Zooming in and out on one's life: autobiographical representations at multiple time scales

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Abstract

The ability to decouple from the present environment and explore other times is a central feature of the human mind. Research in cognitive psychology and neuroscience has shown that the personal past and future is represented at multiple time scales and levels of resolution, from broad lifetime periods that span years to short-time slices of experience that span seconds. Here, I review this evidence and propose a theoretical framework for understanding mental time travel as the capacity to flexibly navigate hierarchical layers of autobiographical representations. On this view, past and future thoughts rely on two main systems—event simulation and autobiographical knowledge—that allow us to represent experiential contents that are decoupled from sensory input and to place these on a personal timeline scaffolded from conceptual knowledge of the content and structure of our life. The neural basis of this cognitive architecture is discussed, emphasizing the possible role of the medial prefrontal cortex in integrating layers of autobiographical representations in the service of mental time travel.

INTRODUCTION

Time is a central feature of mental life. All we ever directly experience is the present moment, and yet our minds relentlessly create other times. Consider the myriad of mental trips to the past and future that we make on a daily basis: we think about what we did minutes ago, remember a conversation we had yesterday, reflect on a decision we made last year, make plans for the week-end, ponder options for our next vacation, envision opportunities for our career, and so forth. This ability to decouple from the present environment—mental time travel—is no small feat and may be central to what makes us humans (Suddendorf & Corballis, 2007; Tulving, 2005). Its significance and impact on personal and collective life cannot be overstated—it drives many of our decisions and actions (Baumeister et al., 2016), and grounds our very sense of who we are (Prebble et al., 2013).

The cognitive and neural mechanisms that support mental time travel are increasingly well understood (D'Argembeau, 2012; Schacter et al., 2012; Sheldon & Levine, 2016; Suddendorf et al., 2018; Szpunar, 2010). Research has shown that mental representations of past and future events are constructed from informational contents provided by episodic and semantic memory (Irish & Piguet, 2013; Schacter et al., 2017). In addition, a growing number of studies suggest that mental time travel also relies on higher-order autobiographical knowledge—general representations of one's past and anticipated future—which places remembered and imagined events in a personal life context (Conway, 2005; D'Argembeau & Mathy, 2011). Here, I review this evidence and propose a theoretical framework for understanding mental time travel as the capacity to flexibly navigate layers of autobiographical representations at multiple time scales, from broad lifetime periods that span years to short-time slices of experience that span seconds.

REPRESENTATIONS OF THE PERSONAL PAST

A wealth of evidence indicates that the personal past is represented in memory at multiple time scales and levels of specificity or generality (Burt et al., 2003; Conway & Bekerian, 1987; Dijkstra & Kaup, 2005; Mace & Clevinger, 2013; Piolino et al., 2010; Skowronski et al., 2007; Thomsen, 2009). Not only are we able to remember specific events, but we extract regularities from our experiences (Barsalou, 1988), organize them in coherent themes and sequences (Brown & Schopflocher, 1998), and ultimately construct an overarching personal story that gives meaning and purpose to our life (McAdams, 2001). Fundamentally, this diversity of memory representations can be understood in terms of two main representational systems that retain traces of prior experiences and that organize knowledge about the content and structure of our life: episodic memory and autobiographical knowledge (Conway, 2001, 2005).

Episodic memory

Episodic memory represents dimensions of prior experience (e.g., perceptions, actions, thoughts, emotions) for events that usually span minutes or hours, allowing us to mentally relive specific happenings—a lunch with colleagues, a trip to the library, a conversation with a friend, and so forth (Conway, 2009; Tulving, 2002). The various features that constitute an experience are processed in distributed brain regions and the evidence suggests that the medial temporal lobe (in particular the hippocampus) is involved in the integration of memory details to support the conscious representation of past events (Davachi, 2006; Horner & Doeller, 2017; Moscovitch et al., 2016; Reagh & Ranganath, 2018; Rugg & Vilberg, 2013; Schacter et al., 1998). Of particular interest here are studies that shed light on the temporal structure of episodic memories, revealing how the unfolding of events is represented.

Memories for real-life events are typically composed of a succession of moments or slices of prior experience that are organized in chronological order (S. J. Anderson & Conway, 1993; Jeunehomme et al., 2018; Radvansky et al., 2005). Cognitive and neural evidence indicates that these memory units are formed as a result of the segmentation of experience into discrete events and sub-events (for reviews, see Brunec, Moscovitch, et al., 2018; Clewett et al., 2019; Radvansky & Zacks, 2017). Dynamic changes in various dimensions of ongoing experience (e.g., locations, characters, objects, and goals) determine the perception of event boundaries (Zacks et al., 2007), which structure the integration and separation of information into meaningful memory components (Clewett et al., 2019; Radvansky & Zacks, 2017). A recent fMRI study provided compelling evidence that event segmentation processes occur at multiple time scales throughout the cortical hierarchy, beginning with short segments in primary sensory regions and building into event models in the posteromedial cortex and angular gyrus, with the latter corresponding to a larger extent to the segments identified by human observers (Baldassano et al., 2017). Event boundaries in higher-level areas triggered the hippocampus to encode the current situation model into episodic memory, which was later reinstated during memory retrieval (see also Ben-Yakov & Henson, 2018). These and related findings suggest that episodic memories are structured by the interplay of the hippocampus and cortical regions that segment ongoing experience into meaningful units; remembering then involves the reinstatement of a specific event representation in these cortico-hippocampal networks (Oedekoven et al., 2017; Reagh & Ranganath, 2018).

It is important to note, however, that episodic memories are not literal reproductions of the past, but instead summary representations that are constructed from fragments of prior experiences (Conway, 2009; Schacter et al., 1998). While the distinction between episodic and semantic memory is conceptually useful, it is increasingly apparent that the two systems are inextricably intertwined and that the content of episodic memories typically include a conjunction of event-specific information (e.g., perceptual and contextual details) and conceptual processing, reflecting the influence of event schema during remembering and the reinstatement of conceptual processes that were engaged while experiencing past events (Binder & Desai, 2011; Greenberg & Verfaellie, 2010; Irish & Piguet, 2013; Renoult et al., 2019; Strikwerda-Brown et al., 2019).

The fact that episodic memories are not literal reproductions of the past is notably highlighted in recent studies showing that the unfolding of events is temporally compressed when remembering: events are mentally replayed at a faster rate than the actual event duration (Faber & Gennari, 2015; Jeunehomme & D'Argembeau, 2019; Michelmann et al., 2019). To investigate how this compression mechanism operates, Jeunehomme et al. (2018) capitalized on wearable camera technology to compare the temporal structure of episodic memories with the actual content and duration of past events. It was found that memories often included temporal discontinuities in the representation of the unfolding of events: some portions of events were not represented during mental replay (see also Jeunehomme & D'Argembeau, 2019). A recent study that tracked memory replay of video clips using magnetoencephalography provided further evidence for this time-compressed replay mechanism: some video fragments were replayed at the same speed as perception whereas other fragments were skipped, such that mental replay was overall faster than perception (Michelmann et al., 2019). The global rate of episodic memory compression is not constant but varies across events, and depends in part on the grain size of event segmentation (Jeunehomme & D'Argembeau, in press).

Overall, the evidence suggests that episodic memory retains moments or slices of prior experience in chronological sequences that represent the unfolding of events. The temporal structure of memories depends on cortico-hippocampal mechanisms that segment and store events in discrete chunks of experience. The resulting memories are not literal records of experience and often include temporal discontinuities, such that the unfolding of events is represented in a time-compressed form.

Autobiographical knowledge

Autobiographical knowledge involves more abstract, conceptual representations of the events and periods that constitute our life (Conway, 2005; Renoult et al., 2012; Thomsen, 2015). It provides an organized set of representations containing factual knowledge about single life events (e.g., I know that I was in Los Angeles for my 30th birthday), as well as knowledge of regularities in experience (e.g., I know that I lived in Los Angeles for a year). While the organization of autobiographical memory is still debated (see e.g. Brown, 2016; Mace & Unlu, 2019; Schulkind et al., 2012), an influential view is that different layers of autobiographical knowledge are structured in partonomic hierarchies (Barsalou, 1988; Conway & Pleydell-Pearce, 2000).

Conway and Pleydell-Pearce (2000) distinguished between three main domains of knowledge representation that differ in levels of specificity and temporal scope: lifetime periods, general events, and event-specific knowledge. Knowledge in lifetime periods represent features (e.g., places, people, objects, goals, and activities) that were characteristic of delimited spans of time in our life, usually in the range of months or years (e.g., when I lived in X; Thomsen, 2015).[1] General events include knowledge about repeated events (e.g., tennis matches when I was a child), single events that were extended in time (e.g., my trip to Paris last summer), and sets of events that were organized in sequences (e.g., learning to drive) (Barsalou, 1988; Brown & Schopflocher, 1998). Finally, event-specific knowledge concerns experiences that occurred at a specific time and place (e.g., the time I broke my arm at school; Burt et al., 2003). Here, it is useful to distinguish between the experiential content of specific events (which involves episodic memory, as outlined above) and conceptual knowledge about the occurrence of events—representations of the essential content or theme of events, referred to as their gist (Brainerd & Reyna, 2002) or conceptual frame (Conway,

[1] How knowledge of lifetime periods is formed in long-term memory remains to be investigated in detail. According to Brown (2016), lifetime periods derive directly from the structure of experience and represent spans of time during which a person's life experiences are fairly stable (i.e., a period characterized by many repeated experiences). During periods of stability, associations between frequently co-occurring event components are formed, which capture our knowledge of repeatedly encountered people, places, objects and activities. The beginning and end of periods are marked by transitions—events that bring about changes in what people experience on a daily basis. On this view, important life transitions play an important role in organizing memories, regardless of whether these transitions are personal (e.g., a relocation, the birth of a child) or collective (e.g., a war) in nature (Brown et al., 2016).

2009)—which is organized in the autobiographical knowledge base (see also Sheldon, Fenerci, et al., 2019, for a similar distinction between conceptual and perceptual aspects of specific events). It should be noted, however, that while it is useful to distinguish between different knowledge domains, autobiographical representations may in fact involve a continuum of abstraction rather than strict categories (Renoult et al., 2012).

The hierarchical view of autobiographical knowledge organization contends that specific events are represented as parts of general events, which are themselves nested in lifetime periods (Conway, 2005; Conway & Pleydell-Pearce, 2000). For example, the lifetime period "elementary school" may include a series of extended and repeated events, such as "a vacation in Greece", "math lessons in fourth grade", and "Sundays at grandma's house"; each of these general events may in turn subsume a series of specific events that occurred on a given day. This organizational structure has notably been demonstrated in experiments showing that memories of specific events are often embedded in overarching memory structures—corresponding to general events and sometimes referred to as *event clusters*—that organize information about a set of causally or thematically related events (Brown, 2005; Brown & Schopflocher, 1998; Burt et al., 2003).

Autobiographical knowledge may be key to retaining episodic memories in a durable form (Conway, 2001, 2005). Numerous memories are formed each day, but most of these rapidly become difficult to access (i.e., after a few days), unless they are linked to higher-order goals and event structures. Once this integration process has taken place, the retrieval of events not only involves event-specific details—stored in episodic memory—but also higher-order autobiographical knowledge, which places events in a broader life context (Conway, 2005).[2] For example, my mental image of making a sand castell on the beach (an episodic memory) is contextualized by the knowledge that this event happened during a week-end on the Belgian seacoast with my grand-parents (a general event) when I was in primary school (a lifetime period).

Variations in the degree of abstraction of autobiographical representations are reflected in the underlying brain activity. Autobiographical memory retrieval involves widely distributed brain regions, including the medial prefrontal cortex, medial and lateral temporal areas, posterior cingulate/retrosplenial cortices, and inferior parietal lobes (Cabeza & St

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[2] This view is consistent with research on the role of schemas (i.e., summary representations of commonalities across multiple experiences) in memory encoding, retention, and retrieval (Gilboa & Marlatte, 2017), but it should be noted that autobiographical knowledge includes not only summary representations of repeated experiences but also other forms of knowledge about the personal past, such as representations of extended events (Barsalou, 1988) and sets of causally or thematically related events (Brown & Schopflocher, 1998).

Jacques, 2007; Kim, 2012; McDermott et al., 2009; Spreng et al., 2009; Svoboda et al., 2006), and different types of autobiographical representations have been associated with specific neural signatures within this network (Addis et al., 2004; Holland et al., 2011; Levine et al., 2004; Renoult et al., 2016). Of particular interest, a meta-analysis revealed a shift in brain activation from posterior to anterior structures with increasing levels of abstraction of autobiographical contents (Martinelli et al., 2013). The retrieval of specific memories predominantly activated the medial temporal lobes (the hippocampus and parahippocampal gyrus) and posterior cortical structures (including the precuneus and posterior cingulate/retrosplenial cortices)—regions that largely correspond to the episodic recollection network (Rugg & Vilberg, 2013). On the other hand, the retrieval of higher-order autobiographical knowledge—including autobiographical facts, general events, and abstract self-representations—was mainly associated with frontal and lateral temporal regions. Interestingly, the medial prefrontal cortex (mPFC) was the only brain region that was commonly activated by different types of autobiographical representations (see Figure 1A).

The involvement of the mPFC in the retrieval of self-knowledge is well established (Denny et al., 2012; Lieberman et al., 2019), but its exact function remains unclear. Substantial evidence points to a role in schema processing and the integration of incoming information with existing knowledge structures (for review, see e.g. Brod et al., 2013; Gilboa & Marlatte, 2017; Robin & Moscovitch, 2017; van Kesteren et al., 2012), as well as the resolution of conflict and minimization of interference among memory representations (Guise & Shapiro, 2017; Preston & Eichenbaum, 2013). However, the mPFC has also been associated with many other functions, including reward (Sescousse et al., 2013), affect (Roy et al., 2012), valuation (Levy & Glimcher, 2012), decision-making (Bechara & Damasio, 2005), and social cognition (Van Overwalle, 2009). While a theoretical account that integrates the diversity of tasks and domains that involve the mPFC is still awaited, several views converge in pointing to the role of the mPFC in integrating multiple sources of information to compute the broader (e.g., contextual, affective, causal, evaluative, and social) meaning of stimuli or events (Brod et al., 2013; Krueger et al., 2009; Lieberman et al., 2019; Preston & Eichenbaum, 2013; Roy et al., 2012). Thus, in the context of autobiographical remembering, one possibility is that the mPFC serves as an information processing hub that integrates and organizes layers of autobiographical knowledge (see also Moscovitch et al., 2016). This potential role is consistent with fMRI evidence that memories that are integrated in autobiographical clusters are associated with greater mPFC activity, and with increased functional connectivity between the mPFC and posterior regions supporting semantic and episodic memory representations (Demblon et al., 2016) (see Figure 1B). Furthermore, a dorsal region of mPFC has been associated with reflective thinking on the importance and implications of autobiographical events (D'Argembeau et al., 2014). These findings suggest that the mPFC may integrate specific experiences with higher-order autobiographical knowledge, thereby providing a personal context to remembered events. Thus, while the hippocampus supports the conjunction of elements (e.g., entities and their spatial context) that constitute representations of specific events (Cowell et al., 2019), the mPFC may provide an integrated set of associations that go beyond individual events and determine their broader meaning or context (Milivojevic et al., 2015).

In summary, the cognitive and neural evidence reviewed so far indicates that the personal past is represented in layers of knowledge that differ in temporal scopes and levels of specificity or abstraction. Episodic memory depends on cortico-hippocampal mechanisms that organize moments of prior experience in chronological sequences to represent the unfolding of specific events. When maintained in a durable form, episodic memories are integrated with autobiographical knowledge structures that organize information on the content and structure of one's life. Layers of autobiographical knowledge are organized hierarchically in specific events, general events, and lifetime periods. The mPFC may contribute to integrate different knowledge levels across this organizational structure, allowing one to situate mental representations of specific experiences in a broader life context.

-Figure 1 about here-

REPRESENTATIONS OF THE PERSONAL FUTURE

Mental time travel is of course not limited to the past; in fact, we may spend more time thinking about the future than the past in our daily life (F. T. Anderson & McDaniel, 2019; D'Argembeau et al., 2011). Prospection allows us to consider potential future scenarios (e.g., to evaluate opportunities and threats, to envision different courses of action, and to anticipate their consequences), which plays an important role in guiding many aspects of cognition and behavior, including decision-making (Bulley et al., 2016), planning and goal-directed actions (Bulley & Irish, 2018), emotion regulation (Jing et al., 2016), creativity (Addis et al., 2016), and empathy (Gaesser & Schacter, 2014).

Episodic future thinking

A mode of prospection that has received much attention in recent years is *episodic future thinking* (also sometimes referred to as *episodic simulation* or *episodic foresight*), which is the ability to imagine specific events that might happen in our personal future (Atance & O'Neill, 2001; Schacter & Addis, 2007; Suddendorf & Corballis, 2007; Szpunar, 2010). Although not without flaws (Gilbert & Wilson, 2007), episodic future thinking allows us to mentally pre-experience potential events: we can simulate what it would be like to find ourselves in a given situation by picturing its contextual setting and associated objects, people, actions and emotions in our mind's eye (D'Argembeau & Van der Linden, 2004).

Important progress has been made in understanding the cognitive and neural mechanisms of episodic future thinking, with several lines of evidence pointing to the key roles of episodic and semantic memory in the capacity to mentally simulate future events (for a recent review, see Schacter et al., 2017). Neuropsychological studies have shown that patients who have deficits in episodic or semantic memory have difficulties imagining future scenarios (Addis et al., 2009; Hassabis et al., 2007; Irish et al., 2012; Klein et al., 2002; Race et al., 2011). Neuroimaging evidence indicates that the imagination of future events activates brain regions underlying episodic and semantic memory, including the medial temporal lobe, posteromedial cortex, lateral temporal cortex, and inferior parietal lobe (Benoit & Schacter, 2015; Binder & Desai, 2011). Cognitive studies have revealed that imagined events are more detailed when their contextual setting is associated with richer memory traces (D'Argembeau & Van der Linden, 2012; de Vito et al., 2012; Robin & Moscovitch, 2014; Szpunar & McDermott, 2008).

These and other findings indicate that episodic and semantic memory representations provide sources of information for imagining future events. An influential view is that episodic memory allows us to flexibly retrieve and recombine elements of our past experiences (e.g., details about locations, persons, objects, and so forth) into novel representations of events that might occur in the future (Schacter & Addis, 2007; see also Suddendorf & Corballis, 2007). The hippocampus is thought to play a key role in this constructive process (Addis & Schacter, 2012; Sheldon & Levine, 2016), and may be particularly involved in the integration of event details into a coherent spatial scene (Hassabis & Maguire, 2007; Mullally & Maguire, 2014). Besides episodic memory, semantic knowledge contributes to the imagination of future events by providing the conceptual scaffold that is required for constructing meaningful scenarios (Irish & Piguet, 2013). Notably, the temporal organization of event segments may be supported by semantic knowledge of how various entities (e.g., persons, objects) typically relate during the course of events (e.g., knowledge about action sequences and causal relations; Radvansky & Zacks, 2011; Sheldon, Gurguryan, et al., 2019).

Only a few studies have examined the temporal structure of episodic future thoughts, but existing evidence suggests that the unfolding of experience is represented in a similar way for past and future events. Event segments are organized in chronological order both when remembering past events and when imagining future events (R. J. Anderson et al., 2015). As with episodic memories, episodic simulations represent the dynamic unfolding of events in a compressed form; for example, the time it takes to mentally simulate a route is shorter than the time it takes to actually navigate it (Arnold et al., 2016; Bonasia et al., 2016). Evidence that place cell sequences are replayed or preplayed at a faster rate in the rodent hippocampus (for review, see e.g. Ólafsdóttir et al., 2018) hints at the neural basis of this compression mechanism, although the link between hippocampal replay/preplay in rodents and mental simulations in humans remains unclear.

Overall, these findings suggest that episodic future thoughts are constructed from similar informational contents—drawn from episodic and semantic memory—and have a comparable temporal structure as episodic memories: the unfolding of events is represented as a succession of event segments organized in chronological sequences. The capacity to adapt temporal compression rates in episodic simulations may offer an advantage for prospection by allowing the mental exploration of events in more or less detail (Arnold et al., 2016).

The role of autobiographical knowledge in episodic future thinking

The construction of episodic simulations is clearly an important component of episodic future thinking but this constructive process in fact supports the imagination of any kind of events, whether or not they refer to future happenings (Mullally & Maguire, 2014; Schacter et al., 2012). This raises the question of what makes the specificity of episodic future thinking: what gives us the feeling that an imagined event refers to something occurring in our personal future?

A growing number of studies suggests that this feeling emerges from the synergy of imagined events and autobiographical knowledge: for an imagined event to be experienced as a possible future occurrence, it has to be meaningfully integrated with personal goals and general expectations we have about our future life (for review, see D'Argembeau, 2015, 2016). Indeed, the retrieval of autobiographical knowledge is often an important first step in episodic future thinking, which guides and constrains the construction of specific events

(D'Argembeau & Mathy, 2011). To imagine events that might occur next summer, for example, a person could consider the fact that she plans to go on vacation in France and then construct scenarios that are consistent with this goal (e.g., imagining visiting a particular place during her trip). Autobiographical knowledge also contributes to link and organize imagined future events in coherent themes and event sequences. Notably, episodic future thoughts are frequently embedded in event clusters according to their causal and thematic relations (D'Argembeau & Demblon, 2012; Demblon & D'Argembeau, 2014) or their links to future self-images (Demblon & D'Argembeau, 2017; Rathbone et al., 2011).

The phenomenological experience of temporality during episodic future thinking may depend on this synergy between imagined events and autobiographical knowledge. The feeling of travelling to the future—referred to as autonoetic experience (Tulving, 1985)—is not an intrinsic property of event representations (Klein, 2016), and may only arise when imagined events are placed in an autobiographical context (D'Argembeau, 2016). Support for this view comes from studies showing that ratings of autonoetic experience not only relate to the sensory-perceptual qualities of imagined events (e.g., their vividness) but also depend on their relevance to personal goals (D'Argembeau & Van der Linden, 2012; Lehner & D'Argembeau, 2016).[3] Furthermore, the subjective appraisal that an imagined event will or will not occur in the future—referred to as belief in future occurrence—is also modulated by contextualizing autobiographical knowledge (e.g., links with other anticipated events and with general knowledge about the self and one's life; Ernst & D'Argembeau, 2017; Ernst et al., 2019; Scoboria et al., in press).

Neuroimaging and lesion data point to the possible role of the mPFC in the integration of imagined events with autobiographical knowledge. Stawarczyk and D'Argembeau (2015) conducted a meta-analysis of neuroimaging studies of episodic future thinking on the one hand, and a meta-analysis of studies of personal goal processing on the other hand. A conjunction analysis revealed that the two sets of studies were associated with overlapping activation in the mPFC (see Figure 1C), but the direct contrast between the two domains showed that mPFC activity was highest for goal processing. This activation profile suggests that the mPFC somehow contributes to the processing of personal goals, and that such process

[3] It should be noted, however, that autonoetic experience may vary on a continuum rather than categorically, and degrees of autonoetic experience may notably depend on the amount of pre-existing autobiographical information that is consistent with imagined events (Lehner & D'Argembeau, 2016). This does not necessarily mean that autonoetic experience is determined or caused by this factor (see Klein, 2013a, for further discussion of the idea that autonoetic consciousness does not depend on memory content) but, at the very least, the evidence indicates that the degree to which autonoetic consciousness is applied to represented events varies according to contextualizing autobiographical knowledge.

is an important component of episodic future thinking (see also D'Argembeau, Stawarczyk, et al., 2010). Interestingly, patients with mPFC lesions have difficulties imagining both fictitious and future scenarios but are particularly impaired for future events, which may in part relate to difficulties in using self-related knowledge to construct plausible future events (Bertossi, Aleo, et al., 2016). In line with this view, some studies showed that patients with mPFC damage provided fewer self-references when imagining future events (Kurczek et al., 2015), and did not benefit from imagining a personal future scenario compared with imagining a future scenario involving another person (Verfaellie et al., 2019; but see Bertossi, Tesini, et al., 2016).

Therefore, several lines of evidence converge to suggest that episodic future thinking not only relies on the construction of episodic simulations, but also involves higher-order autobiographical knowledge which places events in a personal context. Imagined future events are not randomly generated but are constructed and organized as a function of personal goals and general expectations about our future life. While the evidence is still sparse, current data suggests that the mPFC may contribute to the integration of imagined events with autobiographical knowledge.

MENTAL TIME TRAVEL: NAVIGATING LAYERS OF AUTOBIOGRAPHICAL REPRESENTATIONS

The research reviewed in the previous sections indicates that mental time travel involves a broad spectrum of mental representations that vary in specificity and temporal scope. To account for these findings, we have recently proposed a theoretical framework that articulates the relations between specific event representations and higher-order autobiographical knowledge in the service of past- and future-oriented thinking (Conway et al., 2019; D'Argembeau, 2015, 2016). This account is based on a hierarchical view of autobiographical memory organization (Conway, 2001, 2005) and asserts that a similar representational structure supports future-oriented thinking (D'Argembeau, 2015). Here, I refine this framework to integrate the above-mentioned findings on the temporal structure of event representations and autobiographical knowledge, and propose that mental time travel relies on the ability to flexibly navigate layers of autobiographical representations at different time scales.

Cognitive architecture underlying mental time travel

In line with other theoretical accounts (Hassabis & Maguire, 2007; Rubin & Umanath, 2015; Schacter & Addis, 2007), the proposed framework conceptualizes mental simulations of past and future events as relying on common constructive processes. Simulations of specific events, whether past or future, are constructed using details from prior experiences (drawn from episodic memory; Schacter & Addis, 2007) and semantic knowledge (notably event schema; Irish & Piguet, 2013), in varying proportion depending on the type of events (e.g., memories of past events typically include more episodic details than imagined future events; Addis et al., 2008; Berntsen & Bohn, 2010; D'Argembeau, Ortoleva, et al., 2010). The function of event simulations is to provide a representation of the experiential content of events from an egocentric perspective—depicting what it is like to experience these events. They rely on mental imagery (i.e., depictive representations; Pearson & Kosslyn, 2015) and draw on modality-specific systems for perception, action, emotion, and introspection (Barsalou, 2009).

Remembering past events and imagining future events both involve simulation processes (Michaelian, 2016), but, as such, event simulations may be atemporal in nature—in the sense that simulations lack a broader temporal context that would locate events in the past, present or future, but as described below they have an internal temporal structure that represents the unfolding of events. Neuropsychological evidence indeed suggests that the subjective temporality of events (i.e., the sense that represented contents refer to the personal past or future) is not an intrinsic property of simulations; some patients seem able to form vivid representations of events that correspond to actual past experiences, and yet do not experience these as events that occurred in their personal past (Klein, 2013a, 2016). In our view, simulation processes can in fact be used to mentally represent any kind of events, not only past and future events but also fictitious scenes (Hassabis et al., 2007), events involving others (de Vito et al., 2012), and simulations during literary reading (Tamir et al., 2016), to name just a few (see also Addis, 2018).

The central proposition of our framework is that the personal temporal context of event simulations is provided by autobiographical knowledge, which forms a cognitive representational system—a personal timeline—onto which remembered and imagined events can be mapped (Conway et al., 2019; D'Argembeau, 2015, 2016; see also Fivush, 2011). While event simulations rely on mental imagery, autobiographical knowledge involves conceptual/propositional (language-based) representations, which allow us to link, sequence, and organize life experiences (Paivio, 1991). The autobiographical knowledge base organizes information about the content and structure of one's past, present and future life in hierarchical layers referring to different temporal scopes (Figure 2). At the top of the hierarchy, lifetime periods represent knowledge about large spans of time (typically in the range of years). Moving down the hierarchy, representations of general events encompass progressively shorter spans of time (e.g., in the range of months, weeks, and days).[4] Finally, the lowest level of the hierarchy includes conceptual knowledge about the occurrence of specific events—representations of the essential content or theme of unique events, which have also been referred to as their "conceptual frame" (Conway, 2009) or "gist" (Brainerd & Reyna, 2002; Robin & Moscovitch, 2017). Conceptual knowledge about specific events is conceived as a layer of autobiographical knowledge to account for the fact that we can think about unique events in the past or future without necessarily constructing mental simulations of these events (e.g., my knowledge that I went to a concert last Saturday or that I plan to visit my parents next Tuesday can be accessed without the need to mentally represent the experiential content of these events).

Thus, in our view, the subjective temporality of memories and future thoughts does not lie in event simulations *per se* but in the synergy between event simulations and autobiographical knowledge. The sense of remembering the past or foreseeing the future arises when simulated contents are situated on a personal timeline by virtue of their connection with higher-order knowledge of the content and structure of one's life. Consider the following example to illustrate this process. If I ask you to imagine yourself lying on a sandy beach in a tropical bay, you will probably be able to construct a mental simulation of the situation (Hassabis et al., 2007). However, this simulation will not be experienced as a past or future event, unless you relate it to your personal life (Ernst & D'Argembeau, 2017; Ernst et al., 2019). A sense of future occurrence may arise, for example, if you consider that this event might happen during a vacation that you plan in the Maldives next summer.

It is worth noting at this point that mental time travel requires meta-representational insight into the relation between a represented event and the present: the remembered or imagined event needs to be represented *as a past or future event* (Redshaw, 2014); otherwise one is entirely immersed in the event and the simulated experience is not temporally marked (as is the case in most dreams, for example). This perspectival aspect of mental time travel

[4] We distinguish between two main time scales (lifetime periods and general events) for convenience, but layers of autobiographical representations may in fact involve a continuum of temporal scopes. Furthermore, at a given level of temporal specificity within the hierarchy (e.g., lifetime periods), distinct autobiographical representations may refer to partly overlapping spans of time (e.g., the period "when I was in primary school" may in part overlap with the period "when I lived in Brussels"), such that several autobiographical periods can be represented in parallel (Thomsen, 2015).

(McCormack & Hoerl, 1999) may also emerge (in part) from the organization of autobiographical knowledge. In the autobiographical knowledge base, lifetime periods, general events, and specific events are situated in relation to the present, and this reference point gives autobiographical representations their past or future temporality. Interestingly, what we commonly refer to as the "present" in daily life can vary in temporal scope: the present can variably refer to this instant, this hour or this day, or the current period of our life (e.g., when we say "I presently live in X"). These different meanings of the present are reflected in the hierarchical structure of the autobiographical knowledge base, where it can be seen that the present crosses the current specific event, general event, and lifetime period (see Figure 2).

The subjective temporality of event simulations—the sense of pastness or futureness—may thus emerge from their integration with autobiographical knowledge.[5] Moreover, autobiographical knowledge contributes to the temporal location of events. Substantial evidence indeed indicates that the dates of autobiographical events are typically not represented as such in memories and future thoughts (except for a minority of events that are "time-stamped"), but needs to be reconstructed or inferred (Friedman, 1993; Shum, 1998). To determine when a remembered event occurred or when a future event might occur, people most frequently rely on general knowledge about the periods and events of their life (Ben Malek et al., 2017; Brown et al., 2016; Skowronski et al., 2007; Thompson et al., 1993).

Although event simulations are not intrinsically located in time, they typically do have an internal temporal structure (Figure 2). Some simulations may be like snapshots that capture slices of experience (e.g., the mental image of a picture presented during a memory experiment), but most represent events unfolding in time—usually in the range of minutes or hours. The dynamic unfolding of events is represented by sequences of experience units—event segments—that are typically organized in chronological order (R. J. Anderson et al., 2015; S. J. Anderson & Conway, 1993; Jeunehomme et al., 2018). These experience units are cohesive representations of elements (i.e., people, objects, locations, actions, emotions, and thoughts) that define particular moments or segments of experience (Jeunehomme & D'Argembeau, in press; Jeunehomme et al., 2018). Event segments can be processed at multiple timescales but the units of event simulations may mainly correspond to spans of time

[5] It is important to note, however, that once a past or future event has been integrated with autobiographical knowledge, its broader personal context may not always be explicitly represented as such when thinking about this event on a given occasion. But even in this case, a raw sense of temporality may arise because the autobiographical context of the event is available in the background.

in the order of seconds, and may be structured to represent psychologically meaningful changes in various dimensions of experience across time (e.g., changes in entities, contextual settings, goals, actions, and so forth; Clewett et al., 2019; Radvansky & Zacks, 2017). An important advantage of this representational structure is that the unfolding of events can be represented in a compressed form, allowing one to reproduce or simulate experiential contents with fewer time requirements (Arnold et al., 2016; Jeunehomme & D'Argembeau, 2019; Michelmann et al., 2019).

-Figure 2 about here-

-Figure 3 about here-

Neural networks underlying event simulation and autobiographical knowledge

A variety of theoretical accounts have been offered to describe the putative roles of different brain regions and networks in episodic recollection (e.g., Clewett et al., 2019; Moscovitch et al., 2016; Ranganath & Ritchey, 2012; Rugg & Vilberg, 2013), episodic future thinking (e.g., Gilmore et al., 2018; Mullally & Maguire, 2014; Schacter et al., 2017), and autobiographical memory (e.g., Cabeza & St Jacques, 2007; Grilli & Verfaellie, 2014; Palombo et al., 2018). Synthesizing several of these accounts, I suggest an outline of the main neural structures that map onto the proposed roles of event simulation and autobiographical knowledge in mental time travel (Figure 3).

The construction of event simulations, whether past or future, may mainly rely on the interaction between the hippocampus and posterior cortical regions underlying the representation of event segments and situation models (i.e., sensory regions and higher-order posterior areas, including the parahippocampal cortex, posterior cingulate cortex, retrosplenial cortex, precuneus, and angular gyrus; Baldassano et al., 2017; Ranganath & Ritchey, 2012). The hippocampus may construct high-dimensional event representations that integrate multiple event features (e.g., objects, people, spatial context, and sequential information) represented throughout the cortical hierarchy (Clewett et al., 2019; Cowell et al., 2019; Horner & Doeller, 2017), thereby supporting the mental simulation of specific events or scenes (Mullally & Maguire, 2014; Schacter et al., 2012). The evidence suggests that the longitudinal axis of the hippocampus may in fact provide a gradient of representational granularity, with an anterior-to-posterior gradient of coarse-to-fine grained representations (Brunec, Bellana, et al., 2018; Collin et al., 2015; Grady, 2019). Indeed, work on rodents and humans suggest that the posterior hippocampus (in interaction with posterior neocortical structures) mediates the representation of the perceptual details of events, whereas the anterior hippocampus (in interaction with anterior neocortical structures) mediates the representation of the gist or general context of events (for review, see Sekeres et al., 2018).Thus, the mental simulation of the experiential content and unfolding of specific events may mainly depend on the posterior hippocampus, in interaction with posterior cortical regions, whereas the representation of the essential content of events—their gist or conceptual frame—may mainly depend on the anterior hippocampus (Moscovitch et al., 2016; Poppenk et al., 2013; Sekeres et al., 2018; Sheldon & Levine, 2016). Besides the hippocampus, the angular gyrus and posterior cingulate cortex may contribute to represent and integrate multimodal contextual details (e.g., sensory-perceptual details) that support event simulations (Ramanan et al., 2018; Stawarczyk et al., 2019).

Higher-order autobiographical knowledge—lifetime periods and general events—may be mainly represented in the anterior temporal lobe (Grilli et al., 2018; Martinelli et al., 2013). Although the representation of semantic knowledge is widely distributed across the cerebral cortex (Binder et al., 2009), and in fact largely overlaps with the episodic memory network (Renoult et al., 2019), the functional parcellation of the temporal lobe using resting-state and task-state data indicates that the anterior temporal cortex is involved in higher-order multimodal semantic representations, whereas more posterior regions support modality-specific representations (Jackson et al., 2018). The anterior temporal lobe may serve as a transmodal conceptual hub that extracts similarity structures and allows for generalization across representational contents (Lambon Ralph et al., 2017), and may thus play a key role in representing the higher-order structure of autobiographical experiences. Note that this does not contradict the view that more posterior (modality-specific) cortical regions also contribute to mental time travel, by providing the sensory-perceptual contents of event simulations (Binder & Desai, 2011; Renoult et al., 2019).

The mPFC may serve as a processing hub within the entire network (Andrews-Hanna, 2012), allowing the integration of different layers of autobiographical representations in the service of past- and future-oriented mental time travel. The mPFC interacts closely with both the hippocampus (Campbell et al., 2018; McCormick et al., 2015; St Jacques et al., 2011) and anterior temporal lobe (Jackson et al., 2018), and may function to integrate event simulations with higher-order autobiographical knowledge (D’Argembeau, Stawarczyk, et al., 2010; Demblon et al., 2016; Stawarczyk & D’Argembeau, 2015). As noted above, several lines of evidence indeed suggest that the mPFC provides an integrated set of associations that go beyond individual events and determines their broader (e.g., contextual, affective, causal, evaluative, and social) meaning (Brod et al., 2013; Krueger et al., 2009; Lieberman et al., 2019; Milivojevic et al., 2015; Preston & Eichenbaum, 2013; Roy et al., 2012). Most notably, the mPFC may integrate specific event representations with higher-order representations of the content and structure of one's life, thereby providing a personal temporal context to remembered and imagined events. Moreover, during the construction of event simulations, the mPFC may also contribute (in interaction with the hippocampus) to organize event segments in chronological sequences that represent the unfolding of events (Baldassano et al., 2018; McCormick et al., 2018). These different integration processes may involve dynamic interactions between the mPFC and regions supporting the representation of event details and conceptual knowledge, and the specific configuration of activated regions within the entire network may depend on modes of mental time travel.

Modes of mental time travel

The hierarchical organization of autobiographical knowledge seems optimal for effective and fast mental travels at different time scales. Higher-order autobiographical knowledge provides an overarching view of our life, allowing us to quickly move along a personal timeline by reviewing broad lifetime periods and general events in both the past and the future. The construction of event simulations then allows us to "zoom in" on a particular period or event to represent the experiential content of specific episodes. Mental time travel may depend on the ability to flexibly navigate these layers of autobiographical representations.

Metaphorically speaking, layers of autobiographical representations can be navigated vertically and horizontally. Vertical travels are made when higher-order autobiographical knowledge is used to identify a specific event from our past or future (D'Argembeau & Mathy, 2011; Haque & Conway, 2001). For example, when attempting to remember a specific event in response to a general cue (e.g., an event associated with the word *garden*), we may start by considering a lifetime period and/or a general event (e.g., I used to play with my cousin in Grandma's garden when I was a child) and then zoom in on this period/general event to mentally represent a specific situation (e.g., the time I fell from a tree and broke my arm). Vertical activations across knowledge structures can also happen in the opposite direction when the mental representation of a specific event is directly accessed (Jeunehomme & D'Argembeau, 2016; Uzer et al., 2012), and then activates higher-order autobiographical knowledge which provides a temporal context to the represented event. For example, a cue in the environment (e.g., the face of an old friend I haven't seen for a while) may activate a specific memory (e.g., the time we were stuck on a train that was broken down), which is then located in time using higher-order autobiographical knowledge (e.g., this happened when we were in high school).

Horizontal travels within layers of autobiographical representations are made, for example, when we mentally review broad periods of our life (Thomsen, 2009) or when we consider a series of specific events in the context of a general event (e.g., planning places to visit during our vacation in France next summer; Brown & Schopflocher, 1998; D'Argembeau & Demblon, 2012). The main (though not necessarily only) mode of mental travel within a given layer of autobiographical representations may be to "jump" back (for the past) or forward (for the future) to a particular point in time (i.e., a given event or period), and then "move" forward in time such that events or periods are explored in chronological order. This horizontal mode of mental time travel seems to operate in the same way for different layers of autobiographical representations, including life periods (Holm et al., 2016), specific events (Brunec et al., 2015), and event segments (R. J. Anderson et al., 2015; S. J. Anderson & Conway, 1993; Jeunehomme et al., 2018).

In our framework, the level of specificity of mental time travel depends on which layers of autobiographical representations are activated. Autobiographical knowledge about the past and future (including knowledge about the occurrence of specific events) can be accessed without representing the experiential content of events, resulting in abstract forms of mental time travel (R. J. Anderson & Dewhurst, 2009; Barsalou, 1988; D'Argembeau et al., 2011; Thomsen, 2009). The mental experience of remembering or foreseeing occurs when event simulations are constructed in relation to autobiographical knowledge (D'Argembeau & Van der Linden, 2012; Ernst & D'Argembeau, 2017; Lehner & D'Argembeau, 2016; Rubin et al., 2003; Scoboria et al., 2015). While event simulations are more likely to be formed when thinking about specific events, simulation processes can also be recruited for representing general events and life periods (e.g., mental images summarizing the experiential content of repeated events; Brewer, 1986; Renoult et al., 2012).

The form that mental time travel takes notably depends on temporal distance: with increasing distance from the present, the frequency of past and future thoughts declines (Berntsen, 2019; Spreng & Levine, 2006), and represented events become less specific and less detailed (Addis et al., 2008; Berntsen & Bohn, 2010; D'Argembeau et al., 2011; D'Argembeau & Van der Linden, 2004). Thus, event simulations are more likely to be formed for temporally close events, whereas distant events are more likely to be represented in terms of abstract features (Trope & Liberman, 2003). The increased accessibility and specificity of the recent past and near future may serve the purpose of keeping us connected to current goals and plans (Conway et al., 2016).

While the use of event simulation varies as a function of temporal distance, the speed of access to autobiographical knowledge seems invariant across different time scales. Indeed, it has been found that the rate of event production is the same whether people recall what they did yesterday, last week, or last year; similarly, the rate of production of future events is similar when people think about what they intend to do tomorrow, next week, or next year (Maylor et al., 2001). Maylor et al. (2001) argued that pragmatic factors lead us to adapt the specificity of events to the searched period (i.e., we tend to produce specific events for short time intervals, but general events for long time intervals), such that the speed of access to events is scale-invariant over widely varying time scales (see also Moreton & Ward, 2010, for evidence of scale invariance in retrieval rates for time scales up to 5 years; whether scale invariance extends to longer time scales remains to be investigated). In terms of our framework, this suggests that the speed rate of access to autobiographical knowledge may be similar for different time scales because people can flexibly modulate the level of the hierarchical structure that is searched (e.g., general vs. specific events).

Finally, it deserves mention that mental time travel can not only be initiated voluntarily but can also occur spontaneously (Berntsen, 2010, 2019; Christoff et al., 2016; Cole & Kvavilashvili, 2019; Smallwood & Schooler, 2015). Involuntary autobiographical memories and future thoughts are indeed common in everyday life (Berntsen & Jacobsen, 2008); when we are not entirely focused on a given task, personal goals, current concerns, and other autobiographical contents tend to spontaneously come to mind (Baird et al., 2011; Cole & Berntsen, 2016; Stawarczyk et al., 2011). Voluntary and involuntary modes of mental time travel may in fact operate on the same underlying representational systems, but the voluntary mode additionally requires cognitive control processes to initiate and monitor information search, whereas involuntary mental time travel involves the automatic activation of autobiographical representations in response to situational cues (Berntsen, 2010; Dixon et al., 2014). In line with this view, there is evidence that both voluntary and involuntary memories activate brain areas supporting episodic recollection, but voluntary memories are uniquely associated with lateral prefrontal regions supporting cognitive control (Hall et al., 2014). Similarly, mind-wandering and deliberate future thought are associated with largely overlapping neural networks, but deliberate future thought additionally relies on the lateral prefrontal cortex (Stawarczyk & D'Argembeau, 2015). Note that these differences between spontaneous and deliberate thoughts may mainly relate to the initial construction of mental representations; but for both kinds of thoughts, control processes may also be involved in ensuring the continuity of the train of thought once initiated (Smallwood, 2013; see also Christoff et al., 2016, for further discussion of the role of the frontoparietal control network in implementing deliberate constraints on thought). Thus, while the representational systems proposed in our framework can support both voluntary and spontaneous modes of mental time travel, the deliberate access to, and flexible navigation across, layers of autobiographical representations may critically depend on cognitive control processes.

Relations to other theories

The recent discovery of behavioral and neural commonalities between autobiographical remembering and future thinking has led to important theoretical developments in the cognitive neuroscience of memory and imagination. The *constructive episodic simulation hypothesis* (Schacter & Addis, 2007; Schacter et al., 2012) has highlighted the contribution of episodic memory in allowing people to flexibly retrieve and recombine elements of past experiences to construct event simulations. The *scene construction theory* (Hassabis & Maguire, 2007; Mullally & Maguire, 2014) has focused on the role of the hippocampus in the mental representation of scene imagery—a spatially coherent representation of the world populated with people and objects and viewed from an egocentric perspective (see also Rubin & Umanath, 2015). The *semantic scaffolding hypothesis* (Irish & Piguet, 2013) has further proposed that general knowledge about the world and event schema provide a framework for constructing coherent event representations. The primary goal of these theories is to detail the mechanisms involved in the construction/simulation of specific events or scenes. The contribution of our framework is the proposal that such event simulation is a necessary but not sufficient component of mental time travel into the personal past and future: simulated events also need to be placed in a broader personal context, which involves higher-order autobiographical knowledge. Thus, our framework is complementary to these previous theoretical accounts of the relations between memory and future thinking.

The idea that mental time travel requires a synergy between event simulation and autobiographical knowledge is somewhat related to the idea that it relies on a particular form of consciousness (referred to as autonoetic consciousness or chronestesia), which allows people to "mentally represent and become aware of their subjective experiences in the past, present, and future" (Wheeler et al., 1997, p. 331; see also Klein, 2016; Nyberg et al., 2010; Tulving, 2005). However, exactly how this form of consciousness arises remains elusive.

According to our framework, the experience of subjective time may depend, at least in part, on the construction of a personal timeline (defined by the structure of autobiographical knowledge) through which one can mentally travel. In other words, the feeling of mental time travel may arise when event simulations are integrated with a mental map of one's personal life.

Finally, it should be noted that while the present framework emphasizes the role of a personal timeline in mental time travel, other temporal maps can of course also be used to mentally travel into the past and future—most notably culturally shared representations of time. Very elegant studies have elucidated the cognitive and neural mechanisms that allow people to mentally travel in calendar time (e.g., Arzy et al., 2009; Gauthier et al., 2018; Gauthier & van Wassenhove, 2016). However, mental time travel into the personal past and future needs not be, and in fact frequently is not, linked to conventional time. The location of autobiographical events in culturally shared time frames requires additional processes to coordinate personal and conventional time lines (Friedman, 2005; McCormack & Hoerl, 1999; Shum, 1998).

CONCLUSION

Time may just be a construction of the mind—our own subjective perspective on the universe (Rovelli, 2018). At any given moment, we can decouple from the "here and now" to mentally explore other times. This capacity for mental time travel provides increased flexibility in preparing for future contingencies, which may be the central function of memory (Klein, 2013b; Suddendorf & Corballis, 2007). Our very sense of self may in part arise from the countless mental trips to the past and future that we make on a daily basis (Prebble et al., 2013). In this article, I have argued that mental time travel relies on a cognitive architecture that allows us (1) to simulate experiential contents that are decoupled from sensory input, and (2) to locate these simulations on a personal timeline scaffolded from conceptual knowledge of the content and structure of our life. The autobiographical knowledge base is organized in hierarchical layers that differ in specificity and temporal scope, forming personal reference frames onto which simulated events can be mapped. While event simulations and autobiographical knowledge can operate independently of each other, they frequently interact to support the formation of specific memories or future thoughts. The subjective temporality of mental time travel—the sense of re-experiencing the past and pre-experiencing the future—may emerge from the synergy of these two systems.

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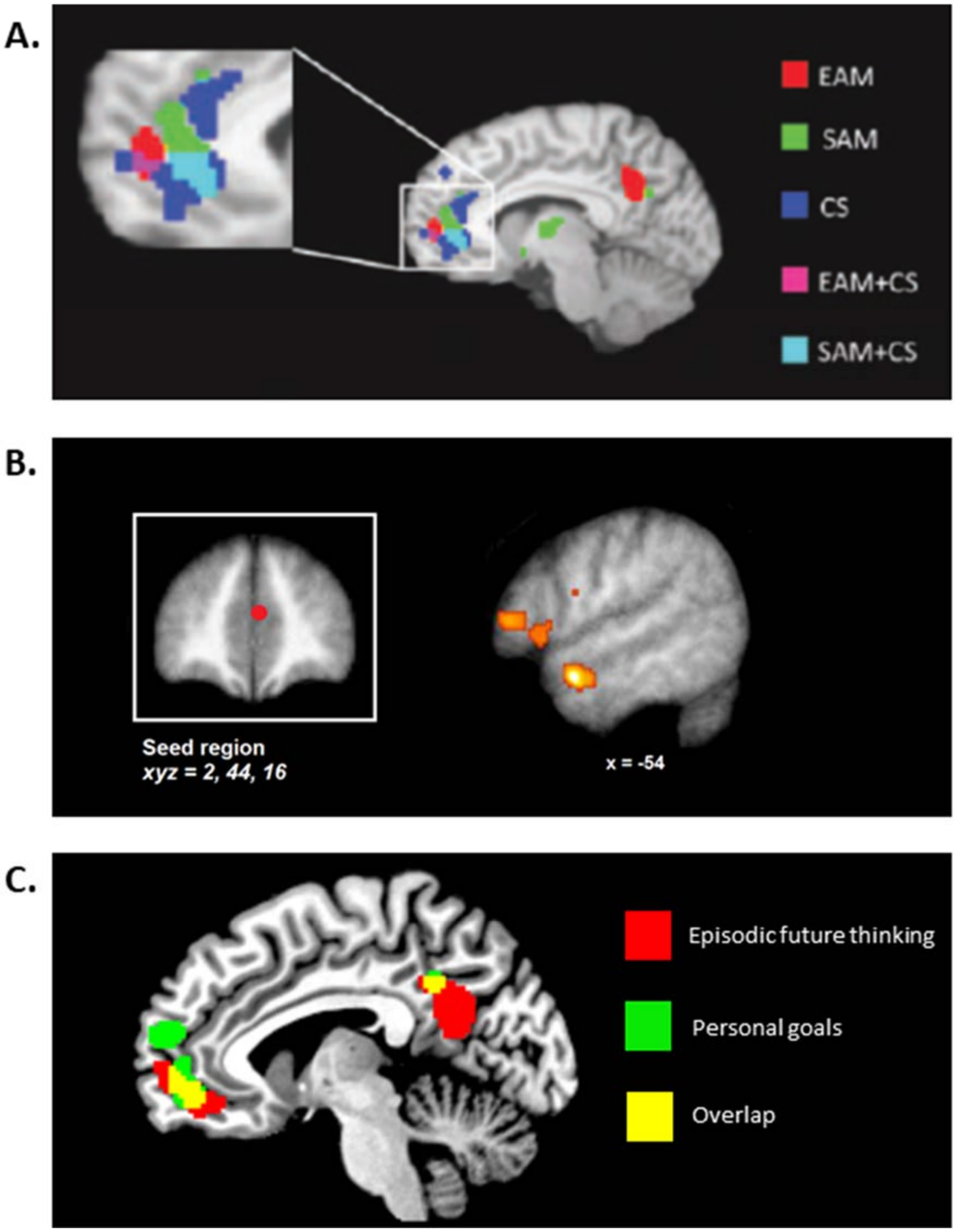
Figure legends

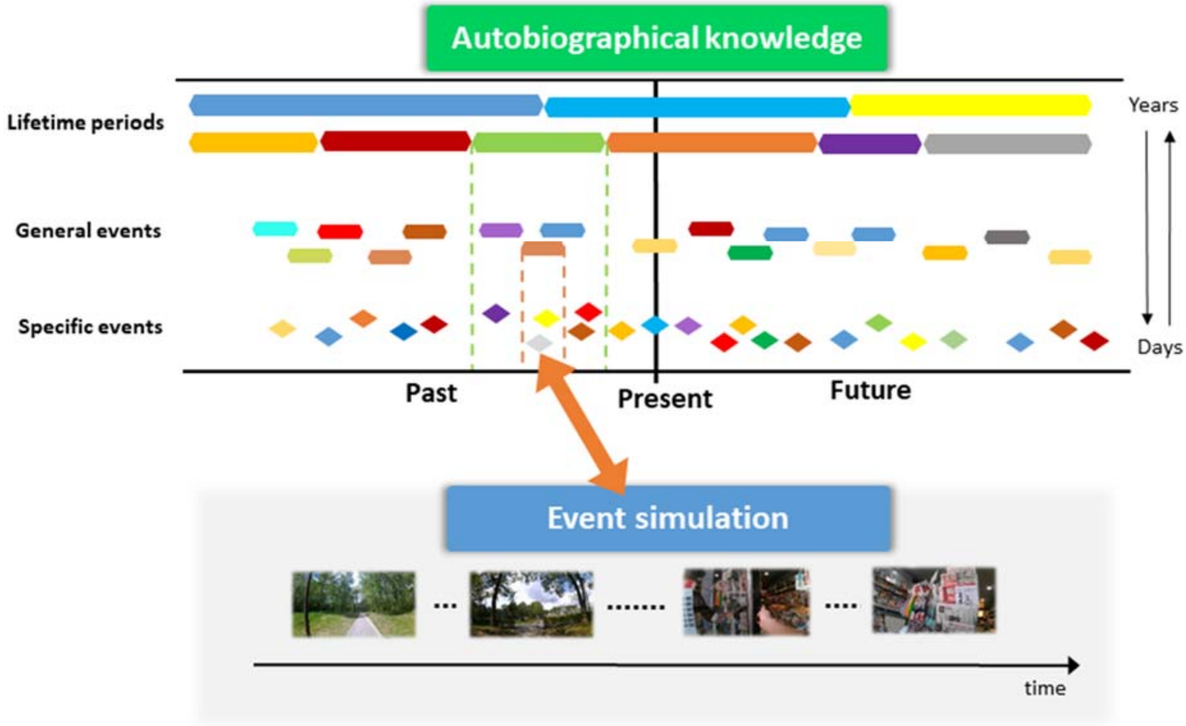
Figure 1. Involvement of the medial prefrontal cortex (mPFC) in autobiographical memory and future thinking. (A) A meta-analysis of neuroimaging studies showed that the mPFC is the only brain area that is commonly activated in responses to different types of autobiographical representations: specific memories (red color), general events and autobiographical facts (green color), and conceptual self-images (blue); overlaps between different types of representations are indicated in purple and turquoise (reproduced from Martinelli et al., 2013). (B) The mPFC shows increased functional connectivity with brain regions supporting autobiographical knowledge (including the left temporal pole shown here) and episodic representations when processing specific events that are part of the same autobiographical cluster (adapted from Demblon et al., 2016). (C) A meta-analysis of neuroimaging studies showed that episodic future thinking (red color) and the processing of personal goals (green color) are associated with overlapping activation in the mPFC (yellow color; adapted from Stawarczyk & D'Argembeau, 2015).

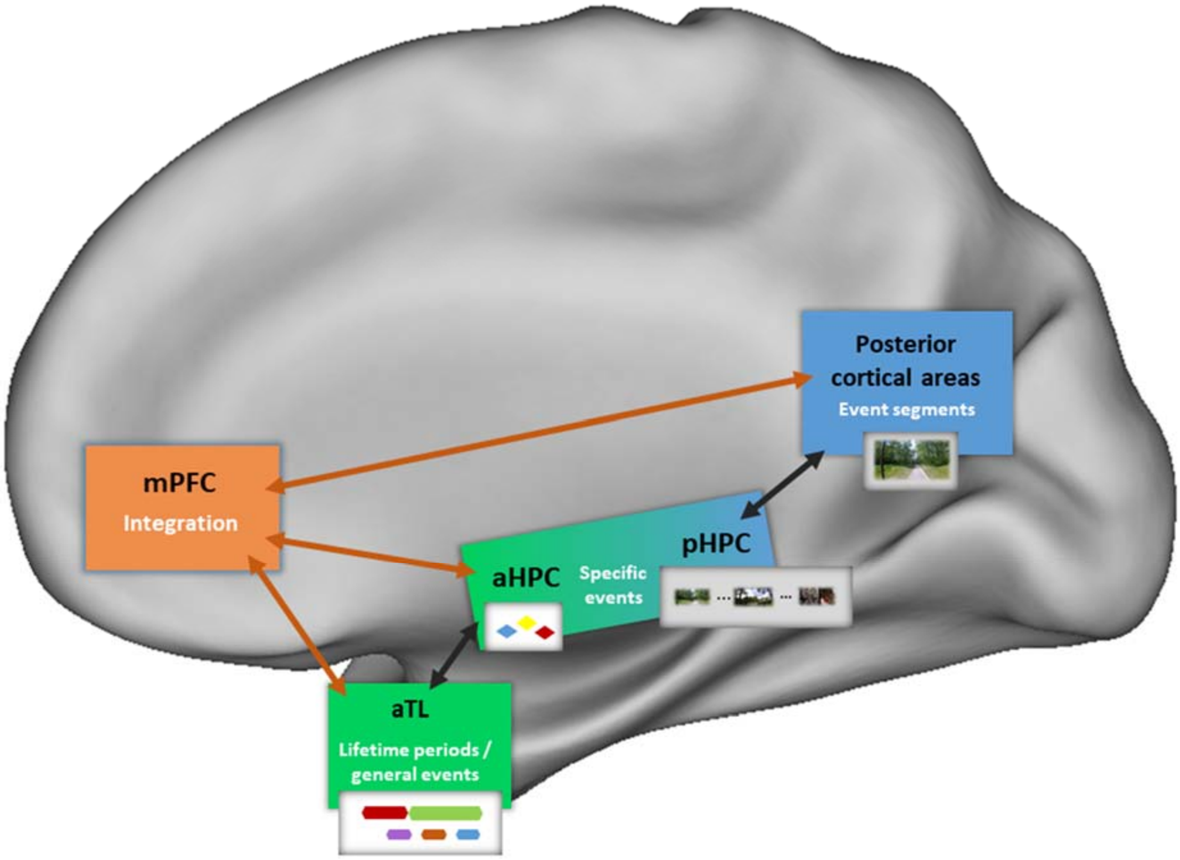
Figure 2. Cognitive architecture underlying mental time travel. Simulations of past and future events are constructed using details from prior experiences and semantic knowledge. The dynamic unfolding of events is represented by a sequence of experience units—event segments—that are typically organized in chronological order (here illustrated by the pictures). The function of event simulations is to represent the experiential content of past or future events, but the subjective temporality of memories and future thoughts does not lie in simulations *per se*. The personal temporal context of event simulations is provided by autobiographical knowledge, which forms a cognitive representational system—a personal timeline—onto which remembered and imagined events can be mapped. The autobiographical knowledge base organizes conceptual representations about the content and structure of our past, present and future life in hierarchical layers that differ in specificity and temporal scope: lifetime periods, general events, specific events. The sense of remembering the past or foreseeing the future arises when event simulations are situated on this personal timeline by virtue of their connection with autobiographical knowledge. The figure illustrates this process by showing the connection (orange arrow) between the simulation of a specific event and its

corresponding conceptual representation in the autobiographical knowledge base ("going to the bookstore"; represented by the grey diamond), which is nested (dashed brown lines) within a general event ("my exam session"; represented by the short brown rectangle) that is itself part (dashed green lines) of a lifetime period ("when I was a university student"; represented by the long green rectangle).

Figure 3. Neural network underlying mental time travel. Event simulations are constructed from event segments that are processed in posterior brain areas (sensory regions and high-order regions, including the posterior cingulate/retrosplenial cortex, precuneus, and angular gyrus) and compiled in the posterior hippocampus to form chronological sequences that represent the unfolding of specific events (blue rectangles). The anterior hippocampus may represent conceptual knowledge about specific events, whereas higher-order autobiographical knowledge (general events and lifetime periods) may be represented in heteromodal areas, including the anterior temporal lobes (green rectangles). The mPFC (orange rectangle) is hypothesized to integrate these different representational layers, notably event simulations with autobiographical knowledge, such that simulated experiences are places in a broader personal context. These neural structures map onto the proposed roles of autobiographical knowledge and event simulations in mental time travel outlined on Figure 2. mPFC: medial prefrontal cortex; aHPC: anterior hippocampus; pHPC: posterior hippocampus; aTL: anterior temporal lobe.


A.
EAM
SAM
CS
EAM+CS
SAM+CS
B.
Seed region
xyz = 2, 44, 16
x = -54
C.
Episodic future thinking
Personal goals
Overlap


Autobiographical knowledge
Lifetime periods
General events
Specific events
Years
Days
Past
Present
Future
Event simulation
time


Posterior
cortical areas
Event segments
mPFC
Integration
pHPC
aHPC
Specific
events
aTL
Lifetime periods /
general events