given event was previously experienced (Perrin and Michaelian 2017). That is, re-construction is more fluent than construction de novo, as details have been previously associated (Addis 2018).

Interestingly, the prevailing models of episodic memory as a distinct faculty typically characterize memory as constructive, thus also implying memory is modifiable in ways akin to ‘imagination’. For instance, conjunction errors (i.e., the integration of erroneous details into a memory) involve recombinations of details, and there is no reason to suggest this would be any different from the recombination process argued to underlie future imagination (Addis and Schacter 2012; Schacter and Addis 2007). Furthermore, just as schemas facilitate the reconstruction of memories, schemas also modify memories to fit with our general understanding of the world (e.g., cultural schemas; Bartlett 1932) and ourselves (e.g., self schema; Conway and Pleydell-Pearce 2000), again bringing memories into the domain of imagination.

By the continuist view, failures of source/reality monitoring occur because remembered and imagined events are often very similar in content and phenomenology, for instance, when imagined events are elaborate, vivid, and plausible (Devitt et al. 2016; Garry et al. 1996; Johnson et al. 1993). Thus it may be that one of the only consistent differences between a memory and a vivid imagining is a relative difference in the fluency of construction (Michaelian 2011), although even fluency differences can dissipate with repeated imaginings (Wiebels et al. 2019). As aforementioned, neuroimaging has provided evidence of overlap between past and future events, consistent with the continuist view. Specifically, both forms of MTT engage aspects of the DMN (Fig. 1), including medial prefrontal, medial and inferior lateral parietal, and anterolateral temporal cortices, and the medial temporal lobes (Addis et al. 2007). These activation patterns are evident whenever we are engaged in simulation, whether that simulation is spontaneous (e.g., mind-wandering; Christoff et al. 2016) or intentional, whether focused on our own past and future or someone else's (i.e., theory of mind; Buckner and Carroll 2007), or within entirely fictional worlds (Behrens et al. 2018; Hasson et al. 2015; Mar 2004; Richardson 2012). In fact, Richardson suggests the 'time' be removed from the term 'mental time travel' to capture this more general capacity that does not necessarily have to involve traversing personal time.

Of course, how scholars define the concept "system" has considerable influence on where these theories sit with respect to continuism and discontinuism. In the *Science of Memory: Concepts* volume, the consensus of the field at that time was that "memory system" refers to a collection of brain regions that are functionally and biologically dissociable (Squire et al. 2007). Prior to this, Schacter and Tulving (1994) defined a brain system as operating on distinct type(s) of information, having distinct rules of operation, and distinct neural substrates. My contention is that, according to these criteria, memory and imagination are indeed *one* neurocognitive system.

4 Continuist Reformulation of the Constructive Episodic Simulation Hypothesis

Instead of conceptualizing imagination as *reliant on* the episodic memory system, I suggest both memories and imaginings are instant iations of the same neurocognitive process: constructive episodic simulation (Addis 2018). This revised version of the constructive episodic simulation hypothesis diverges from our original theory (Schacter and Addis 2007) in a number of important ways: (1) I emphasize the role of pre-existing knowledge, including semantic, conceptual and schematic content, in constructing both past and future events; (2) I reformulate our hypothesis that remembering and imagining tax *distinct* types of associative processes, namely reintegration and recombination respectively, instead suggesting that simulations vary in 'associative strength' depending on the associative history of constituent details (i.e., whether details have been previously associated); (3) I propose that associative schematic processes guide the construction of a simulation, providing a framework for the simulation and a means for iteratively refining it until an event boundary is reached; (4) Continuums of associative strength and schema-reliance provide a continuist framework that clarifies the involvement of the DMN and related networks, and accommodates both similarities and differences between past and future events; (5) I suggest that constructive episodic simulation applies not only to remembering and imagining, but also to perceiving events; and (6) I hypothesize that, as a way of interpreting, predicting, and interacting with the world, simulations are situated within complex cognitive 'spaces' that code for multiple dimensions of experience.

Not only does this proposal incorporate emerging theoretical perspectives and empirical evidence, it also provides a parsimonious account of the commonalities and differences between past and future events observed in neuroimaging, cognitive and neuropsychological studies. Moreover, this reconceptualization meets Schacter and Tulving's (1994) criteria for a single, shared neurocognitive system: irrespective of whether a simulation is remembered or imagined in the past or the future, the same types of content are acted on by the same set of cognitive operations and mediated by the same brain system.

4.1 Content Similarities across Remembered and Imagined Events

There is considerable evidence to support the claim that remembered and imagined events comprise similar content. Past and future events tend to centre on similar themes, such as social/leisure activities, relationship episodes, successes/failures, illnesses/ accidents of the self/others (D'Argembeau and van der Linden 2004), and events from the individual's cultural life script (e.g., in Western societies, typical events include graduating, getting a job, getting married, etc.; Rasmussen and Berntsen 2013). Irrespective of theme, simulations of past and future events contain the same types of details, as demonstrated in numerous studies utilizing the Autobiographical Interview to examine event transcripts. Simulations usually comprise the time of the event (or other temporal information); a spatial location or scene (cf. scene construction hypothesis, Hassabis and Maguire 2007; for a similar view see Rubin and Umanath 2015); sensory information about entities (e.g., objects, people, self etc.), including physical attributes, locations within the scene, and time of appearance; semantic knowledge about entities; sequences of intentions and actions (including direction and speed of movements) of self and others, and consequences of those actions; dialogue; and internal experiences such as thoughts, emotions and bodily sensations (Addis 2018; Dannenberg et al. 2018; Levine et al. 2002). Much of the literature to date has focused on whether constituent details are episodic or semantic in nature, finding that across past and future events the numbers of episodic details is strongly correlated, as are the numbers of non-episodic details (e.g., Addis et al. 2008). Additionally, the relative numbers of different sub-types of episodic details are also remarkably similar (see Fig. 2; Irish et al. 2012b).

Classifying details as either episodic or semantic according to the traditional definition (Tulving 1972) is problematic. The classification of a detail as episodic is based, at least in part, on the episodicity of the event representation itself which may not reflect the episodicity of the constituent details. In addition, many theories and coding schemes assume that sensory-perceptual details are 'episodic' as long as these details are part of a specific episode, while accompanying conceptual details are 'semantic', and any sensory-perceptual details comprising non-specific events (e.g., general autobiographical events) are 'non-episodic' and possibly conceptual in nature (e.g., Conway and Pleydell-Pearce 2000; Levine et al. 2002). However, it is difficult (if not impossible) to determine whether any one detail is represented perceptually or conceptually on the basis of verbal descriptions alone, and neuroimaging profiles have not (as of yet)

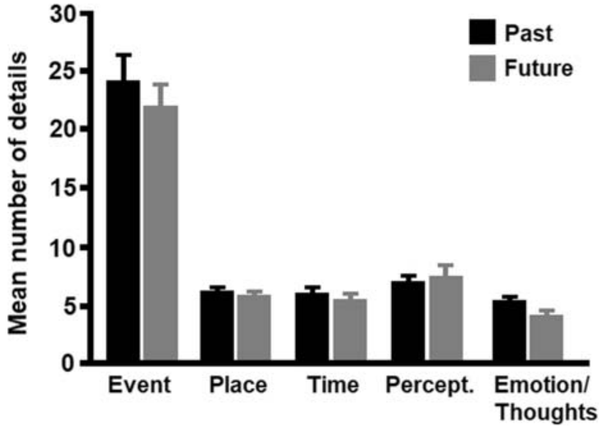

Fig. 2 Mean number of episodic details comprising past or future simulations broken down by detail subtypes. Percept. = perceptual. Adapted from Irish et al. (2012b)

resolved the issue given that episodic and semantic memory engage overlapping DMN regions (Binder et al. 2009; Burianova and Grady 2007). Therefore, I suggest that instead of determining the episodic-semantic nature of individual event details (henceforth called 'elements'), it may be more informative to consider the representations at different scales – both at the level of the individual constituent elements and at the level of the whole event representation.

At the level of individual elements, there are varying degrees of *resolution*. This notion is consistent with evidence that many regions across the brain exhibit anterior-to-posterior gradients of resolution (fine-grained to coarse; Sheldon and Levine 2016), and relatedly spatial and time scales (small/short to large/long; Hasson et al. 2015; Peer et al. 2019). High-resolution details tend to be fine-grained perceptual features (e.g., an edge) or discrete elements of semantic information (e.g., an individual fact), while low-resolution details are coarser representations abstracted over multiple instances (Sheldon and Levine 2016). It is hypothesized that perceived elements are stored in the content-specific regions of the brain that initially processed the information, such as sensory cortices and regions mediating abstracted information (cf. Craik and Lockhart 1972; Fuster 1997).

Representations (i.e., event simulations) are flexible (as opposed to unitized; Graf and Schacter 1989) assemblages of two or more distinct elements. While representations may vary in resolution, I posit that this variance likely reflects the resolution of the constituent elements. In other words, the relative proportion of elements at different resolutions comprising a given event representation denotes the resolution of that representation ('*proportional resolution*'). As I recently argued (Addis 2018), some apparent differences between past and future events likely reflect differences in proportional resolution rather than fundamental differences in content or underlying mechanisms. For example, remembered past events often include larger proportions of high-resolution sensory-perceptual elements and have been associated with increased activity in sensory cortices (Addis et al. 2009), while imagined future events are thought to comprise more content of a lower resolution, such as concepts and schemas, and have been associated with activity in lateral temporal (Binder et al. 2009) and medial prefrontal (Gilboa and Moscovitch 2017) cortices, respectively (e.g., Addis et al. 2009; Addis et al. 2011). Interestingly, representations at the longest/largest scales are supported by high-level DMN regions such as medial prefrontal, medial parietal, and lateral parietal regions (Hasson et al. 2015; Peer et al. 2019), and thus the involvement of these DMN regions during simulation may similarly reflect the larger scale of an event representation (e.g., typically spanning at least minutes if not hours to days; and possibly also traversing large-scale spaces, such as a city or country).

Event simulations can also vary in *elaborateness*, or the absolute number of constituent elements (ranging from pairings of two visual features to construct an object simulation, to rich event simulations), and in structural *complexity*, that is, the ways in which constituent elements are associated with each other. Complexity can range from the simple co-occurrence of items to the highly complex and multidimensional (Dannenberg et al. 2018; Zacks and Tversky 2001). A complex simulation could include multiple, intersecting layers of complex relations (e.g., nested, causal, etc.) between elements, where each layer represents a different type of structure (e.g., temporal, spatial, goal, social, self, etc.) that captures the organization within the event itself and/or positions the event within a broader cognitive space (see Section 4.4). For instance, one might simulate an event (that itself is related to other events) that constitutes a spatiotemporal trajectory of actions and interactions between multiple locations (that each include particular spatial layouts and objects), multiple people including the self (each with their own set of social relations, active goals, intentions and behaviours), and so on (for a similar view, see Dannenberg et al. 2018). This level of complexity is so commonplace, Zacks and Tversky describe such events as “the stuff of all our lives” (p. 19).

There will be situations in which these three qualities – proportional resolution, elaborateness, and complexity – map onto each other. And although these qualities are likely often correlated, this need not always be the case. Indeed, there are many forms of memory that do not fit easily on a simple continuum of episodic to semantic (e.g., general autobiographical events) and so this conceptualization may offer a way to account for such exceptions. It is likely that there is a ‘minimal combination’ of these three qualities required to give rise to MTT into the past and future: (1) in terms of complexity, that the simulation is nested at least within the self-schema; and (2) in terms of proportional resolution, that the simulation contains some proportion of high-resolution elements. For instance, by traditional definitions, representations of repeated events are classified as semantic because, although nested in the self-schema, the absence of a specific spatiotemporal context supposedly precludes MTT. However, there is evidence to suggest that general events are in fact more like specific events in that they contain similar levels of perceptual content and do provide a sense of re-experiencing (Addis et al. 2004; Rubin and Umanath 2015). Once these two requirements are met, the elaborateness of the simulation will not alter the presence or absence of MTT. For instance, a high-resolution snap-shot of a traumatic experience will not be elaborate given it is temporally-restricted to a few moments, and may be further limited by selective attention during the traumatic experience to the central (vs. peripheral) details (Kensinger et al. 2007). Nevertheless, these non-elaborate fragments can be associated with such strong re-experiencing that they are mistaken for present reality (e.g., in post-traumatic stress disorder; Brewin 2014).

4.2 Associative Processes Underpin the Constructive Simulation of Events

If memory and imagination are manifestations of the same neurocognitive system, then the operational rules of simulation should be the same irrespective of whether the simulation is a remembered or imagined event (or, as discussed in Section 4.5, a perceived event). The *modus operandi* of the constructive simulation system is associative, with different associative processes occurring at different levels of the simulation process: between elements, within and between schemas, and between schemas and the emergent simulation.

4.2.1 Associations between Elements

It is widely accepted that episodic memories are sets of associated elements that are reconstructed at retrieval (Schacter et al. 1998), and that the hippocampus is critical for mediating the (re)creation of associations at encoding and retrieval. Perhaps the most debated finding in the future imagination literature is differential future-related activity in the hippocampus. Specifically, while some aspects of the hippocampus are commonly engaged by remembering and imagining, the anterior hippocampus has been found to be more active when imagining versus remembering (Addis and Schacter 2012). This effect is more apparent when the future simulations are specific (Addis et al. 2011), are constructed de novo (van Mulukom et al. 2013) and are especially novel (e.g., implausible future events; Weiler et al. 2010). While Maguire and colleagues argue that the hippocampus supports scene construction during both memory and imagination (Hassabis and Maguire 2007), we have argued that the hippocampus plays a more general associative role, supporting the construction of both scenes *and* the events that play out within those scenes (Roberts et al. 2017a). That is, the hippocampus mediates the associations between *all* elements comprising the simulation, whether scene-related or not. In this vein, we previously interpreted differential anterior hippocampal activity as reflecting recruitment of additional, and possibly distinct, associative processes during future simulation, specifically the *recombination* of details, as compared to the *reintegration* of the previously associated details comprising a past event (Addis and Schacter 2012; Schacter and Addis 2007).

The hypothesis that remembering and imagining differentially taxes reintegration and recombination has been fruitful in terms of providing a basis for numerous empirical investigations. However, I recently reformulated this hypothesis (Addis 2018), instead proposing that all simulations – whether remembered or imagined – vary along a continuum of ‘associative strength’ depending on the associative history of constituent elements (i.e., whether elements have been associated previously; Horner and Burgess 2013). Associative strength reflects a change in the weights between elements that occurs simply by virtue of those elements occuring together (cf. Hebb 1949). For instance, an incoming perceptual element is processed with increasing depth as it proceeds from unimodal sensory to higher-order cortices and associated with other pre-existing, accumulating, or newly incoming elements to form increasingly elaborate and complex simulations (cf. Levels of Processing, Craik and Lockhart 1972; Hasson et al. 2015). Although any given simulation is a temporary, emergent construction, its generation changes the associative weights between its constituent elements. As a result of repeated similar experiences – either externally experienced (perceived) or internally generated (remembered/imagined) – layers of weights accumulate and further adjust the associative strength between constituent elements. Critically, increased associative strength means that the activation of one element is more likely to activate other strongly associated elements. In this way, associative strength influences and shapes subsequent simulations by influencing the particular elements/relations that will be reactivated together (e.g., 'chunks' or assemblages of associated elements may be incorporated). Moreover, when associative strength is sufficiently high, multiple elements may be fused or unitized to create a new singular element (Graf and Schacter 1989) albeit at a lower resolution.

Moreover, associative strength is the likely mechanism underlying the fluency of event simulations (cf. Michaelian 2011). Importantly, this more parsimonious (and continuist) explanation of how the simulation system supports the construction of both remembered and imagined events can still accommodate observed differences in associative processes. For example, associative strength can explain findings that past events are constructed more fluently and quickly than imagined events (Anderson et al. 2012; Wiebels et al. 2019), given that associative strength is higher for remembered events. As discussed further in Section 4.3, it can also account for the recasting of past events as future events by patients who cannot otherwise imagine the future (e.g., in semantic dementia; Irish et al. 2012b).

4.2.2 Associative Schematic Processes

Much recent attention has been focused on schemas within the context of memory, but less so on the contribution of schemas to other forms of simulation such as imagined events. It is generally agreed that a schema is a complex, higher-level knowledge structure with four defining features (Ghosh and Gilboa 2014; Gilboa and Marlatte 2017): (1) it is an associative network that organizes lower-level representations; (2) it is acquired gradually via the abstraction of elements (and their inter-relationships) that feature commonly across multiple experiences; (3) its constituent elements lack specific detail, being generalities derived from differing instances of similar experiences; and (4) it has a dynamic and adaptable structure, continually evolving with ongoing experience such that new information can be incorporated ('assimilation') or, when required, the structure itself can be modified to account for building evidence contrary to the current structure ('accommodation'). In addition to these essential characteristics are several non-essential features. For instance, schemas themselves can be organized hierarchically, with sub-schemas nested in one or more higher-order schemas. Notably, a shared sub-schema acts as a cross-connection between two higher-order schemas, but may also lead to competition between schemas. Moreover, chronology is a common organising framework for schemas, particularly event schemas, but it is important to note that chronological order does not render the schema fixed (although event scripts may be an exception; Schank and Abelson 1977). As Bartlett (1932) suggested, the ability to 'rupture' chronological relationships is critical for flexible and adaptive behaviour, otherwise all actions would be determined solely by the preceding event.

I propose that schemas provide structure to event simulations in the same way whether the event is perceived, remembered or imagined (Addis 2018). Relevant schemas are activated on the basis of available information, such as incoming perceptual and/or internally-generated information (e.g., prediction; Rumelhart and Ortony 1977). In the simplest case, a single pre-existing 'event' schema relevant to the situation is activated. As a template, the schema provides predictions about the elements that are/were/will be likely experienced in the past/present/future event, and if those details not readily available (i.e., not currently perceived or activated), the schema guides the addition of relevant conceptual content to the simulation. Rumelhart and Ortony (1977) suggest that elements within schemas are distributions of all possible values of that detail (based on cumulative experience), enabling generation of the most likely or typical 'default' value when necessary (e.g., when a specific value is not retrieved via memory, or incoming information does not specify the value). This process may be akin to the "filling in" of memories with conceptual information mentioned earlier (Michaelian 2011). It may be that many elements in a simulation typically considered 'episodic', such as perceptual details, are in fact conceptual (e.g., the 'average' restaurant table can be used in a simulation of a special dinner) unless the specifics of the simulated event demands the exact detail(s) be incorporated (e.g., the dress I stained while eating dinner). Moreover, the schema provides a structure in the form of predicted relations between elements, including the temporal, spatial and causal associations that predominate in simulations of events that unfold over time and in space.

The role of schemas in constructive episodic simulation is undoubtedly more complicated than this example, scaling with the complexity of the simulation itself. Multiple schemas will be activated including relevant 'event' schemas, each specifying elements and relations to be incorporated in the simulation, other relevant schemas (e.g., higher-order schemas, such as the self-schema, in which the event schema is nested), as well as 'reasoning schemas' that guide *how* other activated schemas are (consciously or unconsciously) adjusted, biased and/or integrated. That is, schemas not only shape the content of simulations, but also how we reason about the past, present, and future, and how we situate events more broadly with respect to our self and our lives (Section 4.4). Higher-level forms of relational reasoning, such as analogy and inference, involve mapping correspondences and creating higher-order relations between schemas (i.e., relations between relations; Gentner 1983; Holyoak 2012). These operations occur under the guidance of 'reasoning schemas' that reference current goals, contextual constraints and social norms, and rules for the reasoning process itself (e.g., cause-and-effect, preconditions, covariations; Hummel and Holyoak 2003; Rumelhart and Ortony 1977). Importantly, relational reasoning enables prediction, constraint and selection of the possible elements from all relevant elements specified in activated schemas, and the possible nature of their associations. Thus, relational reasoning facilitates the flexible reorganization of schemas and elements to construct new schemas (Holyoak 2012; Hummel and Holyoak 2003), and provides structure and coherence (e.g., temporal structure, causal structure, etc.) to our experience.

Relational reasoning may be particularly useful when a given simulation requires the creation of a new event schema to integrate weakly associated pieces of information. Although it has been previously speculated that a schema or "framework" is required to scaffold the integration of details into an event simulation (Irish et al. 2012a; Irish and Piguet 2013), the nature of this scaffolding process remains relatively unspecified. I propose that what has been referred to as scaffolding is *relational reasoning*. We recently suggested that when simulating novel or unusual events, processes such as conceptual expansion and spreading activation through semantic networks may be required to expand the 'simulation space' so as to incorporate disparate ideas into a novel yet coherent simulation (Roberts and Addis 2018). Such semantic processes likely fall under the purview of higher-level reasoning schema. While it has been suggested that conceptual knowledge may also play a direct role in integration (Irish and Piguet 2013), it seems unlikely to be the case. Although concepts and categories bear resemblances to schemas (e.g., being acquired gradually and organised in associative networks), their relative fixedness is a direct result of inter-relationships being based on fixed definitions (i.e., the defining features of a category; Ghosh and Gilboa 2014) and thus they lack the adaptability necessary for higher-level associative processes such as relational reasoning. In contrast, the flexible associative relationships comprising schemas (e.g., temporal associations) are well-suited to scaffolding the construction of a simulation.

Although much remains to be determined with respect to the role of schema in event simulations, what is clear is that schemas are essential to their construction, irrespective of temporal orientation. Importantly, differing levels of reliance on schemas may explain some of the apparent differences between different types of simulation, as discussed in more detail below (Section 4.3). Furthermore, the cognitive flexibility afforded by schema and relational reasoning may be the key to the adaptive nature of simulation. Perhaps the truly prospective aspect of MTT is found in the schemas that provide structure and meaning to our future perceptions, memories and imaginations (cf. Neisser 1976).

4.2.3 Associations between Schemas, Elements, and the Emergent Simulation

Given the flexible nature of schemas, it is unlikely that a framework generated early in event construction would remain static and untouched by the simulation process as it unfolds. Thus, I conceive of simulation as an iterative, dynamic process that unfolds over seconds to minutes (Addis 2018). As internally-generated and/or externally-perceived multimodal information is accumulated and integrated with the event schema, the emerging simulation is held online in working memory (cf. episodic buffer; Baddeley 2000) enabling it to be successively modified and refined. While such modifications include the addition of newly available elements (activated via association or perception), perhaps more important is the ongoing interactivity between the simulation and relevant schema. Critically, the iterative nature of the simulation process enables associative schematic processes to play out: it allows schemas to be modified or created in response to the emerging simulation, and for schemas to fill in, adjust, reorganize, or completely rework the simulation. The net sum is that (in most cases) the coherence, plausibility, and relevance (to self and goals) of the simulation is enhanced. The simulation is held online and continually refined until an event boundary is reached (Zacks et al. 2007); such boundaries include shifts in attention occurring both within the inner world (e.g., a change in an internally-generated event representation) and the external word (e.g., a change in context).

4.3 Continuums of Associative Processes in Simulation

In Addis (2018) I explained apparent differences between past and future events as reflecting different relative proportions of elements and schemas. Expanding upon that hypothesis, I suggest that during simulation, the contributions of both associative strength *and* associative schematic processes vary along continuums. The degree to which associative strength and/or schemas contribute to a given simulation very much depends on the nature of that particular simulation and is perhaps most dependent on its self-relevance. When imagining *non-personal events* (i.e., events that do not feature the self), the involvement of self-schemas decreases linearly with psychological closeness to the protagonist (de Vito et al. 2012a) as does the engagement of ventromedial prefrontal regions mediating self-schemas (e.g., D'Argembeau et al. 2010; Szpunar et al. 2007). Correspondingly, the inherent complexity of the simulation likely also decreases because, for one, it is not nested within the self-schema – the most complex, multidimensional knowledge structure that humans possess. Moreover, associative strength is likely lower for non-personal events, given that existing assemblages of pre-associated elements from one's prior experiences are less relevant, if at all. Non-personal events are not as elaborate as self-relevant events, for instance comprising fewer episodic details (Grysman et al. 2013), an effect also evident with disruption of self-schemas following ventromedial prefrontal damage (Verfaellie et al. 2019). The overall proportional resolution of non-personal simulations is also likely lower, with a greater proportion of lower-resolution elements such as general semantic knowledge (Szpunar et al. 2007). With lower reliance on the self-schema, as well as reductions in complexity, associative strength, elaborateness and proportional resolution, it is not surprising that imagining non-personal events is associated with lower activity levels in many DMN regions relative to imagining personal events (including parahippocampal cortex, posterior cingulate, and cuneus; e.g., D'Argembeau et al. 2010; Szpunar et al. 2007).

Turning to the spectrum of *self-relevant events*, all forms of simulation involve self-schemas (e.g., personal goals, trait self-knowledge, life narratives, etc.) albeit to differing degrees (e.g., simulations can be more or less relevant to personal goals; D'Argembeau and Van der Linden 2012). Figure 3 illustrates the proposed mapping of various types of self-relevant simulations to the continuums of associative strength and schema reliance, as well as to activation of the DMN and frontopartietal control network. Notably, the relation of the two continuums to brain networks differs. The degree of schema-reliance has a positive linear association with the involvement of anterior aspects of the DMN and frontopartietal control network to support higher-level relational reasoning processes and activation of conceptual content (Roberts and Addis

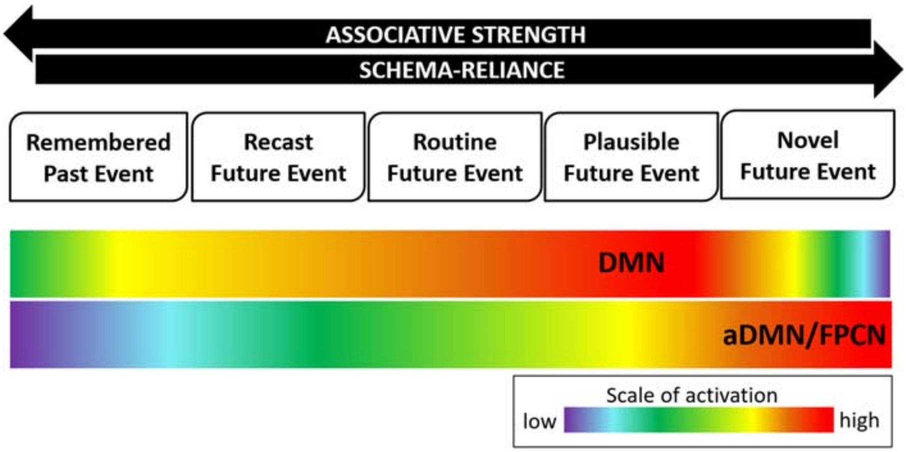

Fig. 3 Proposed mapping of various forms of self-relevant simulation to continuums of associative strength and schema-reliance, and to involvement of the default mode and related networks. aDMN = anterior DMN; DMN = default mode network; FPCN = fronto-parietal control network

2018). In contrast, associative strength has a non-linear, U-shaped relationship with DMN activity, increasing as associative strength decreases and constructive demands ramp up – but only to a point. Our neuroimaging studies suggest that the threshold sits somewhere between the simulation of plausible future events and highly novel or implausible events, and once reached, DMN activity decreases, while activity in anterior DMN and frontoparietal network increases. When taken together, these two continuums can explain the complex patterns of findings yielded by cognitive neuroscience research on past and future MTT over the last decade, including the results of our neuroimaging studies examining future simulation (used to illustrate these continuums below). Moreover, this conceptualization takes into account our increasing understanding of these whole brain networks as dynamic entities, with patterns of activity and connectivity (both within-network and with other networks) shifting as required by ever-changing situational demands (Cabral et al. 2014; Shine et al. 2016).

At one end of the continuums are the types of simulation that allow for the incorporation of large assemblages of related elements with strong associative weights, such as *remembered past events*. For instance, past events will, on average, contain a higher proportion of strongly-associated elements than most future events and are therefore constructed more fluently. Thus, although the DMN is active, it is not maximally so, as indicated by studies showing activity during future simulation exceeds that during remembering (e.g., Addis et al. 2007). Although the contribution of schemas during remembering is at the lower end of the continuum, schemas nevertheless play a number of roles, including (but not limited to) organizing activated elements, identifying inaccurate, irrelevant, or missing content, guiding corrections or the filling of gaps, and relational reasoning between the event schema and other relevant schemas such as the self. Next, imagining future events by *recasting past events* into the future is highly similar to remembering, again utilizing substantial chunks of content where elements are linked by strong associations. Schematic input will also be required as it is in remembering, thus fairly limited but with the addition of situating the recast event in the future and ensuring the content is still relevant and plausible. To my knowledge, no neuroimaging study has directly examined recast events, however, this phenomenon has been observed in patients with semantic dementia who can recall past events and recast past events into the future, but are unable to imagine novel future events (Irish et al. 2012a), exemplifying the similarity of remembering and recasting. *Imagining general future events*, such as routines, can also leverage sizeable 'chunks' of previously associated information (e.g., from recent routines); if imagining a novel routine, the degree of associative strength decreases, while dependence on schemas increases along with constructive demands. Even so, the constructive demands and degree of DMN activity are unlikely to exceed that evident when simulating specific future events.

Further progressing along these continuums, imagining specific *plausible future events* is associated with greater DMN activity relative to imagined routines and past events (Addis et al. 2011). Given that many regions in the DMN are thought to mediate the flexible associations underpinning episodic memory, why would activity in the DMN peak when associative strength – and thus elaborateness and proportional resolution – is lower than in other types of simulation, such as past events (D'Argembeau and van der Linden 2004)? Drawing on recent evidence regarding the role of the DMN in the online processing of narratives (Baldassano et al. 2017; Chen et al. 2016; Hasson et al. 2015), it may be that higher-level DMN regions (e.g., angular gyrus, posterior cingulate) accumulate activated elements and hold the emerging simulation online, while iterative interactions with schemas serve to refine the simulation. Critically, holding a larger collection of singular or weakly associated elements online (as is proposed to be the case with future events) is a more intensive operation than holding a few chunks of associated elements (as with past events), thus placing greater demands on the DMN. However, this is not to say that future simulations are only comprised of singular elements. Chunks of elements will still be activated (in addition to singular elements), particularly when future simulations are plausible, hence associative strength is not at floor level in Fig. 3. Nevertheless, it is likely that these chunks will be smaller than those comprising remembered events, thereby effectively increasing the number of elements held online. Additionally, it may be that strength of pre-existing associations within or between these chunks are looser or more distant, and thus more DMN support is required to keep them active for the duration of the simulation. Importantly, this proposal can also explain greater activity in anterior DMN regions, including the anterior hippocampus, during future relative to past events (Addis 2018). Increased schema-reliance has been associated with activity in and connectivity between anterior hippocampus and medial prefrontal cortex (Gilboa and Marlatte 2017; Gilboa and Moscovitch 2017) and, if schema-reliance is associated with a greater proportion of conceptual elements, activity and connectivity between anterior hippocampal and anterolateral temporal cortex (Binder et al. 2009; Sheldon and Levine 2016) should also be heightened.

When imagining *novel future events*, however, the experience being simulated diverges sufficiently from previous experience (e.g., novel/implausible situations) that the associative strength of the content decreases. Consequently the elaborateness of these simulations is lower; it is more difficult to flesh out a simulation in detail when one is less familiar with the situation, when more remote associations are incorporated, and when elements comprising the simulation are strongly associated to other, irrelevant content. Thus, with fewer elements being integrated and held online, overall demands on posterior DMN regions (e.g., angular gyrus, posterior cingulate) in particular are likely to be lower. We observed this phenomenon during simulation of future events involving incongruent (relative to congruent) details (Roberts et al. 2017b), as have others during tasks involving simulation of events in unfamiliar (versus familiar) contexts (Szpunar et al. 2009).

Schema-reliance also increases under such conditions, as a more explicit structure for the simulation – that might otherwise be provided by 'chunks' of strongly-associated elements if the event were closer to previous experience – is needed. However, given that the simulation is overall less elaborate and the schematic framework more tenuous, there is less evidence of increased engagement of anterior regions of the DMN. Interestingly, in the Roberts, Wiebels, et al.'s (2017b) study, anterolateral temporal activity only emerged in the incongruent simulation condition when examining the coupling of the DMN with other brain networks such as the frontoparietal control network, as well as the salience network (thought to support a switching function that facilitates interactivity between the DMN and frontoparietal control network, Menon and Uddin 2010). Such findings fit with the notion that brain networks functionally couple and uncouple as required by task demands, and a number of studies report the emergence of connectivity between DMN and frontoparietal control network as the need for flexible or creative thinking increases (e.g., Beaty et al. 2015; Roberts and Addis 2018; Spreng et al. 2010). Such flexible thinking is required to a greater degree when existing schemas are inadequate and require modification, including integration with other schemas to construct a feasible framework via associative schematic processes (e.g., relational reasoning; see Section 4.2.2). Notably, Roberts, Wiebels, et al. found that individual differences in the capacity to think flexibly during future simulation was associated with activity in lateral temporal cortex as well as the rostrolateral prefrontal cortex. Critically, this latter region borders the anterior DMN and frontoparietal control network, and has been implicated in relational reasoning (e.g., Christoff et al. 2001). Moreover it is logical to predict that there will be an increase in medial prefrontal activity give this region's purported role in supporting schema (Gilboa and Marlatte 2017). However, this might not be evident if the quantity of schematic information active is similar to when imagining plausible events, even if used more flexibly; this will be a question for future research.

It is important to note that although schema-reliance and associative strength vary across this spectrum of simulation tasks, from past events through to novel or implausible future events, neither process is unique to the simulation of past or future events, and both remembering and imagining is associated with coupling of the DMN and frontoparietal control network (Dixon et al. 2018). These continuums have been constructed on the basis of findings that reflect the *average* characteristics across multiple simulations, but individual simulations can diverge from this pattern. For instance, some past events are low in associative strength and high in schema-reliance, such as 'patchy' or schema-inconsistent memories that are difficult to reconstruct, less elaborate, and more conceptual in nature (Webb et al. 2016).

4.4 Situating Simulations within Cognitive Spaces

In this reformulation of constructive episodic simulation, I propose that simulations are situated within multi-dimensional cognitive spaces akin to cognitive maps (Tolman 1948). Research on cognitive maps has primarily focused on spatial mapping (O'Keefe and Nadel 1978), with the discovery of specific cell types in the medial temporal lobes coding for particular aspects of environmental space (e.g., place and border cells), associations and distances between those aspects (e.g., grid cells), and between the self and the environment (e.g., head direction cells). However, attention is shifting to cognitive maps beyond spatial navigation, including non-spatial contexts, time, social space (including social networks and the location of others in space), and the self (for recent reviews see Arzy and Schacter 2019; Behrens et al. 2018), supporting the compelling prediction that simulations can be situated within multi-dimensional cognitive space(s). These spaces have the capacity to code for complex inter-relationships between all aspects of experience (i.e., the associations between schemas), and also to facilitate inferences about unexperienced simulations. That is, building up a space of associations between schemas will also inherently code for the "spaces in between" existing schemas – what Behrens et al. (2018) call the latent state space – which constrains possibilities thereby facilitating sophisticated reasoning and deduction (see Dannenberg et al. 2018 for a similar view). These cognitive space(s) thus enable the creation of associations that have never been experienced in reality – for instance, between events separated in time and space, between separate events that share a common element (i.e., transitive inference) or regularities (i.e., statistical learning). Importantly, these processes enable the generalization of schemas to different situations, thus allowing for flexible behaviour across shifting situations and providing priors to inform predictions (see Section 4.5).

An interesting proposal from Arzy and Schacter (2019) is that the self continually interacts with cognitive maps. Specifically, cognitive mappings code the location of the self within the space as a point of reference, enabling for instance, translations between allo- and ego-centric forms of spatial navigation, and between past and future events within the timeline of one's own life. Moreover, the self contributes priors (e.g., expectations, beliefs, etc.) that further shape relevant cognitive maps. This theory conceives of the self and cognitive maps as distinct types of entities, but I would argue that the self is a cognitive space in its own right. Over a lifetime of experience and reflection, we construct and continually refine distributions of various aspects of the self (e.g., one's life story, trait self-knowledge, etc.), meaning that the self is the most elaborate knowledge structure we possess. As such, the 'self space' is likely the overarching cognitive space within which schemas of all self-relevant simulations are nested. Simulations of remembered and imagined events constructed within this space would inherently possess a level of complexity conferred from being embedding within the self space. Critically, this nesting is one of the necessary conditions of MTT I suggest in Section 4.1 (along with the simulation having a sufficient proportion of high resolution elements). Ernst et al. (2019) make a similar suggestion, arguing that the integration of future events with high-level autobiographical knowledge (including aspects of self, such as personal goals) contextualizes the events within the cognitive space of one's life. Their results demonstrate that pre-experiencing vivid future events (i.e., future MTT) is not sufficient to convey the sense that the event will actually occur in one's future without this contextualization with autobiographical knowledge; similar findings are reported for remembered past events (Scoboria et al. 2014).

Although speculative, I hypothesize that the role of the hippocampus in simulation is to localize any given past or future event within relevant multi-dimensional cognitive space(s). For instance, if thinking about my good friend Geneviève, my current representation of her could be positioned within any number of cognitive spaces: a space of shared experiences, a social map (networks of inter-related friends and colleagues), a spatial map (e.g., where she lives/works, places we frequent), my self schema (e.g., where she fits in my life story, traits we do and don't share), other conceptual spaces, and so forth. Cognitive spaces could possess any number of interacting dimensions. This hypothesis therefore implies that cells that appear to be spatial in nature (e.g., place cells, etc.) may have putative mapping functions that can be utilized within any activated cognitive space(s). By this account, the hippocampus does not *construct* or represent simulations per se, but rather acts to contextualize the emergent simulation within broader knowledge structures. Indeed, the hippocampus has reciprocal connectivity with most areas of the brain, positioning it anatomically to play such a role. Although this proposal requires much research, this idea could help to reduce the tension between spatial/relational, and mnemonic/prospective accounts of hippocampal function.

4.5 Simulation as a Domain-General Cognitive Capacity

Where does this simulation system sit with respect to other domains of cognition? I have previously suggested that perception is associated with the schema-guided construction of an internal simulation of experience – a process that is fundamentally no different to remembering or imagining events (Addis 2018). In other words, perception is underpinned by the same neurocognitive system as memory and imagination. During perception, various streams of incoming sensory information are processed and continually interact with relevant schemas to form an emerging simulation supported by higher-level DMN regions. Importantly, schemas also guide the incorporation of pre-existing elements into the simulation of present experience, such as previously-perceived elements (depending on associative strength with activated elements) and conceptual knowledge, to fill in gaps in perception, provide deeper levels of meaning, and so on. Essentially this simulation process is the same as that engaged during remembering and imagining, although the balance of incoming to pre-existing elements will be different. One important implication of this hypothesis for the construct of MTT is the possibility that both 'travel' and 'time' are not *essential* to constructing a mental rendering of experience. Projecting the self beyond the present – into the past, the future, or fictional worlds – might be only one instantiation of a domain-general simulation capacity that also enables us to comprehend the present.

While this theoretical view departs from most of the (mildly discontinuist) theories currently influential in psychology and cognitve neuroscience, there are some notable exceptions that have taken a similar continuist stance. In their Levels of Processing theory, Craik and Lockhart (1972) proposed that what we think of as memory is actually the processing of information, including the perception of incoming information. That is, there is *"no special 'store' or 'faculty' of memory—or even special memory processes. Encoding processes are simply those processing operations carried out primarily for the purposes of perceiving, understanding and acting; retrieval processes ('remembering') represent an attempt on the cognitive system's part to re-enact encoding processes as completely as possible"* (Craik 2007, p. 132; for similar 'processing' models, see Fuster 1997; Hasson et al. 2015; McIntosh 2007). Neisser (1976) also viewed memory as non-distinct from other aspects of cognition and perception. Rather, he argued that what we construe as memory is just one manifestation of experience-dependent modifications of the schemas that have guided our previous actions and perceptions, and that will do so again in future.

Interestingly, Neisser's (1976) approach, and my own proposal herein, can also be considered variants of predictive coding theory. Predictive coding proposes interactions between an *internal model* of experience and actual experience, with the difference between the two ('prediction error') being used to revise the model thus improving its predictive power during subsequent experiences. Work on predictive coding has focused on how predictions facilitate and modify perception (e.g., Dayan et al. 1995), but it is also being applied to how multiple internal models simultaneously guide our inferences in complex social environments (Isomura et al. 2019). My proposal is built on predictive coding principles: an ongoing, dynamic bi-directional interactivity between schemas (models of prior experience) and the emergent simulation (one's current conscious experience) whereby schemas shape the simulation, and the simulation modifies schemas. Moreover, 'predictive error' signals when a schema fails to provide an adequate model which can then be either switched out or modified via relational reasoning processes.

It is likely that neural dynamics play an important role in supporting ongoing interactions between schemas and the emerging simulation to enable its iterative refinement. For instance, the simulation itself – as an emergent and transient mental construction – may be underpinned by small networks (or 'process-specific alliances') that assemble and disassemble as needed (Cabeza and Moscovitch 2013). In fact, small transient patterns may each reflect different assemblies of associated elements (the 'chunks' of content referred to in Section 4.3) integrated to form the event simulation. Moreover, cyclical oscillations (perhaps if viewed as ongoing 'waves' of information transfer) may support the *iterative* top-down and bottom-up interactions between cortical regions supporting schemas (ventromedial prefrontal cortex), conceptual elements (anterolateral temporal cortex) and perceptual elements (sensory-specific cortices) held together online as a simulation by higher-level DMN regions (angular gyrus, posterior cingulate). Moreover, as the simulation is iteratively constructed, each version would need to be situated in relevant cognitive spaces by the hippocampus if latent inferences are to be leveraged in refining the simulation. However, research exploring the unfolding sequence of the neural dynamics during simulation, and the frequencies at which these processes exist, using techniques such as electroencephalography and magnetoencephalography, is required to test these speculative hypotheses.

5 Summary and Conclusions

Simulation is the ongoing process of interpreting and understanding our own realities; each individual's unique experiential history modifies their schemas as well as their idiosyncratic corpus of previously-encountered elements (including the associative strength between said elements), and moulds the multi-dimensional cognitive spaces in which these simulations are situated. My reformulation of the constructive episodic simulation hypothesis takes a more continuist position than we have previously, demonstrating that memory and imagination are the *same* process underpinned by the *same* neurocognitive system. First, this *domain-general simulation system* acts on the same information; schemas and elements at various levels of resolution (ranging from perceptual features to concepts) are used to construct simulations of past and future experiences that vary in proportional resolution (i.e., the balance of elements at various resolutions), elaborateness, and complexity. Second, the same rules of operation govern memory and imagination. Simulation is an inherently constructive process governed by associative processes operating at different scales: associations (of varying strength) between elements; associative schematic processes that enable construction of a suitable schema (e.g., relational reasoning), as well as the dynamic interplay between schemas and the simulation itself (cf. predictive coding); and finally, associations between schemas that form multi-dimensional cognitive spaces within which any given simulation is mapped by the hippocampus. Third, memory and imagination are subserved by the same neurocognitive system: the DMN, with the dynamic involvement of the frontoparietal control network (with the salience network interfacing the two) as required. I have argued that this simulation system can be leveraged in service of other forms of cognition, including the perception of ongoing experience – a proposal with important implications for the concept of 'MTT'. Not only is 'time' a non-essential aspect of MTT given that simulations of perception reflect the present, it also obviates the need for 'travel' as simulating current experience does not remove one entirely from their present. This leaves 'mental' – that simulation is the *mental* rendering of experience – as the central process. Indeed, projecting the self into the past, the future, and/or fictional worlds are only some instantiations of a general simulation capacity that also enables us to comprehend and respond to the ever-changing complexities of the present.

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