Autobiographical representations at multiple time scales

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Abstract

Autobiographical memory enables us to mentally travel back in time to revisit and reflect on various aspects of our personal lives. These mental journeys through time can take place on different temporal scales, from specific moments of experience that last a few seconds to periods of life that span years. This chapter reviews current data on the nature, characteristics and organization of autobiographical representations at these different time scales. It is argued that mental time travel relies on the interplay between a representational system that supports the simulation of non-occurrent experiential content and higher-order knowledge about the structure of one's life that places simulated content in an autobiographical context. Within this knowledge structure, layers of representational content refer to different spans of time and are organized hierarchically, enabling efficient and rapid mental travel across different temporal scales.

Keywords: autobiographical memory, episodic memory, future thinking, mental time travel, simulation

Autobiographical memory enables us to mentally travel back in time to revisit and reflect on various aspects of our personal lives. These mental journeys into our personal history can take place on different time scales, from specific moments of experience lasting a few seconds, to periods of life spanning years.[1] Not only can we remember the precise moment we received our diploma or the moment we proposed, but we can also take a quick look back at our years at university or our stay abroad during the last summer vacation. The aim of this chapter is to discuss the nature, characteristics and organization of autobiographical representations at these different time scales. To this end, I will focus primarily on research into memory for real-world events but will also draw on some laboratory studies of memory for 'naturalistic events' (e.g., memory for films depicting everyday events), insofar as these studies have shed important light on the microstructure of memories.

The chapter begins with an overview of the variety of autobiographical representations we form when thinking about our personal past, with the aim of illustrating that these representations differ considerably in their temporal scope. The following sections then examine the mechanisms that enable us to revisit our personal past at different time scales, starting with the mental reliving of specific events, then moving on to longer periods of life. It will also be noted that similar mechanisms enable us to mentally travel into the future. Finally, the cognitive architecture that supports these different types of mental time travel will be discussed.

Varieties of autobiographical representations

Autobiographical memory refers to the set of mental representations we have about ourselves and our personal lives, which can take a multitude of forms. Not only are we able to remember specific events from our past, but we extract regularities from our experiences (Barsalou, 1988), organize them in coherent themes, sequences and periods (Brown & Schopflocher, 1998a; Thomsen, 2015) and, ultimately, construct an overarching personal story that gives meaning and purpose to our entire life (McAdams, 2001).

[1] Some authors (implicitly or explicitly) restrict the use of the term 'mental time travel' to the projection of the self into a specific (past or future) event. Here, I use the term more broadly to refer to any consideration of the past or future, which includes not only specific events but also more general representations of one' life course.

Ever since autobiographical memory emerged as a field of research, efforts have been made to classify these different types of autobiographical representations. Brewer (1986) initially characterized autobiographical representations according to their type of input (a single event or a series of repeated events) and their format (imaginal or non-imaginal). Crossing these two dimensions, he distinguished between specific memories (imaginal representations of single events), generic memories (imaginal representations summarizing a set of repeated events), autobiographical facts (non-imaginal or propositional representations of single events), and the self-schema (non-imaginal knowledge about self-characteristics formed over the course of repeated experiences). An influential view later developed by Conway (Conway, 2005; Conway & Pleydell-Pearce, 2000) is that different types of autobiographical representations are organized in memory as a partonomic hierarchy, in which representations of specific experiences are summarized and structured into general (extended or repeated) events, which are themselves part of representations of broader life periods. More recently, dimensional rather than categorial approaches have been proposed to organize different forms of autobiographical representations. Rubin (2022) advanced a conceptual space that situates representations according to their explicit-implicit nature, degree of self-reference, and scene construction involvement, while Addis and Szpunar (2024) highlighted the roles of temporal specificity (specific vs. general), content (perceptual vs. conceptual), and self-relevance (idiosyncratic vs. shared).

Whether conceived as categories or dimensions, current evidence suggests that different forms of autobiographical representations are functionally dissociable and rely, at least in part, on distinct neural substrates (for review, see Conway et al., 2019; D'Argembeau, 2020; Klein & Gangi, 2010; Renoult et al., 2012). For example, there is evidence that knowledge of personal attributes such as personality traits is represented independently of memories of specific experiences (Klein & Lax, 2010). Furthermore, neuroimaging studies have shown that the representation of personal traits is mainly associated with activations in the medial prefrontal cortex and lateral temporal cortex (Araujo et al., 2013; Murray et al., 2012; van der Meer et al., 2010), whereas the retrieval of specific memories activates a more extensive brain network that includes the medial prefrontal cortex, medial and lateral temporal areas, posterior midline structures, and inferior parietal lobes (Cabeza & St Jacques, 2007;

Kim, 2012; Svoboda et al., 2006). A meta-analysis that directly compared the neural correlates of representations of personal characteristics, knowledge of personal facts, and memories of specific events showed that each type of representation was associated with unique brain activations (Martinelli et al., 2013). While these findings indicate that different types of autobiographical representations are dissociable, these representations generally interact and modulate each other to create a globally coherent view of the self (Conway, 2005). For example, there is evidence that self-images organize and modulate the accessibility of specific memories and, reciprocally, that the accessibility of self-images can be influenced by the retrieval of specific memories (Rathbone & Moulin, 2024).

An important dimension that differentiates autobiographical representations is their temporal scope: representations of our past can span shorter or longer periods. Sometimes we remember a fragment of a past episode that lasted a few seconds (for example, the moment I fell off my bike), other times we recall the whole event of which that fragment is a part, a specific event that may have lasted several minutes or hours (for example, a bike ride with my friends). Then we may consider the wider context of this specific episode, an extended event that may have lasted several days or weeks (for example, a week's vacation in the Alps during the summer). And this extended event is itself part of a period or chapter in our lives that may have lasted months or years (for example, when I was a doctoral student). This division of time is admittedly somewhat arbitrary and, in fact, there may not be clear boundaries between different temporal categories, but autobiographical representations may instead involve a continuum of temporal stretches. Nevertheless, to account for current knowledge on autobiographical memory, it is useful to distinguish between representations of short periods of the past that refer to what are commonly called specific events, and representations of broader periods that summarize a multitude of past experiences.

Mental travels on short time scales

An essential aspect of autobiographical memory is that it enables us to mentally revisit specific experiences we have had in the past. Remembering your first kiss, getting your driver's license, graduating from high school or having a drink with

friends last weekend are all examples of mental travel on short time scales, during which we relive specific events that usually lasted a few minutes or hours. An important feature of these events is that they have a temporal structure: events unfold over time, involving a continuous flow of information that changes dynamically. This section discusses how this temporal structure is represented during the mental reliving of events.

We tend to remember details of an event in chronological order, suggesting that autobiographical memories preserve the temporal structure of the events they represent (S. J. Anderson & Conway, 1993). However, memory does not function like a camera that produces a literal record of events. Instead, memories provide *summary* records of experience—they preserve fragments of sensory-perceptual-conceptual-affective processing (Conway, 2009). In particular, the course of events is temporally compressed in memory (D'Argembeau et al., 2022). To appreciate this phenomenon, try, for example, to remember your breakfast this morning. Try 'reliving' the event from start to finish, reexperiencing its course in as much detail and vividness as you can. Even if you are able to do this with respectable detail, it will take you two or three minutes at most, whereas in reality you may have spent ten minutes at the table. Our mental replay of an event in memory is faster than its actual duration.

To study this temporal compression of events in memory, recent studies have compared the time taken for people to remember a series of everyday events with the actual duration of these events (for review, see D'Argembeau et al., 2022). Participants were invited to take a walk around the university campus to perform several activities they would normally do in their daily lives (e.g., buy a magazine, have a drink in the cafeteria, post a document). During their walk, the participants' experience was recorded using a small wearable camera that recorded events from a first-person perspective. After their walk, participants were asked to recall the events they had experienced, and the content of their memories was compared with the camera recordings. For each event to be recalled, participants were presented with pairs of pictures (taken by the camera during their tour) representing the beginning and end of an event, and their task was to mentally replay (in silence) everything that had happened between the two moments, in as much detail as possible, as if they were reliving the event in their minds. The time required for this mental replay was

recorded. The temporal compression of an event in memory was then calculated as the ratio of the actual event duration (as recorded by the camera) to the duration of mental replay. This showed that, on average, events were mentally replayed eight times faster than their actual duration (Jeunehomme & D'Argembeau, 2019). However, the rate of event compression was not constant but varied substantially from event to event. For example, events in which participants performed specific actions (e.g., buying a magazine) were less compressed than events that only involved spatial navigation (e.g., going from one place to another with no action to perform except walking) (see also Folville et al., 2020).

To determine how the course of events was represented in memory, the researchers also asked participants to describe, after silently recalling each event, the content of their memories, in as much detail as possible. The analysis of these verbal reports showed that memories were made up of a succession of moments of prior experience—referred to as *experience units*—which represented the unfolding of events in chronological order (Folville et al., 2020; Jeunehomme & D'Argembeau, 2019). Each unit was itself composed of a set of details characterizing a given moment of experience, such as the people, objects, actions, and mental states involved. Interestingly, however, the succession of experience units representing the course of events included discontinuities: participants sometimes mentally 'jumped' from one moment of experience to another without necessarily representing everything that had happened in between (Jeunehomme et al., 2018). For example, when starting to relive her tour on campus, a participant had a mental image of exiting the building, then immediately an image of the right turn at the end of the path leading to a parking lot, without representing the entire portion of the walk between the building and the turn. When recalling the purchase of a magazine, another participant recalled arriving at the store door, then taking the magazine from the shelf inside the store, and finally paying the salesperson on the other side of the store; these three moments of past experience were separated by dozens of seconds in the actual event, but these intermediate moments (e.g., the passage from the shelf to the cashier's desk) were not recalled (Jeunehomme et al., 2018). To characterize the segments of experience that were recalled and those that were not, participants were presented with a slideshow of photos taken during their tour and were asked to indicate, for each unit of experience they had recalled, which moment in the

slideshow corresponded to their memory representation. The number of experience units recalled per unit of time (i.e., per minute) of the actual duration of the event was then calculated. This showed that the rate of temporal compression of an event in memory was inversely related to the density of units of experience recalled: the lower the number of experience units recalled per unit of time of the actual event duration, the faster the event was replayed (Folville et al., 2020; Jeunehomme & D'Argembeau, 2019).

Collectively, these studies suggest that when we mentally travel back to the past to 'relive' a past event, the course of the event is compressed in memory because certain parts of the continuous flow of information that characterized our experience are not represented. Such temporal gaps in mnemonic representations (i.e., the omission of parts of events) may be an effective way of summarizing the unfolding of events, in a similar way to how events are condensed in movies using cuts (Schwan & Garsoffky, 2004). To test this hypothesis, Jeunehomme and D'Argembeau (2023) compared memory replay times for videos depicting continuous events and edited versions of the same videos in which less informative parts were removed. They reasoned that if events are condensed in memory representations by omitting some portions of events, edited movies that leave out less informative segments of the sensory stream should be less compressed in memory than intact movies, because the deleted parts in edited movies correspond to segments that would normally be omitted in the memory representations. In support of this view, it was found that the mental replay of an edited video took proportionally longer than that of an intact video. These findings suggest that memories compress the course of events by retaining the most informative parts of the sensory stream, while omitting other parts of the events.

A key question is how the units of experience that make up memories are initially formed. Research on event cognition has shown that people make sense of the continuous stream of experience by segmenting it into discrete units: events and sub-events (for review, see Radvansky & Zacks, 2017; Zacks, 2020). This segmentation follows significant changes in the perceptual or conceptual features of ongoing experience (e.g., changes in location, persons, objects, goals, and so)[2] and occurs at

[2] Research using video stimuli has shown that multiple dimensions contribute to event segmentation, with the likelihood of perceiving an event boundary increasing with the number of event dimensions

multiple timescales, with groups of fine-grained sub-events (e.g., fill the sink with soaped water, scrub the dishes, rinse the dishes, dry the dishes, and so on) clustering in larger units (e.g., washing the dishes, making coffee, and so on) (Sargent et al., 2013). This structure of event processing has important consequences for the way events are represented in memory, with the event segments formed during perception corresponding to the representational units in memory (Zacks, 2020). Therefore, events that are segmented into finer sub-events are recalled with a higher density of experience units, with event boundaries (segmentation points) being much more likely to be remembered than other parts of events (Jeunehomme & D'Argembeau, 2020). Furthermore, there is evidence that event boundaries are access points for memory retrieval, and that a compressed replay of events is achieved by skipping ahead to the next event boundary (Michelmann et al., 2023).

The units of experience that are remembered when mentally reliving the course of an event may correspond to records of the content of working memory during the initial experience of the event. According to event segmentation theory, when we experience an event, we form a mental model of the current situation which is maintained in working memory (Zacks et al., 2007). Information accumulates in the event model until an event boundary is perceived, at which point the model is transferred to long-term memory and the content of working memory is updated to represent the new situation (Radvansky & Zacks, 2017). Following this view, it could be that when the temporal distance between two event boundaries is long, the information accumulated in the event model exceeds the capacity of working memory, so that the event model transferred to long-term memory only partially represents the corresponding event. To investigate this possibility, Leroy et al. (2024b) sought to determine at what point events start to be compressed in working memory by measuring the time taken by participants to mentally replay short videos depicting a single event (with no event boundary) that lasted 3, 6, 9, 12 or 15 s. They

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that shift (Magliano et al., 2014). For real-world personal events, the individual's (short-term) goals may play a particularly important role in the segmentation process. According to Conway (2009), one of the main functions of episodic memories is to keep records of recent goal processing: memories represent knowledge about specific actions and action outcomes, providing a means to check on recent progress with current goals and plans. Therefore, events might be segmented and retained in episodic memory as a function of the goal structure of an experience. In line with this view, there is evidence that events are segmented in finer units and are less compressed in memory when they involve goal-directed actions (Jeunehomme & D'Argembeau, 2020).

found that remembering duration increased with video duration, but in a non-linear manner: remembering duration closely followed event duration for 3- to 9-s events, but then increased less steeply for 12-s and 15-s events. These results suggest that the temporal limit of working memory capacity in maintaining representations of continuous events is reached between 9 and 12 s. Beyond this duration, the event model maintained no longer represents the complete course of the current event, and temporal compression occurs (see also (Leroy et al., 2024a), for evidence that the rates of temporal compression of events in long-term memory are related to individual differences in working memory capacity).

Neuroimaging studies suggest that the mental reliving of specific events from our past mainly relies on the medial temporal lobe (including the hippocampus) and posterior regions of the autobiographical memory network (Martinelli et al., 2013). Recent studies on the encoding and retrieval of ‘naturalistic’ events (using movie stimuli) have led to a better understanding of the neural mechanisms at work in these regions (Baldassano et al., 2017; Ben-Yakov & Henson, 2018; Geerligs et al., 2022). During the initial perception of events, segmentation processes occur at multiple time scales throughout the cortical hierarchy. Early sensory regions represent relatively short-lived segments of experience, whereas higher-order regions including the posteromedial cortex and angular gyrus support more extended episode representations that correspond to the event boundaries identified by human observers. Event boundaries in these higher-level areas trigger the hippocampus to encode the current situation model in memory, which is later reinstated in the posteromedial cortex and angular gyrus during memory retrieval (Baldassano et al., 2017). Event representations that are more compressed during memory retrieval are associated with reduced neural reinstatement in the posteromedial cortex (Musz & Chen, 2022). Furthermore, a study investigating the retrieval of real-world events has shown that the posteromedial cortex displays higher temporal dynamics when recalling events that include more experience units (Jeunehomme et al., 2022). Together, these studies suggest that the posteromedial cortex plays a key role in representing the dynamic unfolding experiential contents when we travel mentally over relatively short time scales. More generally, there is evidence for a hierarchy of temporal integration windows in the brain that supports the processing and retention of information at multiple time scales, with processing time scales increasing

gradually along the cortical hierarchy, from early sensory areas with short (milliseconds-long) integration windows up to higher-order areas with minutes-long integration windows (Hasson et al., 2015). The mental reliving of specific autobiographical events likely relies on multiple levels of this hierarchy, with regions in the apex of the hierarchy (including the posteromedial cortex) allowing the accumulation and integration of the basic experience units that make up memories.

Mental travels on longer time scales

In addition to offering the possibility of reliving specific episodes from the past, autobiographical memory gives us a general view of the content and structure of our life history (Conway, 2005). For example, we can easily segment our lives into broad periods or chapters, such as when I was in elementary school, when I lived in London, during my relationship with Emily, or my first year at the university. In fact, when asked to tell their life story in a free format, people describe broad life chapters much more frequently than specific memories (Thomsen, 2009). Representations of these extended periods of the past are generally more abstract (i.e., less experiential) than specific memories (Acevedo-Molina et al., 2020; Melega et al., 2024), but nevertheless include important knowledge about the people, activities, places, and objects that characterized them (Brown, 2016; Conway & Pleydell-Pearce, 2000; Thomsen, 2015). Note that the term ‘autobiographical period’ has been used to refer to the entire range of temporal categories that people use when thinking about their past, which can be brief (e.g., a week’s vacation in France) or more prolonged (e.g., my college years) (Thomsen, 2015).

In his influential model of autobiographical memory, Conway (Conway, 2005; Conway & Pleydell-Pearce, 2000) put forward the idea that autobiographical periods and other forms of higher-order autobiographical representations (e.g., summaries of repeated experiences) play a key role in the organization and retrieval of specific memories. According to this view, the general knowledge we have about the periods and events of our lives (hereafter referred to as *autobiographical knowledge*) allows us to organize specific memories, and to locate the events they represent in a broader autobiographical context. Therefore, most of the time, remembering a specific event involves not only the representation of the content of the past episode,

but also the retrieval of higher-order knowledge that places this event in the context of our lives (Conway, 2001). For example, I remember building a sandcastle on the beach and then seeing it destroyed by the tide (a specific event), and I know that this event happened during a week's vacation by the North Sea when I was a child (contextualizing autobiographical knowledge).

The role of autobiographical knowledge in the functioning and organization of autobiographical memory has been demonstrated in several lines of research. First, there is evidence that autobiographical knowledge can be used to access specific events from one's past. When examining the kind of mental representations that people bring to mind when attempting to retrieve specific memories, Haque and Conway (2001) found that autobiographical knowledge (e.g., an autobiographical period) is frequently accessed before the recall of a specific event, suggesting that this knowledge guides the retrieval process (see also D'Argembeau & Mathy, 2011). Supporting this view, there is also evidence that cueing autobiographical knowledge can facilitate access to specific memories (Conway & Bekerian, 1987; Sheldon et al., 2020). However, although autobiographical knowledge can help in the recovery of specific memories, it should be noted that multiple retrieval strategies can be used (Mace et al., 2021), and that specific memories are frequently accessed directly, without first resorting to autobiographical knowledge (Uzer et al., 2012).

Even when a specific memory is accessed directly, autobiographical knowledge is often activated at a later stage, enabling us to situate the retrieved event in time. The sense of time is an important dimension of autobiographical recollection: when we mentally travel into the past, we have the impression that the events we remember occurred at specific times, even if we don't necessarily know the exact date (Tulving, 1985). However, research has shown that most memories are not time-stamped and that the temporal location of events needs to be inferred or reconstructed (Friedman, 2004). Several strategies can be used to determine the temporal location of events, but people most often capitalize on their general knowledge of the periods and events in their lives (Shum, 1998; Thompson et al., 1996). For example, in some studies, participants were asked to date a series of personal events that had been recorded in a diary, and to report the strategies they used for locating these events in time. Participants most often reported using their knowledge of autobiographical

periods (e.g., the last part of a semester, a vacation in Europe) to infer when past events occurred (Thompson et al., 1993).

The role of autobiographical knowledge in the organization of specific memories has been highlighted by studies examining how memories are associated with each other. In an event-cuing paradigm, participants are asked to recall a specific event, which is then used to cue other specific memories. For example, the memory of visiting the Colosseum might evoke the memory of enjoying an excellent spaghetti carbonara in old Rome. Then, participants are asked to assess how the events produced are related to each other; for example, they may be related because they involve the same person or place, because they are causally linked, because they are part of the same general event, and so on (Brown & Schopflocher, 1998a). Using this paradigm, research has shown that specific events are often integrated into overarching event sequences (called event clusters), based on their themes, causal relations and/or temporal proximity (Brown & Schopflocher, 1998a, 1998b; D'Argembeau & Demblon, 2012; Wright & Nunn, 2000). The memory of visiting the Colosseum and the memory of eating spaghetti belong to the same cluster because they both occurred during a week's vacation in Rome. Such associations between specific events in a person's life can be formed not only automatically, but also by consciously reflecting on the meaning and implications of our previous experiences. Autobiographical reasoning is a reflective process that creates such links between different life events, ultimately leading to the construction of a life story to provide a coherent account of one's past (Habermas & Bluck, 2000).

While specific memories mainly involve posterior regions of the autobiographical network, higher-order autobiographical knowledge relies primarily on temporal and frontal regions (Addis et al., 2004; Grilli et al., 2018; Martinelli et al., 2013; Renoult et al., 2012).[3] In addition to being involved in various forms of higher-order autobiographical representations (Martinelli et al., 2013), prefrontal and lateral temporal regions are recruited early on during the active retrieval of specific events, suggesting that they support strategic search operations and the initial recovery of autobiographical knowledge (Addis et al., 2012). Interestingly, the medial prefrontal

[3] Note, however, that differences in brain activations between specific memories and higher-order autobiographical knowledge may be quantitative rather than qualitative, reflecting a continuum of representational contents (Tanguay et al., 2023).

cortex is commonly activated during the processing of specific and general autobiographical representations (Martinelli et al., 2013), and appears to play a leading role in the retrieval of specific events, preceding and driving hippocampal activity (McCormick et al., 2020). Although the precise mechanisms supported by this region are not fully understood, substantial evidence points to its role in processing schemas and integrating information with existing knowledge structures (Brod et al., 2013; Gilboa & Marlatte, 2017; van Kesteren et al., 2012). In the context of autobiographical memory, the medial prefrontal cortex could serve as an information processing hub that integrates and organizes different types of autobiographical representations (D'Argembeau, 2020; Moscovitch et al., 2016). Consistent with this view, there is evidence that memories that are integrated into higher-order autobiographical clusters are associated with greater activation of the medial prefrontal cortex, and with increased functional connectivity between the medial prefrontal cortex and posterior regions that support semantic and episodic memory representations (Demblon et al., 2016). In addition, a dorsal medial prefrontal region has been associated with autobiographical reasoning, suggesting that it may play a role in creating links between the different events that make up a person's life story (D'Argembeau et al., 2014).

Mental travels into the future

Our mental journeys through time are not limited to the past, but also extend into the future. In fact, most people spend more time thinking about the future than the past in their daily lives (Baumeister et al., 2018). Over the past 20 years, evidence has accumulated showing that remembering the past and imagining the future are closely related mental activities (for review, see Addis, 2020; D'Argembeau, 2020; Schacter et al., 2017). For example, patients presenting memory deficits also have difficulty imagining the future (Hassabis, Kumaran, Vann, et al., 2007; Race et al., 2011; Tulving, 1985), and neuroimaging studies have shown that remembering the past and thinking about the future rely on largely the same brain structures (Addis et al., 2007; Benoit & Schacter, 2015; Szpunar et al., 2007). As with the past, the representation of the future can operate at multiple time scales, from short moments of anticipated events (e.g., the very instant when I will propose) to long periods of life (e.g., my retirement years). Research has shown that the nature and structure of

these different types of future-oriented autobiographical representations are analogous to those underlying representations of the personal past (D'Argembeau, 2020).

To date, most studies have focused on the ability to mentally simulate specific events that might happen in the future—referred to as episodic future thinking or foresight (Atance & O'Neill, 2001; Suddendorf & Corballis, 2007). The underlying mechanisms are increasingly well understood, with evidence showing that future thoughts are constructed based on details extracted from specific events experienced in the past, as well as semantic knowledge such as event schema (Irish & Piguet, 2013; Schacter & Addis, 2007). As with the recollection of past events, the mental simulation of future events does not consist of a continuous unfolding, but rather imagined experiences are summarized and compacted during future thinking. To investigate this compression of simulated experiences, Jeunehomme et al. (2020) compared the time taken for people to simulate future events with the actual duration of these events when they were subsequently experienced. For example, participants were asked to imagine going to the reception desk at the entrance to the university building to request information about the building's closing time. For half of the events, participants first imagined the events and then experienced them, while for the other half, they first experienced the events and then remembered them (as in the studies described earlier). It was found that the unfolding of events was temporally compressed in future simulations, and that the rate of event compression was even higher than for past events, consistent with evidence that future events are generally less detailed than past events (Addis et al., 2008; Berntsen & Bohn, 2010; D'Argembeau & Van der Linden, 2004). Interestingly, however, variations in compression rates between different types of events (actions vs. spatial displacements) were similar for the past and the future, suggesting that similar mechanisms operate to summarize the unfolding of events (Jeunehomme et al., 2020).

As well as representing specific events, people also form more general representations of themselves and their lives when they think about the future, notably by envisioning anticipated autobiographical periods (e.g., when I'll work as a freelancer, my next vacation in Japan, when I'll have moved to my new apartment) (R. J. Anderson & Dewhurst, 2009; D'Argembeau et al., 2011; Thomsen, 2015).

These autobiographical representations are essentially based on the individual's personal goals and general expectations (D'Argembeau, 2016), which are in part shaped by cultural life scripts (i.e., shared knowledge about events that form a prototypical life course in a given culture, such as graduation, marriage, and children) (Berntsen & Bohn, 2010). As in the case of memories of past events, several lines of research have shown that higher-order autobiographical knowledge guides the construction, organization, and temporal location of specific future thoughts. The process of constructing a specific future event often begins with access to autobiographical knowledge (D'Argembeau & Mathy, 2011), although future thoughts can also be directly or spontaneously accessed (Berntsen & Jacobsen, 2008; Cole & Kvavilashvili, 2019; Jeunehomme & D'Argembeau, 2016). As with past events, autobiographical knowledge organizes future events in clusters (D'Argembeau & Demblon, 2012), and helps situate them in time (Ben Malek et al., 2017). In addition, the phenomenological experience associated with episodic future thinking, such as the feeling of pre-experiencing an event and the belief that it will actually happen in the future, depends on the integration and consistency of imagined contents with autobiographical knowledge (Ernst & D'Argembeau, 2017; Lehner & D'Argembeau, 2016).

Cognitive architecture supporting mental time travel

The evidence reviewed in the previous sections shows that people undertake multiple forms of mental travel into the past and future, differing in their temporal scope and level of abstraction. This ability to mentally visit other times is a complex cognitive activity that relies on multiple systems and processes, including long-term memory structures, working memory, executive functions, mental imagery, and metacognition (Addis, 2020; D'Argembeau et al., 2010; Redshaw & Suddendorf, 2020; Schacter et al., 2012; Suddendorf & Corballis, 2007). Without minimizing this complexity, it has been proposed that mental time travel is fundamentally based on the interaction between two main components: a representational system that supports the simulation of non-present experiential contents, and higher-order knowledge about the structure of one's life that places simulated contents in an autobiographical context (Conway et al., 2019; D'Argembeau, 2015, 2020). This section aims to detail

this dual-system cognitive architecture proposed as the basis for mental journeys into our personal past and future.

A first component of mental time travel is a system that enables the simulation of non-occurrent experiential contents, i.e. contents decoupled from current sensory-perceptual input. These simulations are constructed using details from prior experiences (Schacter & Addis, 2007) and semantic knowledge (Irish & Piguet, 2013; Szpunar, 2010), in varying proportion depending on the type of simulated event.[4] The main feature of the simulation system is its depictive representational format: simulated events rely on mental imagery (Pearson & Kosslyn, 2015) and modality-specific systems for perception, action, emotion, and introspection (Barsalou, 2009). In other words, the mental processes that 'run' the simulation emulate those that would actually operate in the simulated scenario (Moulton & Kosslyn, 2009). The function of simulations is to inform us about what it would be like to experience a non-occurrent situation (e.g., what we would perceive, how we would act, what we would think and feel, and so on).

Simulated events often take the form of a spatially coherent scene that integrates multiple elements (e.g., persons and objects) and is represented from an egocentric perspective (Hassabis & Maguire, 2007; Rubin & Umanath, 2015). Furthermore, many simulations extend in time: while some resemble snapshots that capture slices of experience (e.g., the mental image of a painting you have recently seen), most simulations of real-world events have a temporal structure, representing the unfolding of events (i.e., a segment of time that has a beginning and an end). However, as we have seen, the simulated course of an event is generally not isomorphic to the actual situation but is compressed in time: it consists of a sequence of experience units that summarizes the key segments of the simulated experience, while omitting other (less informative) segments (D'Argembeau et al., 2022; Jeunehomme & D'Argembeau, 2023). Event segments are processed on multiple timescales, but the subjective units of event simulations typically correspond to time spans on the order of seconds[5] and

[4] For example, on average, memories of past events include more episodic details than imagined future events, while the latter rely more on event schemas (Addis et al., 2008; Berntsen & Bohn, 2010; D'Argembeau & Van der Linden, 2004).

[5] Each experience unit that constitutes event simulations may correspond to the temporal window of the 'subjective present' or 'experienced nowness' (Montemayor & Wittmann, 2014; White, 2021). Some authors consider that there is a temporal integration of perceptual information that generates a sense of what is going on (the subjective present), on a time scale of approximately 3 seconds

represent psychologically meaningful changes in various dimensions of experience across time (e.g., changes in entities, contextual settings, goals, actions, and so on). An important advantage of this representational structure is that it allows us to simulate experiential content with less time, freeing up cognitive resources for other tasks. Indeed, if remembering or imagining an event took as long as the actual situation, we'd be inattentive to what is going on around us most of the time, given how often the mind wanders into the past and future in our daily lives (Smallwood & Schooler, 2015).

While simulations have an internal temporal structure that represents the unfolding of events, they lack a broader temporal context that situates events in the past, present or future. In fact, simulation processes can be used to represent all kinds of events, not only past and future events, but also fictional scenes (Hassabis, Kumaran, & Maguire, 2007), counterfactuals (De Brigard & Parikh, 2019), or events involving other people (de Vito et al., 2012). Indeed, there is evidence that similar processes support the simulation of past, future and a-temporal events (Addis, 2020; Buckner & Carroll, 2007; Hassabis & Maguire, 2007), and that temporal orientation is not an intrinsic component of simulations (Mahr et al., 2021; Mahr & Schacter, 2022). In short, while simulations represent events as unfolding over time, their content does not in itself indicate whether these events concern the past or the future (D'Argembeau, 2020; Mahr, 2020).

In our view, the temporal location of simulations is determined by a second system—autobiographical knowledge—which organizes the knowledge we have about periods and events in our lives (Conway et al., 2019; D'Argembeau, 2015, 2020). While simulations rely on mental imagery, autobiographical knowledge involves conceptual/propositional (language-based) representations, a format well-suited to linking, ordering and organizing information (Paivio, 1991). Knowledge about the content and structure of one's past, present and future life is organized in hierarchical layers referring to different temporal scales, with extended periods of life (usually of the order of years) subsuming progressively shorter periods of time (i.e., of the order

(Montemayor & Wittmann, 2014; Pöppel, 2009). Intriguingly, this corresponds to the estimated duration of the units of experience that people recall when mentally replaying the course of events (Jeunehomme & D'Argembeau, 2023). However, this temporal window is probably malleable and may be best characterized by the information structure of perceptual input than in terms of time covered (White, 2021).

of months, weeks and days). The lowest level of the hierarchy includes conceptual knowledge about the occurrence of specific events, summarizing the essential content or theme of unique events—their ‘gist’ (Brainerd & Reyna, 2002; Robin & Moscovitch, 2017) or ‘conceptual frame’ (Conway, 2009). Such conceptual knowledge enables us to think about unique events without necessarily simulating them mentally (e.g., I can access knowledge that I went to a concert last Saturday without the need to mentally represent the experiential content of this event).

Together, layers of autobiographical knowledge form a sort of personal timeline onto which simulated events can be mapped. The sense of remembering the past or foreseeing the future arises when simulated contents are situated on this personal timeline, meaning that they are integrated with the individual's knowledge of the content and structure of their life. In the above example of the memory of building a sandcastle, my sense of the past does not reside in the mental image of the sandcastle on the beach, but arises because this image is linked to the knowledge that this event happened to me during a week's vacation at the North Sea, when I was a child.[6] Consider another example, this time concerning the future, to illustrate how the temporality of simulations arises. If I ask you to imagine yourself visiting the Louvre Museum, you'll probably be able to construct a mental simulation of the situation, perhaps arriving near the glass pyramid or admiring the Mona Lisa or the Venus de Milo. However, this simulation will not necessarily be experienced as a future event, unless you relate it to your personal life (Ernst et al., 2019; Ernst & D’Argembeau, 2017). A sense of future occurrence may arise, for example, if you consider that this event could happen during the vacation you plan to take in Paris next summer.

The hierarchical structure of autobiographical knowledge enables us to quickly travel mentally through different time scales. Higher-order autobiographical knowledge provides an overview of our lives, allowing us to move quickly along a personal timeline, by reviewing the major periods and general events of the past and future. The hierarchical structure of autobiographical knowledge then enables us to zoom in on a particular period or general event to identify specific episodes that they contain.

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6 Note that, once an event has been integrated with autobiographical knowledge, this contextualizing knowledge need not necessarily be explicitly represented for the sense of pastness to arise. A raw sense of temporality may arise because the autobiographical context of the event is available in the background.

When needed, the construction of event simulations enables us to represent the experiential content of these episodes. Mental time travel thus depends on the ability to navigate flexibly through these layers of autobiographical representations, and its level of specificity or abstraction depends on which layers of autobiographical representations are activated on a given occasion. 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; D'Argembeau et al., 2011). The mental experience of projecting oneself into a specific past or future event occurs when event simulations are constructed in relation to autobiographical knowledge (Ernst & D'Argembeau, 2017; Rubin et al., 2003; Scoboria et al., 2015). It is also worth noting that simulation processes can be recruited not only when thinking about specific events, but also to represent experiential aspects of general events and life periods (e.g., mental images summarizing what one's elementary school was like) (Brewer, 1986; Renoult et al., 2012).

Mental time travel can not only be initiated voluntarily, but also occurs spontaneously (Berntsen, 2010; Cole & Kvavilashvili, 2019; Smallwood & Schooler, 2015). Voluntary and involuntary modes of mental time travel rely 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). Indeed, voluntary and involuntary memories commonly activate brain areas supporting episodic recollection, but voluntary memories additionally recruit lateral prefrontal regions involved in cognitive control (Hall et al., 2014). Similarly, mind-wandering and deliberate future thinking are associated with largely overlapping neural networks, but deliberate future thinking additionally relies on the lateral prefrontal cortex (Stawarczyk & D'Argembeau, 2015). Cognitive control processes may play an important role in the coordination and integration of simulations with higher-order autobiographical knowledge, and in the capacity to deliberately access and flexibly navigate layers of autobiographical representations during mental time travel.

Conclusion

Autobiographical representations take a multitude of forms, varying in their levels of abstraction and temporal specificity. Fundamentally, however, they can be conceived as relying on a cognitive architecture that enables non-occurrent experiential contents to be simulated and situated in an autobiographical context. The mental simulation of specific episodes involves compressed representations that summarize the course of events in a sequence of event segments, informing us about what it was or would be like to experience those events. Higher-order autobiographical knowledge gives us a bird's eye view of our past and future, enabling us to connect and organize specific events, and to place them in the context of our entire life. The ability to travel mentally into our personal past and future at different time scales relies on the interplay of these two cognitive systems.

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