Event segmentation and the temporal compression of experience in episodic memory

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Abstract

Recent studies suggest that episodic memory represents the continuous flow of information that constitutes daily life events in a temporally compressed form, but the nature and determinants of this compression mechanism remain unclear. In the present study, we used wearable camera technology to investigate whether the temporal compression of experience in episodic memory depends on event segmentation. Participants experienced a series of events during a walk on a university campus and were later asked to mentally replay these events. The temporal compression of events in memory and grain size of event segmentation were estimated based on records of participants' experience taken by the camera. The results showed that the temporal compression of events in memory (i.e., the density of recalled moments of experience per unit of time of the actual event duration) closely corresponded to the grain size of event segmentation. Specifically, grain sizes of event segmentation and temporal compression rates were four to five times lower when remembering events that involved goal-directed actions compared to other kinds of events (e.g., spatial displacements). Furthermore, temporal compression rates in memory were significantly predicted by the grain size of event segmentation and event boundaries were more than five times more likely to be remembered than other parts of events. Together, these results provide new insights into the mechanism of temporal compression of events in episodic memory.

Keywords: Episodic memory; Temporal compression; Event segmentation; Wearable camera; Actions; Goals

Introduction

Episodic memory would not be functional if remembering an event took as much time as the original experience: the continuous flow of experience is somehow compacted in memory, such that the time to remember an event (i.e., the duration of mental replay) is shorter than the actual duration of the past episode. This phenomenon has been referred to as the temporal compression of events in memory. The mental replay of routes, for example, takes less time than the actual navigation of these routes (Arnold, Iaria, & Ekstrom, 2016; Bonasia, Blommesteyn, & Moscovitch, 2016).

While the precise mechanisms of episodic memory compression are not fully understood, recent studies suggest that past events are represented as a succession of moments or slices of prior experience (referred to as “experience units”) that introduces discontinuities in the events' temporal unfolding (i.e., portions of the continuous flow of experience are not represented in memory; Jeunehomme & D'Argembeau, in press; Jeunehomme, Folville, Stawarczyk, Van der Linden, & D'Argembeau, 2018). For example, when remembering the event of buying a newspaper earlier in the morning, 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 represented in memory. As another example, when remembering his walk to the shop, the same participant experienced a mental image of getting out of the laboratory building immediately followed by a mental image of passing near a bus stop; in the actual event, these two moments of experience were separated by more than one minute. Jeunehomme and D'Argembeau (in press) have proposed that the temporal compression of events in episodic memory occurs, at least in part, because of these discontinuities in the representation of the unfolding of events, such that longer temporal gaps between remembered moments would lead to greater compression rates (see Figure 1). However, the nature and mechanism of formation of the moments of experience that constitute memories remain unclear.

The process by which people parse the continuous stream of experience into events and sub-events might play an important role in the formation of experience units in episodic memory. According to event segmentation theory (Kurby & Zacks, 2008; Zacks, Speer, Swallow, Braver, & Reynolds, 2007), people make sense of a dynamic complex world by segmenting it into meaningful units. On this view, ongoing perception involves the construction of an event model that captures information about the spatiotemporal framework, entities and objects, and other salient features of the current situation. This working model biases the perceptual processing stream and allows one to comprehend and predict the unfolding of the event. When significant changes in perceptual or conceptual features of ongoing experience occur, predictions based on the current event model become more difficult and prediction errors increase. At such points, people update their mental model of the current situation. This updating process results in the segmentation of the stream of experience into events, with event boundaries being perceived as the subjective experience that an event has ended and a new event has begun. More generally, it has been argued that any form of contextual stability and change (in external or internal contextual states) contribute to the extraction of discrete events from ongoing experience (Clewett & Davachi, 2017).

Previous studies have shown that event segmentation has important consequences for long-term memory. In particular, there is evidence that event boundaries are more richly encoded (Baird & Baldwin, 2001; Newtson & Enquist, 1989; Swallow, Zacks, & Abrams, 2009) and determine the organization of events in episodic memory (Dubrow & Davachi, 2013; Ezzyat & Davachi, 2011; Horner, et al., 2016; Radvansky & Copeland, 2006). Thus, the grain size of event segmentation during encoding modulates what is retained, such that increasing the number of event boundaries enhances memory (Lassiter, Stone & Rogers, 1988; Pettijohn et al., 2016). These and related findings suggest that event boundaries serve as anchors for episodic encoding and determine the temporal structure of memories (Brunec, Moscovitch, & Barense, 2018; Clewett & Davachi, 2017; Radvansky & Zacks, 2017).

The moments of past experience that people describe when remembering the unfolding of events (Jeunehomme et al., 2018) might be formed and stored in episodic memory as the continuous stream of experience is segmented into events and sub-events. Experience units in episodic memory may thus be determined by periods of changes in perceptual and goal processing that result in the formation of event boundaries (Williams, Conway, & Baddeley, 2008), such that the temporal compression of events in memory may depend (at least in part) on the grain size of event segmentation. On this view, events that are segmented in finer units should be associated with a higher density of discrete moments of experience in episodic memory and, consequently, with a lower temporal compression rate when remembering. A recent study on memory for animated geometric shapes has provided initial support for this hypothesis (Faber & Gennari, 2015). Specifically, it was found that the time needed to mentally replay an animation increased with the number of perceived sub-events (after the actual duration of the animation had been taken into account), suggesting that memory compression depended on the grain size of event segmentation. However, to our knowledge, the relationship between event segmentation and memory compression has not been investigated for more complex, real-world events.

In our previous work, we found that the compression of prior experience in episodic memory was lower for events that involved goal-directed actions (e.g., buying a newspaper) than for events that involved spatial displacements (e.g., going from the laboratory to the campus newsstand; Jeunehomme & D'Argembeau, in press; Jeunehomme et al., 2018). These two kinds of events correspond to what Tversky, Zacks, and Lee (2004) referred to as "events by hands" (i.e., interactions with objects) and "events by feet" (i.e., changes of location). Differences in compression rates when remembering these events may in part be due to the way they are segmented. Spatial displacements are primarily segmented as a result of changes in direction of movement (e.g., turns at landmarks), whereas actions (events by hands) are typically perceived as a hierarchy of coarse and fine units that correspond to changes in goals and sub-goals (Tversky et al., 2004). Consequently, actions may be associated with a finer event segmentation, which could account for their lower compression rate in episodic memory.

Here we tested this hypothesis (1) by comparing the grain size of event segmentation for events that involved actions, spatial displacements, or no particular action or change in spatial location, and (2) by examining to what extent event segmentation predicts temporal compression rates in episodic memory. As in our previous study (Jeunehomme et al., 2018), temporal compression rates were estimated as the number of recalled experience units per minute of the actual event duration (which was recorded using a wearable camera). We expected that the grain size of event segmentation would impact the temporal compression of prior experience when remembering such that events that are segmented into finer sub-events would be associated with a greater density of recalled experience units, thus reflecting a lower compression of the unfolding of events in episodic memory.

Method

Participants

Participants were 25 undergraduate students aged between 18 and 30 years. This sample size was defined a priori using G*Power 3 (Faul, Erdfelder, Lang, & Buchner, 2007) in order to achieve a statistical power of 95% to detect differences in memory compression rates as a function of the types of events (considering an alpha of .05), using effect sizes from our previous study (Jeunehomme et al., 2018). Three participants were excluded and replaced for the following reasons: one participant because he guessed that his memory would be tested and two participants because of a malfunction of the wearable camera. The final sample consisted of 25 participants (11 females; mean age = 23 years, *SD* = 1.94 years). All participants provided written informed consent and the study was approved by the local ethics committee.

Materials and procedure

The experimental procedure consisted in three main phases presented in the following order: a walk on campus, a memory task, and a segmentation task. The first two phases were similar to those used in our previous study of temporal compression in episodic memory (Jeunehomme et al., 2018) and the segmentation task was adapted from previous studies on event segmentation (Newtson, 1973; Zacks, Tversky & Iyer, 2001).

Walk on campus phase. Participants were instructed to perform a series of daily-life activities at different locations on the campus of the University of Liège while their experience was recorded using a wearable camera (Figure 2). To examine the respective contribution of actions and spatial displacements on temporal compression and event segmentation, three kinds of events were proposed: goal-directed actions ("events by hands", which involved interactions with objects; e.g., buying a newspaper), spatial displacements ("events by feet"; e.g., going from the laboratory building to the campus newsstand), and one additional event that involved no particular action or spatial displacement (i.e., sitting at a table in the cafeteria). We included events that involved actions but no change in spatial location and events that involved changes in spatial location but no action (other than walking), such that the contrast between actions, spatial displacements, and sitting events (which implied no particular action or change in spatial location) allowed us to examine the respective contribution of actions and spatial changes on temporal compression rates.

All participants received the same sequence of events (i.e., the type of events was manipulated within participants), which alternated between actions and spatial displacements to avoid potential order effects when comparing the two types of events. The entire set of events was as follows: first, participants had to post a letter in the mailbox of the "psychopathology research unit" (see action 1 on Figure 2). Then, they had to exit the building and to go to the campus newsstand (spatial displacement 2) to buy a daily newspaper (action 3). After having purchased the newspaper, participants had to go to a cafeteria (spatial displacement 4) to buy a drink of their choice (action 5) and they were instructed to choose a table inside the cafeteria and to sit down to drink their beverage (sitting 6). Finally, they had to return to the laboratory to bring the camera back to the experimenter (spatial displacement 7). On average, participants took 34 minutes (range: 24 - 49) to complete the walk.

During the entire walk, participants wore a YoCam (Mofily®; http://www.getyocam.com/), which is a small wearable camera with a 140° angle of view lens that we configured to take a video with a resolution of 720 pixels at 30 frames per second. The YoCam allowed us to record a continuous video of all events experienced by the participants, from a first-person perspective.

To avoid an intentional encoding of the events, participants were not informed that their memory would be subsequently tested. Instead, we used a cover story explaining that the purpose of the study was to evaluate the quality of the video taken by the YoCam when performing various actions in different environments (indoor and outdoor), for a subsequent study investigating activities of university students in their daily life.

Memory task. Immediately after the walk on campus phase, participants received an unexpected free recall task in which they were invited to close their eyes and to try to mentally re-experience everything that happened during their walk, in as much detail as possible (as if they were reliving the entire situation). In addition, while mentally replaying the walk, they were asked to verbally describe everything that came to their minds, as accurately as possible and as it came to mind. Verbal reports were recorded using a digital audio recorder.

Next, participants listened to the audio recording of elements they described during the free recall task and they had to determine the moment of the walk corresponding to each element using the video recording of their past experience. Verbal descriptions of memories consisted of a succession of particular moments of past experience (referred to as experience units). For example, a typical verbal report would start by “I got out of the building” (first experience unit), “then I walked along the parking” (second experience unit), “then, I saw a man I know on the opposite side of the road” (third experience unit), and so on. These experience units were considered one at a time while playing back the audio recording. Most of the time, the identification of distinct experience units corresponded to mentions of transitions or temporal discontinuities in the verbal descriptions of events. For example, transitions between units could take the form of verbal clues (such as “then”, “next”, “after that”), moments of silence or significant changes in actions or environmental elements. Thus, in most cases the identification of distinct experience units from the participant's verbal descriptions was evident for both the experimenter and the participant. However, as in our previous study (Jeunehomme et al., 2018), the final decision was made by the participant when there was a doubt about whether a particular verbal description corresponded to a single or two distinct moments of past experience.

For each experience unit, participants had to identify the corresponding moment of their past experience using the video recording that had been taken by the wearable camera. During a pilot study, we used the original video that had been recorded but it appeared that many participants felt dizzy when looking at the video (especially when looking at spatial displacements). To avoid this issue, we instead used a sequence of still pictures that were extracted from the video. This sequence was created by extracting one frame per second of the actual event duration and participants were presented with a continuous sequence of extracted pictures (on average, the entire sequence included 2081 pictures; range: 1512 – 2978). For each experience unit that had been reported during the recall task, the audio recording was paused and participants were instructed to navigate through the pictures in order to select the picture that best corresponded to their mental representation of this moment of experience while they remembered the events.

Segmentation task. Participant were presented with a continuous sequence of pictures representing their walk (as mentioned above, this sequence was created by extracting one frame per second of video and was the same as for the memory task). Each picture was presented for a duration of 500 ms and participants were instructed to indicate when they believed that one event ended and another began (see Hanson & Hirst, 1989, for similar experimental instructions). More specifically, they were told that events could be divided into smaller parts or units, and the following example was given to illustrate how a daily-life event could be segmented into smaller sub-events: going to work in the morning could involve a sequence of sub-events such as getting out of the house, getting into the car, putting one's stuffs on the passenger seat, starting the car, thinking about a particular job meeting, and so on. In the present segmentation task, participants were asked to segment the sequence of pictures into the smallest events that make sense to them (see e.g., Sargent et al., 2013; Zacks, Tversky & Iyer, 2002) and were instructed to press 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; Figure 3)[1]. The pictures selected as event boundaries were recorded automatically.

After the segmentation task, all participants were debriefed and asked whether they had expected that their memory for the walk would be tested.

Statistical analyses

Because the distribution of our measure of temporal compression was substantially skewed, we used robust statistical methods to analyze our data (these methods perform well in terms of type I error control and statistical power, even when the normality and homoscedasticity assumptions are violated; Wilcox, 2012). More specifically, we conducted paired samples robust *t*-tests and robust repeated-measures ANOVAs using the 20% trimmed means (a robust measure of location that ignores the top and bottom 20% of data) and 2000 bootstrap samples (as a way to deal with bias in standard errors by estimating the shape of the sampling distribution by sampling with replacement from the data), as recommended by Field and Wilcox (2017). Furthermore, to investigate whether temporal compression rates were predicted by the grain size of event

[1] In the present article, we use to terms "event segmentation", "segmentation points" or "event boundaries" to refer to the events and sub-events identified in this event segmentation task, whereas as noted above the term "experience unit" refers to the moments of past experience that constitute episodic memories.

segmentation, we also conducted robust regression analyses. To take the hierarchical structure of the data into account (Goldstein, 2011), we fitted a robust multilevel model (two-level random intercept model, with events as level 1 units and participants as level 2 units). All descriptive statistics refer to the 20% trimmed means and their 95% confidence intervals calculated using the percentile bootstrap method (with 2000 bootstrap samples; Wilcox, 2012).

Results

Temporal compression of events in episodic memory

Verbal reports showed that memories consisted of a succession of moments of past experience, referred to as experience units (see Methods). On average, participants reported a total of 41 experience units, 95% CI [35.47, 50.20]. To estimate temporal compression rates in episodic memory, we used temporal information associated with the pictures selected as corresponding to each recalled experience unit (i.e., the actual time at which the corresponding picture was taken during the walk). More precisely, temporal compression rates were estimated as the number of experience units reported per minute of the actual event duration (Jeunehomme et al., 2018). According to this measure, a greater density of recalled experience units per minute of the actual event duration reflects a lower temporal compression of events in episodic memory.

A robust one-way repeated-measures ANOVA showed that temporal compression rates differed across the three types of events (i.e., goal-directed actions, spatial displacements, and sitting), $F_t = 60.42$, $F_{Crit} = 10.94$, $p < .001$ (see Figure 4A). Post-hoc tests showed that the density of experience units was higher for goal-directed actions than both spatial displacements, $\hat{\psi} = 4.54$, 95% CI [2.99, 6.08], and sitting, $\hat{\psi} = 4.81$, 95% CI [3.20, 6.42]. There was no significant difference in the density of recalled experience units between spatial displacements and sitting, $\widehat{\psi}$ = - 0.27, 95% CI [-0.68, 0.15].

We estimated temporal gaps in episodic memories by looking at the time separating successive moments of past experience described at recall, in terms of the actual event duration. To do so, we computed the actual event duration separating pictures that had been selected as corresponding to recalled experience units. A robust one-way repeated-measures ANOVA showed that temporal discontinuities between recalled moments of past experience differed across the three types of events, $F_t = 12.59$, $F_{Crit} = 10.82$, $p < .001$. Post-hoc tests showed that temporal gaps were shorter for goal-directed actions (trimmed mean = 16.56 s, 95% IC [12.98 – 24.80]) than for spatial displacements (trimmed mean = 63.05 s, 95% IC [47.92 – 85.23]), $\widehat{\psi}$ = -46.49, 95% CI [-72.32, -20.67], and sitting (trimmed mean = 73.88 s, 95% IC [50.14 – 118.70]), $\widehat{\psi}$ = -57.32, 95% CI [-105.19, -9.46]. There was no significant difference in temporal gaps between spatial displacements and sitting, $\widehat{\psi}$ = 10.82, 95% CI [-28.59, 50.25].

Taken together, these results replicate our previous finding that the temporal compression of events in episodic memory is lower for goal-directed actions than spatial displacements and sitting (Jeunehomme & D'Argembeau, in press; Jeunehomme et al., 2018).

Event segmentation

On average, participants identified 55 event boundaries for the entire walk, 95% CI [47.00, 64.67]. To investigate whether the grain size of event segmentation differed between the three types of events (i.e. goal-directed actions, spatial displacements, and sitting), we computed the number of segmentation points identified per unit of time of the actual event duration, separately for each kind of events (see Figure 4B). A robust one-way repeated-measures ANOVA showed that the amount of segmentation points per minute of the actual event duration varied depending on the type of events, $F_t = 49.57$, $F_{Crit} = 15.63$, $p < .001$. Post-hoc tests showed that participants identified more sub-events for goal-directed actions than for spatial displacements, $\widehat{\psi} = 3.59$, 95% CI [2.32, 4.86], and sitting, $\widehat{\psi} = 3.70$, 95% CI [2.39, 5.01]. There was no significant difference in the grain size of event segmentation between spatial displacements and sitting, $\widehat{\psi} = -0.11$, 95% CI [-0.62, 0.40].

Relationship between temporal compression rates and event segmentation

The preceding analyses showed that temporal compression rates in episodic memory, on the one hand, and the grain size of event segmentation, on the other hand, followed similar patterns of variation across the three types of events. Although this finding is consistent with our hypothesis, the observed patterns were based on aggregated data across all events of each type. To more directly investigate whether the rate of temporal compression in episodic memory is predicted by the grain size of event segmentation, we conducted a multilevel regression analysis, with temporal compression rates as outcome variable (i.e., the number of experience units reported per minute of the actual event duration) and the grain size of segmentation as predictor (i.e., the number of segmentation points identified per minute of the actual event duration); all events were included in this analysis. This revealed that the grain size of event segmentation was a significant predictor of temporal compression rates, with the number of recalled experience units increasing with the number of segmentation points ($\beta = 0.61$, $SE = 0.03$, $z = 22.47$, $p < .001$). We also conducted a similar regression analysis using only goal-directed actions to investigate whether differences in event segmentation explains variations in compression rates within this type of event. Again the results showed that event segmentation was a significant predictor of temporal compression rates ($\beta = 0.47$, $SE = 0.08$, $z = 5.22$, $p < .001$). Together, these analyses show that the grain size of event segmentation predicts temporal compression rates, such that a finer event segmentation leads to a lower compression of events in episodic memory.

To further examine the role of event segmentation in the formation of experience units in episodic memory, we compared the probability of recall of segmentation points to the probability of recall of other parts of events (i.e., between segmentation points). To this aim, we created a 4-s time bin around each segmentation point (which corresponded to 2 pictures before and after the picture selected as segmentation point, that is, a 5-picture window)[2] and then calculated the proportion of time bins that corresponded to an experience unit described in the recall phase. We found that, on average, 33.30% of segmentation points were recalled, 95% CI [28.77%, 39.89%]. To estimate the probability of recall of other parts of events, we first computed the total duration of all event parts that did not involve segmentation points by subtracting the duration of the walk by the duration of all 4-s time bins created around segmentation points. The resulting duration was converted in a series of 4-s time bins and we calculated the proportion of time bins that corresponded to an experience unit described at recall. This showed that, on average, 5.90% of time bins with no segmentation point were recalled, 95% CI [4.60%, 7.40%]. These results thus show that event boundaries were more than five times more likely to be remembered than other parts of events.

Discussion

[2] During the segmentation task, each picture was presented on the screen for a relatively short duration (i.e., 500 ms) and pilot tests showed that this sometimes led participants to select a picture that was 1 or 2 pictures before or after the actual segmentation point because they pressed the button too early or too late during the sequence. Consequently, we used a 5-picture window (rather than a single picture) to delimit segmentation points in these analyses.

Recent studies have shown that the continuous flow of information that constitutes daily-life events is temporally compressed in episodic memory. To date, however, our understanding of the nature and determinants of this compression mechanism remains limited. In the present study, we investigated to what extent the temporal compression of experience in episodic memory depends on event segmentation. We found that variations in temporal compression rates when remembering different types of events closely corresponded to the grain size of event segmentation. Specifically, grain sizes of event segmentation and temporal compression rates (as estimated by the density of recalled experience units per minute of the actual event duration) were four to five times lower when remembering events that involved goal-directed actions compared to other kinds of activities (i.e., spatial displacements or sitting at a given location). Furthermore, the rate of temporal compression of events in episodic memory was significantly predicted by the grain size at which people segmented their past experience. Finally, our results showed that event boundaries were more than five times more likely to be remembered than other parts of events.

Episodic memories are summary records of experience (Conway, 2009) that represent the unfolding of events in a temporally compressed form (Jeunehomme & D’Argembeau, in press). More specifically, the present results and our previous findings (Jeunehomme et al., 2018) suggest that past events are represented in episodic memory as a succession of moments or slices of prior experience (referred to as experience units) that includes temporal discontinuities (i.e., some parts of prior experience are not represented in memory; see Figure 1). The novel contribution of this study is the demonstration that the experience units that constitute memories are related to event segmentation. Segments of time surrounding event boundaries were more than five times more likely to be described when remembering events, and the vast majority of segments of time between event boundaries were actually not remembered, leaving temporal gaps in the representation of events. Temporal compression rates in episodic memory depended on the importance of these temporal discontinuities and, consequently, on the grain size of event segmentation. This suggests that events that are perceived in terms of finer sub-events are sampled at a higher rate during encoding, leading to a lower temporal compression when remembering the unfolding of events. The present results thus complement previous observations that event boundaries structure the encoding and organization of information in episodic memory (e.g., Dubrow & Davachi, 2013; Ezzyat & Davachi, 2011; Pettijohn et al., 2016; Radvansky & Copeland, 2006; Swallow, Zacks, & Abrams, 2009) by showing that the segmentation of the continuous stream of experience into discrete events and sub-events allows to represent the unfolding of events in a temporally compressed form.

Another important finding of the present study is that event segmentation and memory compression are not uniform but depend on the type of events. More precisely, we found that grain sizes of event segmentation and rates of temporal compression were four to five times lower when events involved goal-directed actions (or "events by hands"; Tversky et al., 2004). This finding supports the view that a critical function of episodic memory is to keep track of goal processing (Conway, 2009), such that temporal compression rates may be adaptively modulated to maintain goal-relevant information (see also Jeunehomme et al., 2018). Previous studies have shown that event boundaries tend to correspond to changes in goal processing (Hard, Recchia & Tversky, 2011; Zacks, Tversky, & Iyer, 2001), which suggests that episodic memories may be formed depending on the hierarchical structure of goals and sub-goals (Conway, 2009; Williams et al., 2008). Goal pursuit involves action sequences that occur at different levels of specificity; for example, the goal of cooking a dinner for friends can be perceived in terms of broad action sequences such as preparing the ingredients and cooking the meal, which may themselves be represented in terms of finer action units (e.g., looking for the ingredients, washing the tomatoes, peeling the potatoes, and so on; Hard, Recchia & Tversky, 2011). Transitions between goals and sub-goals at these different levels may be points at which experience units are formed in episodic memory. Accordingly, events that involve goal-directed actions may be perceived in terms of finer sub-events, leading to the encoding of a higher density of experience units in episodic memory. Furthermore, the perception of causal links between actions and outcomes may help to bind experience units in an integrated event sequence (Brownstein & Read, 2007; Radvansky & Zacks, 2017). An interesting question for future research would be to examine further this potential role of causal connections in the formation of experience units and the ensuing temporal compression of events in episodic memory.

The present study raises other questions that may also inspire future research on temporal compression in episodic memory. Notably, while our results demonstrate that event segmentation contributes to the formation of experience units in episodic memory, the precise features of ongoing experience that dictate the formation of these units remain to be determined. The present and previous observations (Williams et al., 2008) suggest that actions and goals play a critical role in the creation of segmentation points that structure episodic memories. However, event segmentation can result from multiple aspects of ongoing experience (e.g., changes in agents, goals, causality, space and time; Magliano et al., 2014) and the potential role of each dimension in the formation of experience units in episodic memory should be investigated in detail. Furthermore, the events in this study were rather mundane and occurred in a familiar context (i.e., the university campus). In future studies, it would be interesting to include a greater variety of events to investigate whether the grain-size of event segmentation and memory compression rates depend on various event features (e.g., their emotionality, novelty/familiarity, and personal significance).

It should also be noted that in the present study temporal compression rates were not directly measured (i.e., as the ratio between the duration of mental replay and the actual event duration), but were instead estimated by the density of recalled experience units per unit of time (i.e., minute) of the actual event duration. This density measure was used because our primary interest was to examine to what extent the formation of experience units in episodic memory is related to event segmentation processes; besides, the temporal compression of events as operationalized by the ratio of replay duration to the actual event duration is predicted by the density of recalled experience units (Jeunehomme & D'Argembeau, in press). However, one should note that experience units are probably dynamic and temporally extended, representing short-time slices of prior experience (Conway, 2009; see Figure 1). Therefore, an important avenue for future work will be to investigate further the temporal extension of experience units and to determine the respective contribution of the density and length of experience units to the temporal compression of events in episodic memory.

Finally, it is worth mentioning that the present study examined memory compression rates after a short delay (i.e., a few minutes). In a recent study, we found that the temporal compression of events in memory remained relatively stable over one week and then decreased at a one-month delay, particularly for events that involved goal-directed actions (Jeunehomme et al., 2018). Considering this evidence for delay-dependent changes in temporal compression rates, an important research question would be to examine whether the correspondence between event boundaries and experience units in episodic memory evolves over time. This issue could be investigated, for example, by examining changes in the amount of recalled event boundaries across various retention intervals (see Flores, Bailey, Eisenberg, & Zacks, 2017, for evidence that event segmentation produces durable effects in memory).

In summary, the present data show that episodic memory represents past events as a succession of moments of prior experience that includes temporal discontinuities. The density of experience units within memories depends on the grain size of event segmentation, such that memory compression is lower for events that are segmented in finer sub-events. Goal-directed actions seem to play an important role in the formation of experience units in memory, although the contribution of other dimensions of experience remains to be investigated in detail. Taken together, these findings provide an important step toward understanding how episodic memories represent the unfolding of events in a temporally compressed form.

Compliance with Ethical Standards

Conflict of Interest: The authors declare that they have no conflict of interest.

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments.

Informed consent: Informed consent was obtained from all individual participants included in the study.

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Figure captions

Figure 1. Hypothetical mechanism underlying the temporal compression of events in episodic memory. Past events may be compressed in episodic memory in the form of a succession of moments of prior experience (referred to as experience units; blue boxes) that leaves temporal gaps in the representation of the events' unfolding (grey intervals). As illustrated, the memory of a past event may be characterized by a specific number of experience units (E1, E2, and so on) that represent parts of prior experience. Although the exact nature of these 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 (as illustrated by the varying lengths of experience units). These experience units are separated by portions of prior experience that are not represented in episodic memory (G1, G2, and so on). Temporal compression rates in episodic memory may depend on the duration of these temporal gaps, such that longer gaps would lead to higher compression rates. Taken together, experience units form the pieces of temporally compressed representations of the unfolding of past events. E: experience unit; G: temporal gap.

Figure 2. Overview of the walk on the campus of the University of Liège. (A) Locations in which activities were performed (color circles) and paths taken to go to these locations (color lines). (B) Examples of pictures taken by the wearable camera during the different activities and paths of the walk.

Figure 3. Examples of event segmentation. (A) Sequence of pictures representing a goal-directed action (posting a letter) and the picture chosen to indicate the transition between two sub-events (vertical blue lines). (B) Sequence of pictures representing a spatial displacement (going out the laboratory building) and the picture chosen to indicate the transition between two sub-events (vertical green lines).

Figure 4. Rates of temporal compression and grain size of event segmentation for the three types of events. (A) Temporal compression in episodic memory is estimated as the number of recalled experience units per minute of the actual event duration. (B) The grain size of event segmentation corresponds to the number segmentation points identified per minute of the actual event duration. Error bars represent 95% robust confidence intervals.

Figure 1

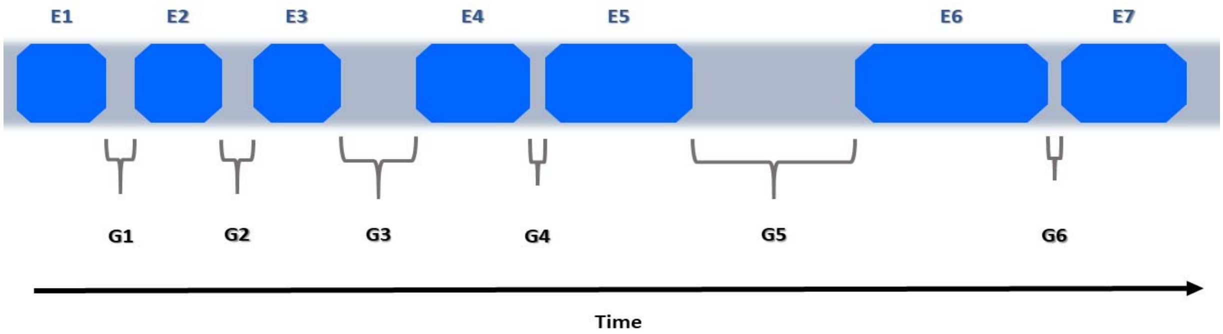
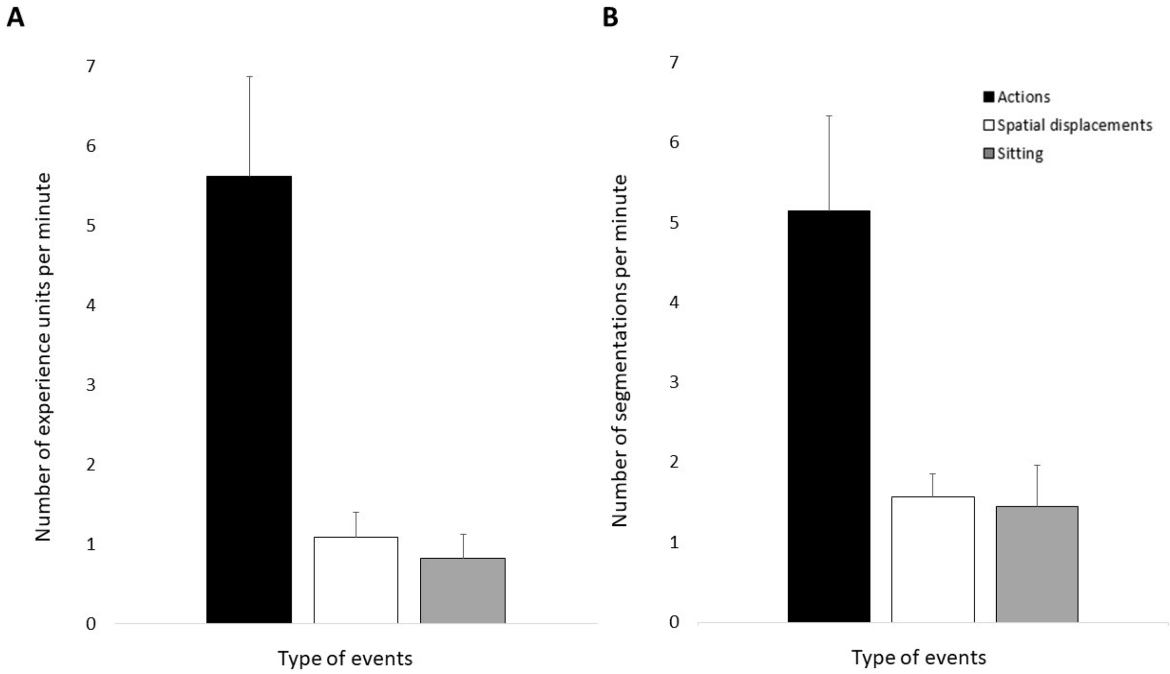


Figure 2

Figure 3

Figure 4


A
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7
6
5
4
3
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1
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Number of experience units per minute
Type of events
Number of segmentations per minute
Type of events
Actions
Spatial displacements
Sitting