Slices of the past: how events are temporally compressed in episodic memory

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Abstract

Remembering everyday events typically takes less time than the actual duration of the retrieved episodes, a phenomenon that has been referred to as the temporal compression of events in episodic memory. Here, we review recent studies that have shed light on how this compression mechanism operates. The evidence suggests that the continuous flow of experience is not represented as such in episodic memory. Instead, the unfolding of events is recalled as a succession of moments or slices of past experience that includes temporal discontinuities—portions of past experience are omitted when remembering. Consequently, the rate of event compression is not constant but depends on the density of recalled segments of past experience.

Keywords: episodic memory, event segmentation, compression, time, autobiographical memory.

Human memory has finite limits on processing and storage capacities (Bates & Jacobs, 2020). At any given moment, only a fraction of the information content of our external and internal environments is perceived and encoded. Further, the continuous succession of moments that constitute our experience is not represented as such in memory. Indeed, episodic memories are not complete records of the flow of experience but instead represent events in a temporally compressed form (Jeunehomme et al., 2018). As an illustration, take a moment to remember your commute to work this morning. As hard as you try, you will not remember every single moment of your journey. Instead, your memory will likely consist of a series of slices of your past experience that includes discontinuities, as if you mentally "jumped" from one moment of experience to another without representing everything that happened in between. For example, you might remember a particular crossroad and then jump to the next crossroad without representing the entire route that linked these two points. Metaphorically speaking, memory for the unfolding of events is more like a time-lapse or an edited movie rather than a continuous video recording. In this article, we review recent research that has advanced our understanding of how the unfolding of real-life events is compressed in episodic memory representations. Note that due to space limitation, we focus on studies that investigated the temporal compression of events in memory but do not address research on memory for temporal information *per se*, such as judgments of duration or recency (see e.g., Block & Reed, 1978; Brunec et al., 2017; DuBrow & Davachi, 2013; Fenerci et al., 2020; Yarmey, 2000).

The time to remember

Episodic remembering is a sort of "mental time travel" in which the rememberer reconstructs a specific event from the past (Tulving, 2002). For complex real-life events that dynamically unfold over time, this reconstruction process typically involves a succession of event details that are organized in chronological order (R. J. Anderson et al., 2015; S. J. Anderson & Conway, 1993). However, memories are not exact replicas but instead summary records of past experience (Conway, 2009). The unfolding of events is somehow compacted in mnemonic representations, such that the time needed to remember an event is shorter than the actual duration of this event in the past—a phenomenon that is here referred to as the *temporal compression of events* (Jeunehomme & D'Argembeau, 2019). Indeed, episodic memory would not be functional if remembering an event necessarily took as much time as the duration of the past episode; if this were the case, we would be wasting a considerable amount of time and resources mentally revisiting the past and would rarely be fully focused on the present moment.

The temporal compression of events in memory representations has been evidenced in recent studies that compared the time needed to remember an event to the actual event duration. In one of the first studies that quantified compression rates, Bonasia et al. (2016) asked participants to mentally navigate familiar routes between campus landmarks. The compression of route representations was calculated by dividing the time it would take to walk each route over the time taken to navigate this route mentally. The results showed that all participants demonstrated consistently compressed representations, with compression factors varying from about 5 to 35 depending on route length and number of turns. However, it is unclear from this study whether these compression rates apply to memory for unique events (i.e., episodic memories) because the mental navigation task that was used could rely on schematic representations (i.e., a mental map of campus acquired over multiple experiences).

To investigate temporal compression rates for unique events, Jeunehomme and D'Argembeau (2019) asked participants to go on a tour on a campus while their experience was recorded using wearable camera technology: a small wearable camera automatically took a continuous sequence of pictures of experienced events from the first-person perspective. The pictures taken during the tour were then used to cue memory for specific events that were clearly delimited in time and which actual duration was known (based on the pictures taken by the camera). For each event, participants were asked to mentally re-experience everything that happened in as much detail as possible, and the duration of their mental replay was measured. It was found that participants consistently spent less time remembering events compared to the actual event duration: on average, events were replayed about eight times faster than the actual event duration, with substantial variation in compression rates across events (see also Chen et al., 2017; Folville et al., 2020; Jeunehomme et al., 2020).

Episodic remembering involves lossy compression

The above-mentioned studies show that remembering an event takes less time than the actual event duration, but how exactly is the dynamic unfolding of past experience represented during episodic remembering? To investigate this question, Jeunehomme et al. (2018) asked participants to verbally describe everything that came to their minds when they remembered events experienced during a tour on campus. The analysis of verbal reports showed that memories consisted of a succession of moments or slices of past experience—referred to as *experience units*—that represented the unfolding of events in chronological order; note that each unit was itself composed of a set of details that characterized a given moment of past experience, such as people, objects, actions, mental states, and so on.[1] Importantly, however, the succession of experience units was not a replica of the continuous flow of past experience but included discontinuities in the representation of the unfolding of events. For example, when remembering buying a newspaper, a participant experienced a mental image of arriving in front of the shop's door, then an image of picking the daily newspaper on the shelf inside the shop, and finally an image of paying the seller on the other side of the shop; these three moments of past experience were separated by several seconds in the actual event, but these intervening instants (e.g., going from the newspaper shelf to the cashier's desk) were not recalled. To provide an estimation of the time separating experience units in terms of the actual event duration, participants were asked to review the sequence of pictures that had been taken by a wearable camera during their tour and they had to select the pictures that best corresponded to each experience unit they recalled. The actual duration separating the selected pictures was computed, which showed that the successive experience units that composed memories represented moments of past experience that were on average about 50 seconds apart in the actual event (with substantial variability across events).

Recent neurophysiological evidence provides further support to the idea that episodic remembering involves temporal discontinuities (Michelmann et al., 2019). At encoding, participants saw short video clips that were composed of three successive scenes and a word cue was presented during one of the scenes; at retrieval, they saw the word cue and had to determine in which scene it had been presented. MEG data showed that each scene that was presented at encoding was associated with a content-specific fingerprint in the oscillatory phase and these scene-specific phase patterns were then used to track the dynamics of memory retrieval. The results indicated that the mental replay of the video clips was overall faster than perception, showing a global temporal compression effect. Interestingly, however, the speed of replay within scenes was slower than the overall compression level of the entire video, with some fragments being replayed at the same speed as perception. This disparity between the slower speed of replay within scenes and the overall compression suggests that participants replayed fine-grained segments of the video while omitting other segments.

Collectively, these studies suggest that the unfolding of events is compressed during episodic remembering because parts of the continuous flow of information that characterized past experience are not represented—a form of compression that engineers would refer to as "lossy compression" (Figure 1). Such temporal gaps in mnemonic representations (i.e., leaving out certain parts of the

[1] Although the exact nature of experience units remains to be investigated in detail, it is likely that most of them are not static snapshots of prior experience but instead consist in dynamic representations of more or less extended portions of prior experience.

events) may provide an efficient way of summarizing the unfolding of events, similarly to the way events are condensed in movies (Schwan & Garsoffky, 2004).

Compression rates are variable and depend on event segmentation

It is important to note that the rate of event compression in episodic memory representations is not constant but varies substantially across events. For example, a consistent finding has been that events in which participants perform specific actions (e.g., buying a newspaper) are less compressed than events that only involve spatial navigation (e.g., going from one place to another with no action to perform except walking) (Folville et al., 2020; Jeunehomme et al., 2018, 2020; Jeunehomme & D'Argembeau, 2019). In fact, the rate of temporal compression of an event in memory (i.e., the time needed to remember an event relative to the actual event duration) is inversely related to the density of experience units that are recalled (i.e., the number of experience units recalled per unit of time of the actual event duration) (Jeunehomme & D'Argembeau, 2019).[2] A critical question then is what determines the density of experience units in episodic memories?

Behavioural and neural evidence suggest that the formation of episodic memory units depends on the segmentation of the continuous stream of experience into events and sub-events (for review, see Radvansky & Zacks, 2017; Zacks, 2020). At any given moment, we make sense of our experience by constructing a mental model of the current situation. Such event models are constantly updated according to dynamic changes in various dimensions of ongoing experience (e.g., changes in location, characters, objects, goals, and so forth), which result in the perception of event boundaries—the perception that an event has ended and another event has begun (Zacks et al., 2007). Event boundaries are created at multiple timescales and the resulting event segments are organized hierarchically, 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) (Baldassano et al., 2017; Sargent et al., 2013). Episodic memories reflect this structure of event processing, with the event segments formed during perception corresponding to the representational units in memory (Baldassano et al., 2017; Radvansky & Zacks, 2017; Zacks, 2020). Thus, event boundaries are better recalled than event middles (Gold et al., 2017; Schwan & Garsoffky, 2004). Furthermore, the grain size of event segmentation during encoding impacts how

[2] Note that a similar relation has been observed for the remembered duration of an event, with evidence showing that duration estimates increase with the amount of information retrieved from memory—more specifically the amount of perceptual or contextual changes in the remembered event (see e.g., Block & Reed, 1978; Fenerci et al., 2020; Jeunehomme & D'Argembeau, 2019; Roseboom et al., 2019).

well events are subsequently remembered: recall is more detailed after fine-grained segmentation than after coarse-grained segmentation (Hanson & Hirst, 1989; Lassiter et al., 1988).

The rate of event compression in episodic memories might thus depend on the granularity of event segmentation. To test this hypothesis, Jeunehomme and D'Argembeau (2020) asked participants to remember a series of events previously experienced during a tour on campus and the density of recalled experience units was quantified based on their verbal reports. Then, participants were presented with a continuous sequence of pictures representing their past experience (which had been taken by a wearable camera) and were asked to segment this sequence into the smallest units that made sense to them. To do so, they pressed a button each time they identified a transition between two events or sub-events (i.e., when one event or sub-event ended and another one began). It was found that the density of experience units reported in the memory task (i.e., the number recalled experience units per minute of the actual event duration) was predicted by the segmentation density of the picture sequence (i.e., the number of event boundaries identified per unit of time). Furthermore, event boundaries were more than five times more likely to be recalled than other parts of events. In fact, many moments of experience between event boundaries were not recalled, leaving temporal gaps in the representation of events. Taken together, these results suggest that events that are perceived in terms of finer sub-events are sampled at a higher rate, leading to a higher density of experience units in episodic memory representations (see also Faber & Gennari, 2015).

Principles that structure the organization of experience units

We have seen that memories for dynamic real-life events are composed of a succession of experience units that represent the unfolding of events in a compressed form. This structure of mnemonic representations raises the question of how sequences of experience units that include temporal discontinuities are organized and linked together to form coherent event representations. Here, we briefly consider three possible (non-mutually exclusive) mechanisms.

First, it is likely that prior knowledge plays a key role in the encoding and retrieval of event structure. In particular, event schemas may provide information about temporal order and causal relations between the event segments that compose memories (Radvansky & Zacks, 2011). Second, the hierarchy of goal processing (goals and sub-goals) may also structure event sequences, notably in terms of actions and their outcomes (Lichtenstein & Brewer, 1980; Williams et al., 2008). Third, contextual states associated with ongoing experience may form a background that contributes to information integration and segmentation in memory representations. Indeed, research has shown that periods of stability or gradual change in contextual features (e.g., one's surroundings and internal states) makes temporally proximal experiences to cohere with one another in memory (Howard, 2017; Polyn & Cutler, 2017), whereas contextual changes create separations in memory (i.e., event boundaries) that lead to distinct representational units (Clewett & Davachi, 2017; DuBrow et al., 2017; Radvansky & Zacks, 2017). While this organizational role of contextual states has been mainly evidenced using laboratory stimuli (i.e., word lists), recent studies have shown that the recall dynamics of real-world events follow similar principles (e.g., a temporal contiguity effect) (Diamond & Levine, 2020; Stawarczyk & D'Argembeau, 2019). Thus, contextual stability may contribute to the integration of information into meaningful experience units, whereas contextual shifts may be used as transition points to skip segments of past experience when remembering the unfolding of events: to speed up remembering, people may transition from one contextual shift to another without necessarily representing everything that happened in between.

A question that remains to be investigated in detail is to what extent the temporal compression of events reflects how they are encoded and stored in episodic memory versus how they are reconstructed at retrieval. In previous studies that assessed event compression rates, participants were instructed to recall everything they could in order to mentally re-experience events in as much detail as possible (Folville et al., 2020; Jeunehomme et al., 2018; Jeunehomme & D'Argembeau, 2019, 2020). Thus, the observation of temporal discontinuities in the unfolding of recalled events probably reflects, at least in part, properties of stored representations (although of course differences in the accessibility of representations may also play some role). In support of this view, it has been shown that during event perception people preferentially sample highly informative regions of the sensory stream over less informative regions, such that certain parts of events (i.e., event boundaries) are more efficiently encoded in memory (Hard et al., 2011; Kosie & Baldwin, 2019). However, this does not preclude the possibility of flexibly adjusting the speed of memory replay at retrieval, according to retrieval goals (Bellmund et al., 2020). Future studies could investigate this flexibility, for example, by manipulating retrieval instructions. In fact, for any given act of remembering, it is likely that the structure of stored representations and retrieval conditions conjointly determine the rate of event compression. Beyond episodic remembering, a similar compression mechanism may also operate when mentally simulating future events (Arnold et al., 2016; Jeunehomme et al., 2020).

Conclusion

The continuous stream of experience that forms the fabric of daily life is not represented as such in episodic memory. When remembering an event, the unfolding of past experience is summarized as a succession of moments or slices of experience that includes temporal discontinuities. This compression mechanism allows us to revisit the past in a speeded manner, with the rate of event compression depending on the density of experience units representing the unfolding of events.

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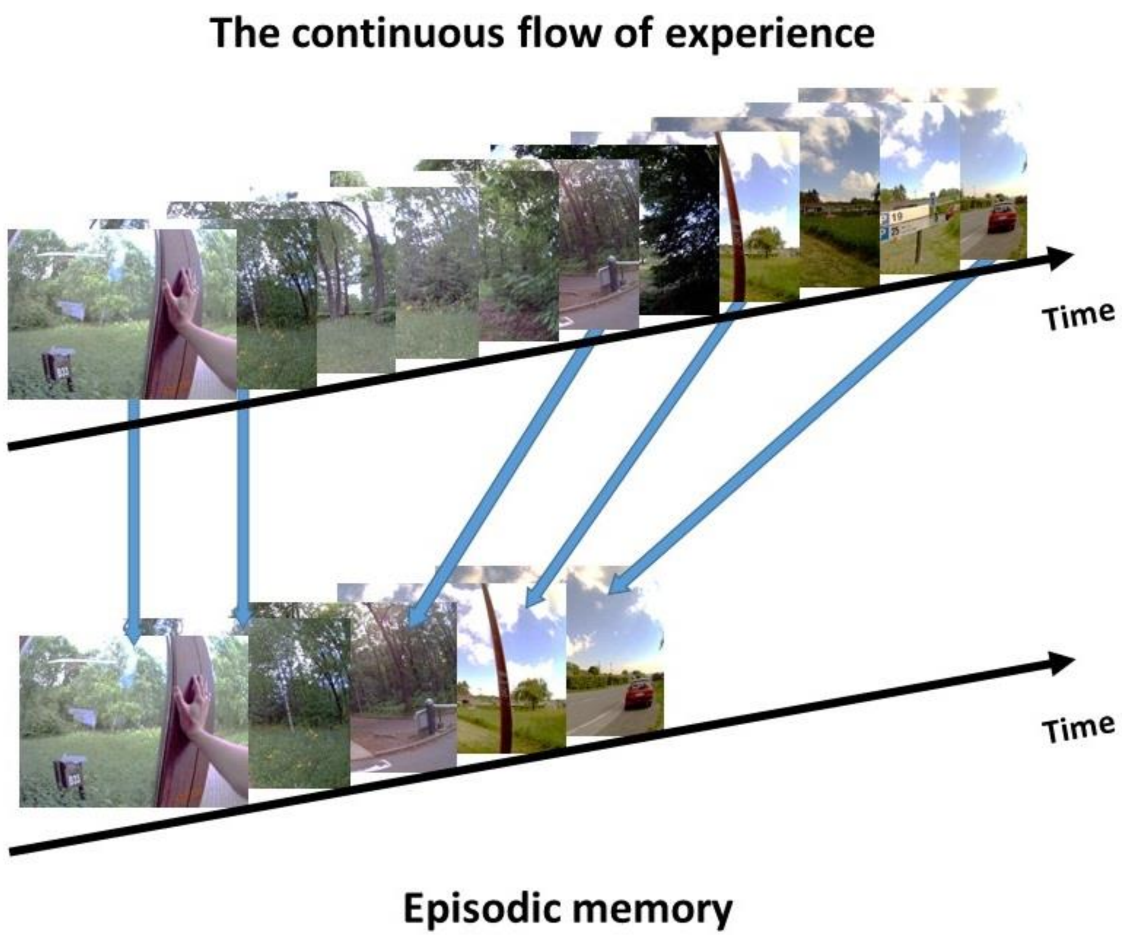

Figure 1. Schematic illustration of the temporal compression of events in episodic memory representations. The continuous flow of past experience (upper panel) is compressed in episodic memory as a succession of moments or slices of experience (lower panel) that includes temporal gaps in the representation of the event's unfolding (i.e., some segments of past experience are not represented).