

Temporal compression in episodic memory for real-life events

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ABSTRACT

Remembering an event typically takes less time than experiencing it, suggesting that episodic memory represents past experience in a temporally compressed way. Little is known, however, about how the continuous flow of real-life events is summarised in memory. Here we investigated the nature and determinants of temporal compression by directly comparing memory contents with the objective timing of events as measured by a wearable camera. We found that episodic memories consist of a succession of moments of prior experience that represent events with varying compression rates, such that the density of retrieved information is modulated by goal processing and perceptual changes. Furthermore, the results showed that temporal compression rates remain relatively stable over one week and increase after a one-month delay, particularly for goal-related events. These data shed new light on temporal compression in episodic memory and suggest that compression rates are adaptively modulated to maintain current goal-relevant information.

Episodic memory allows people to remember specific events from their personal past, such as the last birthday party of a friend or a particular job interview. Ever since Tulving (1972) first made the distinction between memory for such events and other forms of declarative memory, important progress has been made in understanding the cognitive and neural mechanisms underlying the encoding, storage, and retrieval of past episodes (Davachi, 2006; Rugg & Vilberg, 2013; Schacter, Norman, & Koutstaal, 1998; Tulving, 2002). To date, however, episodic memory research has largely focused on the recall or recognition of laboratory materials, such as lists of words or pictures. Because laboratory stimuli are impoverished proxies for daily life events, some fundamental questions remain as to how past experience is represented. In particular, little is known about how the continuous flow of events that makes the fabric of our lives is summarised in episodic memory. To examine this question, the present study capitalises on wearable camera technology (Allé et al., 2017; Chow & Rissman, 2017; Silva, Pinho, Macedo, & Moulin, 2016) to investigate the temporal compression of experience in memory for real-life events.

In daily life, people are faced with a rich and continuous flow of events and experiences. Episodic memory does not retain a literal and complete record of this stream of information, but instead maintains summary representations of past experience (Conway, 2009). How the rich and dynamic flow of ongoing experience is transformed and summarised in episodic memory remains

poorly understood, however. A fundamental question is how events are temporally compressed in episodic memory. Remembering an event typically takes less time than experiencing it, suggesting that only part of the continuous stream of information that constitutes ongoing experience is encoded or retained. One possibility is that episodic memory maintains short-time slices of ongoing experience, such that the memory of an event consists of a succession of moments of past experience that represents this event in a temporally compressed way (Conway, 2008).

Current knowledge on temporal compression in episodic memory mainly comes from studies of spatial memory. Work in rodents has shown that place cells in the hippocampus fire selectively when animals move through particular locations in the environment and, during pauses in exploration, these place cells re-express firing sequences corresponding to recent spatial experience (Buzsaki & Moser, 2013). This neuronal replay is considered a substrate of spatial memory and, interestingly, it has been shown that place cell firing sequences are re-expressed at a faster rate than during previous exploration, suggesting that spatial information is temporally compressed in memory (Davidson, Kloosterman, & Wilson, 2009; Skaggs, McNaughton, Wilson, & Barnes, 1996). A recent behavioural study indicates that a similar compression mechanism occurs during spatial memory replay in humans (Bonasia, Blommestein, & Moscovitch, 2016).

In this study, participants were asked to mentally navigate a series of familiar routes, which varied in length and number of turns, and temporal compression during mental navigation was assessed by dividing the time it would take to actually walk each route over the time taken to navigate each route mentally. The results revealed that the mental replay of familiar routes is temporally compressed and that compression rates are influenced by route length and number of turns: longer routes are more compressed, while turns attenuate compression. Besides spatial memory, there is evidence that memory for audiovisual movies is also temporally compressed: Furman, Dorfman, Hasson, Davachi, and Dudai (2007) investigated memory performance for various events sampled every 20 s in a 27-min movie and estimated that 1.6 events per minute (i.e., 56% of sampled events) are retrievable after a short delay. While these studies provide initial evidence that past experience is temporally compressed in episodic memory, the characteristics and determinants of this compression mechanism remain largely unexplored.

An interesting framework for understanding how the continuous flow of experience is summarised in episodic memory comes from research on event cognition (Radvansky & Zacks, 2014), and in particular from event segmentation theory (Zacks, Speer, Swallow, Braver, & Reynolds, 2007). Event segmentation theory proposes that people experience and interpret everyday events using mental models of how these events should unfold. When perceptual or conceptual features of ongoing experience change, people update their mental model of “what is happening now”, thereby segmenting the continuous stream of ongoing experience into events. Research indicates that the resulting event boundaries (i.e., the transitions from one event to another) are particularly well retained (Swallow, Zacks, & Abrams, 2009) and influence information organisation in episodic memory (Dubrow & Davachi, 2013; Ezzyat & Davachi, 2011; Horner, Bisby, Wang, Bogus, & Burgess, 2016). Furthermore, it has been shown that increasing the number of event boundaries during encoding enhances memory (Pettijohn, Thompson, Tamplin, Krawietz, & Radvansky, 2016).¹ These findings suggest that perceptual and conceptual changes in ongoing experience serve as anchors in episodic memory, such that more changes in the stream of information would lead to lower memory compression rates (Faber & Gennari, 2015a).

Another factor that might contribute to transforming ongoing experience into episodic memories is goal processing. According to Conway (2001, 2009), one of the main functions of episodic

memories is to keep records of recent goal processing (i.e., in the preceding few minutes, hours, or days). On this view, episodic memories represent knowledge about specific actions and action outcomes, which provides a means to check on recent progress with current goals and plans. Therefore, events might be retained in episodic memory as a function of the goal structure of an experience. For example, an activity such as buying a daily newspaper might be represented as a succession of goal-relevant slices or moments of experience, such as looking for one's favourite newspaper in the bookstore, handing money to the employee, and receiving change back. According to this view, temporal compression rates in episodic memory should track the goal structure of experience, such that memories should be less compressed when they involve goal-directed actions. To our knowledge, however, no study to date has systematically examined the role of goal processing in the temporal compression of episodic memories.

Overall, then, direct evidence on how the continuous flow of information that constitutes real-life events is summarised in episodic memory is still sparse. To address this question, we conducted a study in which participants engaged in a series of daily life events (e.g., posting a letter, buying a newspaper) while the content and timing of these were recorded using a wearable camera. Participants were then asked to mentally replay these events in as much detail as possible, and to select the picture taken by the camera that best corresponded to each moment of past experience they recalled. This procedure allowed us to compute the time separating recalled moments of experience in terms of the actual duration of events, thereby providing an estimation of the temporal compression of experience in episodic memory. Using this paradigm, we investigated whether the rate of temporal compression in episodic memory is constant or whether it varies as a function of goal processing and changes in perceptual experience. To examine this question, we compared compression rates for different kinds of events, which varied according to whether or not they involved goal-directed actions and spatial displacements. Thus, our first aim was to document the temporal compression of real-life events in episodic memory and to identify factors that may determine compression rates.

Our second aim was to investigate delay-dependent changes in the content and temporal compression of episodic memories. Most episodic memories become inaccessible after a few days (unless they are integrated with long-term self-knowledge; Conway, 2001, 2009), and the content of remembered events tends to contain fewer episodic details with the passage of time (Winocur, Moscovitch, & Bontempi, 2010). Here, we examined whether and how temporal compression in episodic memory varies with retention interval (which was manipulated between subjects). More specifically, we compared compression rates when events were recalled immediately, after a few days (i.e., 24-h and 1-week delays), and after a longer delay (i.e., one month). Based on previous work on time-dependent changes in memory for real-life-like events (Furman et al., 2007; Sekeres et al., 2016), we expected that memories would remain relatively stable in the few days after encoding but would then contain fewer episodic details and would become more schematic, leading to increased rates of temporal compression when remembering.

Method

PARTICIPANTS

We initially planned to include 32 participants in each delay condition, resulting in a total of 128 participants. This sample size was determined a priori (using G*Power 3; Faul, Erdfelder, Lang, & Buchner, 2007) in order to have a statistical power of 80% (with an alpha of .05, two-tailed) to detect between-group differences with an effect size $d = 0.72$ (the average estimated effect size obtained from Furman et al. (2007), when comparing memory performance across delays ranging

from three hours to three months). A few participants were excluded and replaced by other participants for the following reasons: three participants because of a malfunction of the wearable camera (one in the immediate recall condition, one in the one-week delay condition, and one in the one-month delay condition), five participants who guessed that their memory of the walk would be tested (one participant in the 24-h delay condition and four participants in the one-month delay condition), and two participants who were considered as outliers (Osborne, 2012) because their performance was more than 3 SDs above the mean of their respective condition (one participant in the 24-h delay condition and one participant in the one-month delay condition; note that excluding these participants did not change the pattern of results). The final sample consisted of 128 students aged between 18 and 31 years (74 females; mean age = 23 years, $SD = 2.50$ years); the four groups did not differ in terms of participants' age and gender. All participants provided written informed consent and the study was approved by the local ethics committee.

MATERIALS AND PROCEDURE

The experiment consisted of two main phases: a walk on the university campus, which required participants to perform a series of activities at different locations, and a retrieval phase in which memory for the walk was assessed. To avoid the potential influence of seasonal changes between the different delay conditions, participants were recruited simultaneously in the four delay conditions throughout the four seasons.

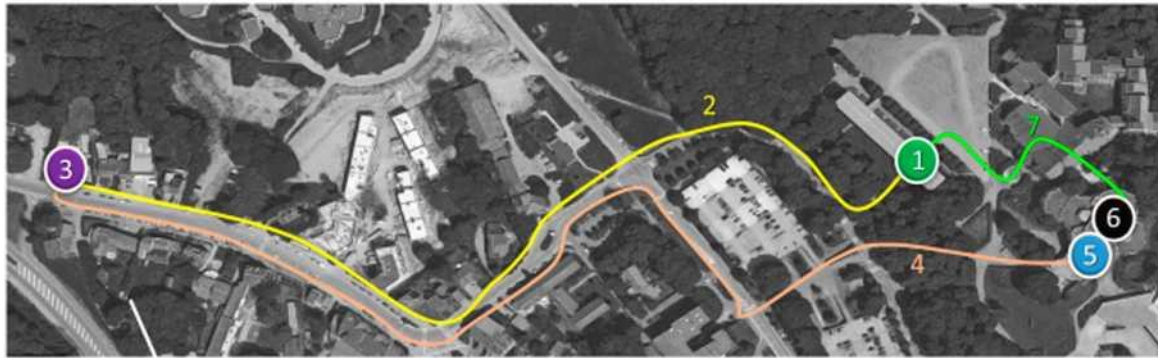
Walk on the campus phase

Participants were invited to perform a series of activities at different locations on the campus of the University of Liège. The proposed set of events was designed such that it involved a series of goal-directed actions (e.g., buying a newspaper) and a series of spatial displacements that did not involve particular actions other than walking (i.e., going from one place to another); these two types of events were presented in alternate order (see Figure 1). We also included one event that involved no particular action and no change in spatial location (i.e., sitting at a table in the cafeteria). More specifically, participants first had to leave the laboratory and to go to the ground floor of the building to post a letter in a particular mailbox. Then, they had to exit the building and to go to the campus newsstand to buy a daily newspaper. After having purchased the newspaper, participants had to go to a cafeteria to buy a drink of their choice and they were instructed to choose a table inside the cafeteria and to sit down to drink their beverage. Finally, they had to return to the laboratory to bring the camera back to the experimenter. Before starting the walk, participants received the letter that they should post, as well as 5 euros for purchasing the newspaper and the drink.

During the entire walk, participants wore an Autographer (OMG Life Ltd.) around their neck. The Autographer is a small wearable camera that automatically and silently takes pictures with a fisheye lens (angle of view of 136°). By taking a continuous set of pictures of ongoing experience from the first-person perspective, this device provides a particularly interesting tool for the investigation of memories for real-life events (for review, see Allé et al., 2017; Chow & Rissman, 2017; Silva et al., 2016). In the current study, we used the fastest capture rate (approximately 10 pictures per minute) to cover the entire walk as fully as possible. Participants were not informed that their memory for the walk would be subsequently tested.

Figure 1. Overview of the walk on the campus of the University of Liège. (A) Locations in which activities were performed (colour circles) and paths taken to go to these locations (colour lines). (B) Examples of pictures taken by the wearable camera during the different activities and paths of the walk.

A



B



They were told that the purpose of the study was to pre-test the quality of pictures taken by the Autographer in different environments (indoor and outdoor) and when performing various actions, for a subsequent study investigating activities of university students in daily life. Before starting the walk, participants were instructed to avoid obstructing the lens of the camera and to behave as naturally as possible while performing the activities.

Once they returned to the laboratory, participants were invited to assess their behaviour and mental states during the walk. Specifically, they rated to what extent they paid attention to the external environment (from 1 = not at all, to 7 = completely), experienced task-unrelated thoughts (from 1 = not at all, to 7 = completely), and behaved in a natural way (from 1 = not at all, to 7 = completely).

Retrieval phase

Immediately, 24 h, 1 week, or 1 month after the walk on campus phase (depending on the delay condition), participants received an unexpected free recall task. More specifically, 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, they were instructed to verbally describe everything that came to mind, as accurately as possible and as it came to mind, when mentally replaying the walk. Participants were further told that their task was not to produce a coherent account of the walk but to faithfully describe everything that comes to mind when attempting to mentally re-experience the entire event (e.g., it was not required to report events in chronological order). Verbal reports were recorded using a digital audio recorder. Immediately after having described everything they remembered about the walk, participants were instructed to assess their feeling of re-experiencing the entire event (from 1 = not at all, to 7 = completely) and of mentally travelling in the past (from 1 = not at all, to 7 = completely).

After the free recall task, participants reviewed all elements they described and, for each of them, they had to determine the corresponding moment of the walk, by selecting the appropriate picture that had been taken by the Autographer. To do so, the audio recording of the free recall was played back to the participant while they navigated the pictures taken during their walk on a computer screen. The verbal descriptions recorded during the free recall task consisted of a

succession of experience units, each corresponding to a particular moment of experience during the walk. For example, a typical recall protocol would start by “I got out of the office and turned right” (first experience unit), “then I saw a woman with a black dress” (second experience unit), “then, I went down the stairs” (third experience unit), and so on. While playing back the audio recording, these experience units were considered one at a time and, for each unit, participants had to select the picture that best corresponded to their mental representation of this moment of experience while they attempted to remember the walk (when a reported experience unit happened between two successive pictures, participants had to select the two pictures; this happened for only 6% of reported experience units). The audio recording was paused after the description of each experience unit, such that participants had time to select the corresponding picture. The segmentation of the verbal reports in distinct experience units was, in most cases, evident for both the experimenter and the participant, but when there was a doubt about whether a verbal description corresponded to a single or two distinct moments of experience, the final segmentation was decided by the participant.

Participants were also told that, while reviewing the photos, some additional elements about the walk that had not been reported during the free recall task could come to mind. Whenever this was the case, they were instructed to verbally describe this additional element in as much detail as possible. As in the free recall task, a digital audio recorder was used to record verbal descriptions of additional elements.

After having reviewed all pictures, participants were asked to rate their familiarity with the different locations and paths constituting the walk (from 1 = not at all familiar, to 7 = extremely familiar; each location and each path was rated separately). Furthermore, participants in the 24-h, 1 week, and 1-month delay conditions had to report, for each location or path, whether they had been back to this location or path since the walk on campus phase (by answering “yes” or “no”; if they responded “yes”, they were asked to specify the number of times they went back to this location or path) and to report to what extent they had thought about the walk since the walk on campus phase (from 1 = rarely, to 7 = very often). Finally, all participants were debriefed and asked whether they had expected that their memory for the walk would be tested.

Scoring of recall content

As mentioned above, the verbal descriptions recorded during the free recall task consisted of a succession of experience units, each unit corresponding to a particular moment of experience during the walk. Each of these experience units included one or several pieces of information (hereafter referred to as “unit components”), which described various aspects of experience that could involve the external environment, mental states, and actions. To assess the content of these components, we developed a coding scheme based on an initial examination of recall protocols that was informed by previous studies investigating components of memories (e.g., Dijkstra & Misirlisoy, 2006; Lancaster & Barsalou, 1997; Williams, Conway, & Baddeley, 2008; see also Levine et al., 2002, for a similar coding method). The following categories were used to classify components: person, object, thought, action with interaction, and spatial movement (see Table 1 for descriptions and examples of each category). These categories were mutually exclusive (e.g. each component was classified in only one category), but an experience unit could include multiple components.

Table 1. Descriptions and examples of scored experience unit components

Component categories	Description and examples
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Person	Description of one or more person(s), with no description of interacting with this/these person(s) (if an interaction was described, the component was classified as “action with interaction”) <i>Examples: I saw a woman; I saw a group of people.</i>
Object	Description of an object or aspect of the external environment with no description of interacting with this object (if an interaction was described, the component was classified as “action with interaction”) <i>Examples: I saw a car; the sun was shining.</i>
Thought	Description of a thought, mental state or judgment <i>Examples: I thought that I have to finish a school work tonight; I was lost in my thoughts; She seemed upset.</i>
Action with interaction	Description of an action performed by the participant involving a direct interaction with an object or a person <i>Examples: I took the money from my pocket; I asked her where I can find the newspaper.</i>
Spatial movement	Description of a movement of the body in the environment <i>Examples: I walked to the cafeteria; I turned left.</i>
Perceptual detail	Description of a sensory detail about an object or a person (i.e., a texture, shape or colour), or of an internal sensation <i>Examples: He wore black glasses; I had a stomach ache.</i>
Spatial detail	Description of a detail replacing the spatial context of an object or a person <i>Examples: The drinks were on my right; A man walked in front of me.</i>
Comment	Explanations or clarifications that do not in themselves describe moments of experience <i>Examples: I always take a coffee in the morning.</i>

For example, the experience unit “While walking, I saw a woman with an umbrella” includes a spatial movement component (*While walking*), a person component (*I saw a woman*) and object component (*umbrella*). Two additional categories (i.e., perceptual details and spatial details) were used to score details that were provided regarding the appearance or location of an object or a person (see [Table 1](#)). For example, “I saw a man with red shoes” was scored as including person (*I saw a man*), object (shoes), and perceptual (*red*) components. Finally, verbal reports that did not describe remembered moments of experience were scored as comments (see [Table 1](#)). Some false memories were also noted (e.g., a participant reported that she took a particular path, whereas the picture taken by the Autographer showed that she actually took another path) but

these were quite rare (most of the participants did not report any false memory and the average number of experience unit that contained false information was 0.76 per participant, range: 0-4) and were excluded from the analyses.

The content of all experience units reported by participants during the retrieval phase was scored by the first author and the reliability of the coding scheme was assessed by asking another trained rater to independently score a random selection of 20% of experience units. Intraclass Correlation Coefficients (ICCs) showed a strong agreement between the two raters regarding the number of components described per experience unit, for all categories of components (persons = .91, objects = .80, thoughts = .79, actions with interaction = .90, spatial movements = .92, perceptual details = .79, and spatial details = .70).

We also examined to what extent reported experience units included details that ensured that the participant was mentally re-experiencing a unique moment of experience rather than reconstructing part of the walk based on schematic knowledge. Indeed, some experience units could be produced based on general knowledge about locations and paths on campus (e.g., *I turned left to go to the newsstand*) or action schemas (e.g., the action of buying a newspaper could be based on script knowledge, such as *I looked for the newspaper on the shelves, I brought the newspaper to the cashier, and I paid*). Therefore, each experience unit was scored according to whether it included unique details that individualised the described moment of experience (e.g., *While walking, I saw a woman with red shoes*) or whether it could have been produced based on schemas and semantic knowledge. As for unit components, inter-rater reliability was computed based on a random selection of 20% of experience units; Cohen's kappa showed a strong inter-rater agreement ($k = .80$).

Results

The main aim of this study was to investigate how real-life events are summarised in episodic memory and to identify factors that may determine rates of temporal compression. To address this question, we first examined how different types of events (which varied according to whether or not they involved goal-directed actions and spatial displacements) were mentally replayed immediately after they had been experienced (i.e., in the immediate recall condition). Having determined the nature of temporal compression in this condition, we then investigated delay-dependent changes in the temporal compression of memories by comparing the four delay conditions included in this study.

HOW PAST EXPERIENCE IS SUMMARISED IN EPISODIC MEMORY

To characterise the nature and determinants of the temporal compression of information in episodic memory, we first analysed recall protocols from the immediate recall condition.

Temporal compression of experience

As a rough indication of the temporal compression of episodic memories, we compared the duration of the actual walk on campus with the duration of its recall. The average time of the walk performed by participants was 33.11 min (SD = 5.69), whereas the average time taken to recall the walk was 4.87 min (SD = 2.86); the ratio between the time taken to complete the walk and the time taken to recall it was on average 8.95 (SD = 5.36).

To investigate temporal compression in a more precise way, we looked at the correspondence between the temporal succession of recalled moments of experience and the temporal unfolding of the actual events. The recalled events were described as a succession of moments of

experience (here referred to as experience units; on average, participants reported 49 experience units, $SD = 18.89$) and we investigated the time at which these moments of experience occurred during the actual events. This was examined by using temporal information associated with the pictures that participants selected as corresponding to each experience unit they described at recall (i.e., for each experience unit, we looked at the actual time at which the corresponding picture was taken during the walk). Two indices of temporal compression were computed based on these data.² First, we looked at the number of experience units reported at recall per unit of time of the actual events. We found that, on average, participants recalled 1.55 experience unit per minute of the actual events ($SD = 0.64$). Although one should be cautious in comparing our results with those of Furman et al. (2007) because the stimuli and retrieval conditions were quite different, it is nevertheless intriguing to note that memory density was very similar in the two studies (1.6 events was retrieved per minute of movie in Furman et al.). Second, we looked at the time separating successive units of experience reported at recall. The large majority of recalled moments of experience (94%) followed the actual chronological order of the events (see Supplemental Material for more detail) and we computed the actual duration separating pictures corresponding to each of these recalled moments. The mean temporal distance between the photos characterising successive experience units was 53 seconds ($SD = 19$).

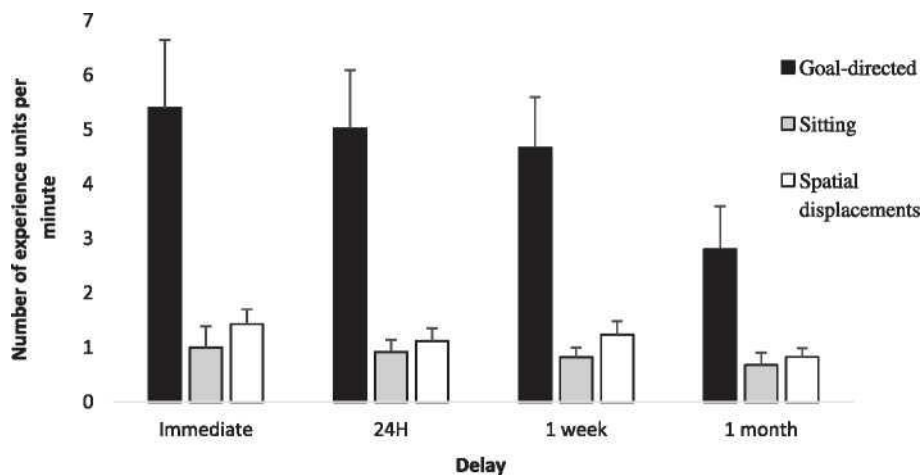
Next, we investigated whether the compression rate of experience in episodic memory is constant or whether it depends on the characteristics of remembered events. More specifically, we examined whether temporal compression varies as a function of goal-directed actions and changes in spatial location. To explore this question, we computed temporal compression rates separately for three kinds of segments of the walk, which varied according to whether or not they involved a particular action to accomplish and whether or not they involved a change of spatial location. The first type of segments (referred to as *Goal-directed actions*) involved performing particular goal-directed actions while spatial location remained relatively stable (i.e., buying the newspaper at the newsstand, buying the drink at the cafeteria; see colour circles 3 and 5 on Figure 1). The second type of segments (referred to as *Spatial displacements*) involved changes in spatial location with no particular action to perform other than walking (i.e., going from one building to another; see colour lines 2,4, and 7 on Figure 1). Finally, the third type of segments (referred to as *Sitting segment*) involved no particular action and no change in spatial location (i.e., sitting at the table in the cafeteria; see colour circle 6 on Figure 1). For each type of segments, we computed the number of experience units reported at recall per minute of the actual segment duration. A repeated measures ANOVA showed that the number of experience units recalled per minute of the actual event differed as a function of segment types (see Figure 2), $F(1.14, 35.39) = 47.98$, $p < .001$, $\eta^2 = .61$ (the Greenhouse-Geisser correction was applied because the sphericity assumption was violated). Planned comparisons showed that goal-directed segments were associated with more recalled experience units per minute than both sitting and spatial displacement segments ($ps < .001$). Moreover, spatial displacement segments were associated with more recalled experience units per minute than the sitting segment ($p = .024$). Taken together, these results suggest that the rate of temporal compression of experience in episodic memory depends on the nature of remembered events: the density of retrieved moments of past experience is strongly modulated by goal-directed actions, and is also influenced (though less strongly) by changes in spatial location.

Components of experience retained

We also sought to determine what components of experience are preferentially retained in episodic memory. Participants in the immediate recall condition reported, on average, 1.80

components ($SD = 0.28$) per experience unit. Table 2 presents the mean number of components per experience unit as a function of component categories. Because perceptual and spatial details were mainly specification of other components (e.g., specifying the colour of an object), we did not include them in the following analyses investigating the prevalence of categories of components. A one-way repeated measures ANOVA yielded a significant effect of component categories, $F(2.65, 82.26) = 55.31$, $p < .001$, $\eta_p^2 = .64$, indicating that the some categories of components were more frequently reported than others.

Figure 2. Differences in temporal compression between segment types in the four delay conditions. Error bars represent 95% confidence intervals.



Follow-up comparisons revealed that spatial movements were the most frequent components ($ps < .001$), followed by objects, which were more frequent than actions with interaction, thoughts, and people ($ps < .007$); actions with interaction were more frequent than thoughts ($p = .038$) and people ($p < .001$).

Finally, we examined whether the rate of temporal compression in episodic memory depends on the components retrieved within experience units. To examine this question, we conducted a series of regression analyses with our main measure of temporal compression (i.e., the number of experience units reported per minute of the actual segment duration) as outcome variable; multilevel modelling was performed (with segments as level 1 units and participants as level 2 units) to take the hierarchical structure of the data into account (Goldstein, 2011). First, we fitted a random intercept model with rates of temporal compression as dependent variable and the type of segments (goal-directed, spatial displacements, sitting) as predictor. In line with the above analyses, we found that the type of segments significantly influenced temporal compression rates, $\chi^2(2) = 95.47$, $p < .001$. Then, we added the total number of components reported per experience unit as a predictor in the model. This did not result in a significantly better fit, $\chi^2(1) = 0.82$, $p = .37$. Similarly, entering the number of components of each type (i.e., people, objects, thoughts, actions, and spatial movements) in the model did not provide a significantly better fit than the model with the type of segments alone as predictor, $\chi^2(5) = 2.96$, $p = .71$. These results thus suggest that the rate of temporal compression in episodic memory depends on the number of recalled experience units, but not on the amount or type of components that constitute these experience units.

Temporal compression and content of episodic memories as a function of retention interval

The above analyses on the immediate recall condition show that the rate of temporal compression in episodic memory is not constant but varies depending on the nature of remembered events. Our next goal was to investigate whether and how the temporal compression and content of episodic memories vary as a function of the retention interval. To examine this issue, we compared recall protocols between the four delay conditions (immediate recall, 24-h delay, 1-week delay, and 1-month delay).

Differences in temporal compression across delays

The time taken to mentally replay the walk during the free recall task significantly differed between delays, $F(3, 124) = 4.38$, $p = .006$, $\eta^2_p = .10$ (see [Table 3](#)). Follow-up comparisons showed that participants took less time to describe their memory of the walk after a 1-month delay compared to the other three conditions ($ps < .05$), with no significant differences between the immediate, 24-h, and 1-week delay conditions. Similar differences were observed for the ratio between the time taken to complete the walk and the time taken to recall it, $F(3, 124) = 3.23$, $p = .025$, $\eta^2_p = .07$ ([Table 3](#)).

Our two indices of temporal compression based on the correspondence between the temporal succession of recalled moments of experience and the temporal unfolding of the actual events also revealed that the rate of temporal compression in memory was higher after a 1-month delay. Specifically, the number of experience units recalled per minute of the actual events differed significantly across delays, $F(3, 124) = 5.58$, $p = .001$, $\eta^2_p = .12$, showing that fewer moments of experience were recalled per minute after one month compared to the other three conditions (with no significant difference between immediate recall, 24-h, and 1-week delays; [Table 3](#)).

Similarly, the time separating pictures corresponding to successive units of experience reported at recall varied according to delays, $F(3, 124) = 4.12$, $p = .008$, $\eta^2_p = .09$. The temporal distance between reported moments of experience was significantly shorter in the immediate, 24-h, and 1-week conditions compared to the 1-month condition ($ps < .05$), revealing that the temporal compression of experience in memory significantly increased after one month; there was no significant difference between immediate recall, 24-h, and 1-week delays ([Table 3](#)). Analysis of the chronological order of reported experience units showed no significant difference between delay conditions (see Supplemental Material).

Table 2. Components constituting experience units in the four delay conditions.

	Immediate		24-h		1 week		1 month	
	<i>M</i>	95% CI	<i>M</i>	95% CI	<i>M</i>	95% CI	<i>M</i>	95% CI
People	0.16	[0.13, 0.19]	0.17	[0.12, 0.22]	0.15	[0.12, 0.19]	0.10	[0.07, 0.12]
Object	0.32	[0.29, 0.36]	0.34	[0.30, 0.39]	0.36	[0.32, 0.39]	0.32	[0.28, 0.36]
Thoughts	0.18	[0.12, 0.24]	0.14	[0.11, 0.17]	0.13	[0.10, 0.16]	0.11	[0.07, 0.15]
Actions with interaction	0.26	[0.23, 0.29]	0.26	[0.24, 0.29]	0.26	[0.22, 0.29]	0.24	[0.21, 0.28]
Spatial movements	0.54	[0.51, 0.57]	0.51	[0.46, 0.55]	0.55	[0.52, 0.59]	0.59	[0.54, 0.64]

Perceptual details	0.07	[0.05, 0.10]	0.09	[0.04, 0.14]	0.07	[0.05, 0.09]	0.05	[0.03, 0.06]
Spatial details	0.13	[0.10, 0.15]	0.17	[0.14, 0.20]	0.19	[0.15, 0.22]	0.12	[0.09, 0.15]
Comments	0.12	[0.10, 0.15]	0.13	[0.10, 0.17]	0.12	[0.09, 0.14]	0.08	[0.05, 0.11]

Table 3. Measures of the temporal compression of experience in episodic memory in the four delay conditions.

	Immediate		24-h		1 week		1 month	
	M	95% CI	M	95% CI	M	95% CI	M	95% CI
Recall time (min)	4.87	[3.84, 5.90]	4.33	[3.43, 5.23]	4.03	[3.47, 4.60]	2.95	[2.42, 3.48]
Ratio duration/recall time	8.95	[7.02, 10.88]	9.44	[7.87, 11.01]	9.66	[7.79, 11.52]	12.54	[10.58, 14.50]
Number of experience units/min	1.55	[1.32, 1.78]	1.39	[1.14, 1.63]	1.39	[1.17, 1.60]	0.97	[0.84, 1.11]
Temporal distance between experience units (s)	53	[46, 60]	57	[48, 66]	62	[50, 73]	77	[64, 91]

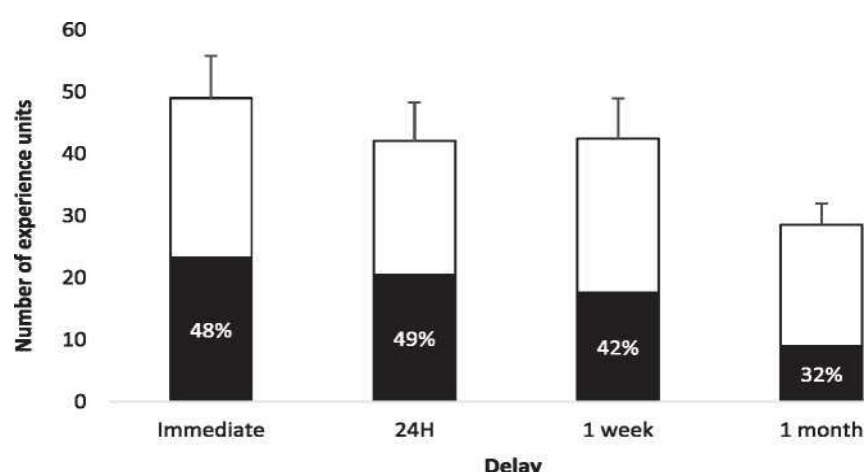
Our previous analysis of immediate recall showed that the temporal compression of experience in episodic memory varied according to the kind of segments under consideration (i.e., goal-directed actions, spatial displacements, and sitting). To investigate whether this effect varies across retention delays, we conducted a 4 (delays) x 3 (type of segments) mixed ANOVA on the number of experience units reported per minute of actual experience (see Figure 2). There was a main effect of delays, $F(3,124) = 5.94$, $p < .001$, $\eta^2_p = .13$, a main effect of type of segments, $F(1.12, 138.77) = 213.06$, $p < .001$, $\eta^2_p = .63$, as well as a significant interaction, $F(3.56, 138.77) = 4.16$, $p = .006$, $\eta^2_p = .09$. This interaction showed that the number of experience units reported per minute of goal-directed segments decreased after one month compared to the other delays (immediate, 24-h, and 1-week; all $ps < .005$), whereas no difference between delays was found for the sitting segment; for spatial displacement segments, we found that the number of experience units per minute was higher in the immediate and 1-week conditions compared to the 1-month condition ($p < .001$ and $p = .012$, respectively). Together, these findings suggest that the impact of goal-directed actions and spatial displacements on the amount of information that is retained in episodic memory decreases over time.

Differences in components of experience retained across delays

The mean number of experience units reported in the four delay conditions is presented in Figure 3. An ANOVA showed that the number of experience units significantly differed across delays, $F(3, 124) = 8.80$, $p < .001$, $\eta^2_p = .18$, indicating that participants reported significantly fewer experience units after 1 month compared to the immediate, 24-h, and 1-week conditions ($ps < .01$); there was no difference between the immediate, 24-h, and 1-week conditions. We also examined to what extent reported experience units included details that ensured that the participant was mentally re-experiencing a unique moment of experience rather than reconstructing part of the walk based on schematic knowledge (see Methods section). An ANOVA showed that the proportion of experience units that included details individualising the described moments of experience varied across delays $F(3,124) = 9.42$, $p < .001$, $\eta^2_p = .19$, indicating that the proportion of unique experience units was lower after one month compared to the other three delay conditions ($ps < .01$).

The mean frequency of the different categories of components constituting experience units are presented in Table 2, as a function of delay condition. A 4 (delay) x 5 (types of components) mixed ANOVA showed a main effect of the type of components, $F(3.58, 444.37) = 289.40$, $p < .001$, $\eta^2_p = .70$, but no main effect of delay, $F(3, 124) = 2.46$, $p = .066$, $\eta^2_p = .06$, showing that the total number of components per experience unit was not impacted by the retention interval. Interestingly, however, there was a significant interaction between the type of components and delay, $F(10.75, 444.37) = 2.07$, $p = .022$, $\eta^2_p = .05$. Follow-up comparisons revealed that participants reported more people components per experience unit in the immediate ($p = .012$), 24-h ($p = .004$), and one-week ($p = .027$) conditions than in the one-month condition. We also found that thoughts were more often reported immediately than after one month ($p = .015$). On the other hand, the number of spatial movements per experience unit was higher after one month than in the 24-h condition ($p = .003$).

Figure 3. Mean number of experience units in the four delay conditions and mean percentage of experience units that included unique contents. Error bars represent 95% confidence intervals. The mean number of experience units that included unique contents is indicated by black filling.



These differences in memory components between delay conditions were not significantly related to the temporal compression of memories (see Supplemental Material).

Because there were significant differences between delay conditions in terms of ratings of attention during the walk and ratings of familiarity with the walk, all statistical analyses were redone while controlling for these two factors. The pattern of results reported above remained unchanged. Additional analyses also showed that the subjective experience of remembering decreased with the retention interval. Finally, we found that the retention interval influenced the number and components of additional experience units that participants recalled when reviewing the pictures of their walk. In short, similar to what we observed for free recall, the number and uniqueness of experience units decreased over time and especially after a one-month delay (see Supplemental Material for detailed analyses).

Discussion

Although important progress has recently been made in understanding the cognitive and neural mechanisms underlying memory for laboratory stimuli, how the continuous flow of events that constitute the fabric of daily life is summarised in episodic memory remains poorly understood. Here, we showed that the prior experience of real-life events is mentally replayed in a temporally compressed way and that temporal compression rates vary adaptively with the type of

remembered events, such that the amount of information that is retained is higher for goal-directed actions. Furthermore, we found that the density of retrieved information remains relatively stable over one week and then decreases at a one-month delay, particularly for goal-directed actions. These results provide novel insights into the temporal compression of real-life events in episodic memory and shed light on factors that determine compression rates.

Episodic memory would not be functional if remembering an event took as much time as the original experience. The present study indeed shows that people mentally replay their prior experience of real-life events in a temporally compressed way. The exact nature of this compression process, however, remains to be clarified. At least two possibilities could be considered. First, it could be that only some moments or slices of prior experience are maintained in episodic memory. On this view, there would be discontinuities in the representation of prior experience, such that events would be represented in episodic memory as a succession of moments³ separated by temporal gaps (i.e., parts of prior experience that are not represented). Another possibility would be that there is a continuous sampling of events and that temporal compression occurs because stored information is subsequently replayed at faster rates (perhaps in varying degrees for different segments of prior experience). Although these two possibilities remain to be investigated in detail, the current findings are more consistent with the view that temporal compression in episodic memory occurs, at least in part, because of discontinuities in the representation of past events. Indeed, our verbal protocols showed that the mental replay of events consisted of a succession of moments of prior experience that frequently involved temporal gaps. For example, a participant remembered seeing roadworks and then remembered walking into the campus newsstand; these two moments of prior experience were separated by several dozen seconds in the actual event and no element referring to what happened between them (e.g., walking along the street) was described in the recall protocol. Our data indicated that such discontinuities in the representation of past events were quite frequent, with the time separating successive moments of prior experience being on average 53 seconds (in the immediate recall condition).

Another important finding of this study is that the rate of temporal compression in episodic memory depends on the nature of remembered events. More specifically, we found that the density of recalled moments of experience was about three times higher when events involved goal-directed actions. This suggests that compression rates in episodic memory are adaptively modulated to maintain goal-relevant information, which may function to keep us informed with specific progress on current goals (Conway, 2008, 2009). The exact mechanisms at play here require further investigation. One possibility is that the higher density of retrieved information for goal-related actions is due to the structuring effect of event segmentation in episodic memory (Kurby & Zacks, 2008; Pettijohn et al., 2016). Events that involve goal-directed actions (e.g., buying the newspaper) may be perceived in terms of finer sub-events (e.g., looking for one's favourite newspaper, handing money to the employee, and receiving change back; Hard, Recchia, & Tversky, 2011) which form the units for memory encoding and thus enhance subsequent recall (Hanson & Hirst, 1989). Another (not mutually exclusive) possibility is that schemas and scripts of goal-directed actions facilitate the encoding and subsequent reconstruction of events (Gilboa & Marlatte, 2017; Rubin & Umanath, 2015; Van Kesteren, Ruiter, & Henson, 2012).

A related question is whether temporal compression in episodic memory is a property of stored information or whether it occurs when editing stored contents at retrieval. In the present study, we did not have direct access to episodic memory traces per se, but only to their expression when remembering events (which can vary according to retrieval conditions; Koriati, 2000; Tulving & Pearlstone, 1966), and therefore, we cannot definitely conclude that our results reflect the

temporal compression of stored information. However, previous laboratory studies suggest that event segmentation during encoding organises experience into discrete segments in episodic memory (Ezzyat & Davachi, 2011, 2014; Kurby & Zacks, 2008). The moments of experience observed in our recall protocols may result from such event segmentation processes, and we are thus inclined to believe that they are indicative (at least in part) of the temporal compression of stored information. Of course, this does not exclude that retrieval conditions may also influence temporal compression in episodic memory. For example, levels of summarisation in the mental replay of past episodes might depend on retrieval goals at a given moment.

Our data also supports the view that the temporal compression of information in episodic memory is modulated by changes in perceptual experience. Indeed, segments of the walk that involved important changes in perceptual information (i.e., spatial displacements) were associated with a higher density of retrieved moments of experience than segments in which perceptual changes were more limited (i.e., sitting at a table). This finding is in line with a recent study showing that the mental replay of sequences of moving or changing shapes is less compressed when changes in the perceptual properties of events increase (Faber & Gennari, 2015a). Real-life events involve a rich and dynamic flow of perceptual information about entities (e.g., objects, people) and spatial locations. Changes in any of these dimensions of perceptual experience may influence people's attention and thus contribute to memory encoding. Furthermore, the amount of changes in perceptual experience may also determine the grain size of event segmentation, thereby influencing the density of information that is retained in episodic memory (Kurby & Zacks, 2008).

Moments of experience that constituted episodic memories were themselves composed of multiple components representing diverse aspects of prior experience, such as places, people, objects, actions, and thoughts (see also Dijkstra & Misirlisoy, 2006; Lancaster & Barsalou, 1997). A particular moment or unit of experience in episodic memory may be conceived as the bound representation of these elements at a given time (Baddeley, 2000). In terms of the frequency of diverse components, we found that spatial information (i.e., spatial movements and details about spatial location) was the most commonly reported component. This supports the view that spatial information (such as spatial landmarks, turns, and boundaries) plays an important role in structuring episodic memories (Bonasia et al., 2016; Horner et al., 2016; Meilinger, Strickrodt, & Bülthoff, 2016). However, the frequency of different types of components in episodic memory may depend to a large extent on the nature of remembered events; in this study, a substantial part of the walk involved spatial displacements (61% of the time spent to complete the walk involved going from one location to another), which undoubtedly contributed to the high frequency of spatial movements in the recall protocols. It is also interesting to note that our results suggest that the temporal compression of episodic memories depends on the number of recalled moments of experience, but not on the amount or type of components that constitute these slices of the past.

Our results also showed that the density of retrieved moments of past experience remained relatively stable over one week and then decreased at a one-month delay. Furthermore, recalled moments of experience were less specific and unique after a one-month delay, which could reflect a higher reliance on schemas and general knowledge for reconstructing events. These findings are in line with previous research on time-dependent changes in memory for real-life-like events, which has shown that recall performance declines mostly after retention intervals longer than a week (Furman et al., 2007). Interestingly, we also found that the reduction in the density of retrieved moments of experience after one month was more pronounced for goal-directed actions. Again, this finding is consistent with the view that episodic memory is particularly tuned to goal-relevant information. In the short term (in the few minutes, hours, and days after encoding), episodic memories may be highly accessible in order to keep track of current goal processing, but

then most memories may become increasingly difficult to retrieve unless they are connected to longer term goals (Conway, 2001, 2009). The goal-directed events investigated here were likely not related to personal long-term goals, which might explain why associated memories declined after a few days.

The current procedure capitalising on the comparison of the mental replay of prior experience with objective records of the timing of events offers new avenues for studying the influence of various factors on the summarisation of real-life events in episodic memory. For example, the current paradigm could be adapted to investigate to what extent various event properties (e.g., emotion, uniqueness, novelty) affect the temporal compression of memories. Another question that would merit further investigation is whether and how temporal compression in episodic memory relates to the perception of the duration of past events (Block & Reed, 1978; Faber & Gennari, 2015a, 2015b) and plays a role in the way stored information is used to mentally simulate possible future events (Arnold, Iaria, & Ekstrom, 2016). Finally, identifying variations in temporal compression rates and how they are influenced by goals may also be promising for further characterising episodic memory deficits in ageing and various patient populations (see Mair, Poirier, & Conway, 2017, for a recent study showing the relevance of wearable camera technology for studying age-related differences in episodic memory for real-life events).

A limitation of the current paradigm that should be acknowledged, however, is that the temporal compression of information in episodic memory was estimated based on verbal reports of recalled events. Although we took care to ask participants to describe their mental replay in as much detail as possible in order to obtain verbal reports that most closely correspond to what is remembered, it remains possible that some of the recalled information was not described. Indeed, the level of detail of verbal reports may be influenced by conversational norms (e.g., one would not typically describe an action such as “taking the newspaper” in as much detail as “I moved my right arm, opened my hand, and grabbed the newspaper”), and thus the grain size of described moments of experience may be affected by concurrent verbalisation. To address this limitation, it would be interesting in future studies to assess temporal compression in memory for real-life events using measures of mental replay that do not rely on verbal reports (see e.g., Faber & Gennari, 2015a).

In conclusion, the present study provides evidence that episodic memory represents past events in a temporally compressed way, with the density of moments or slices of prior experience varying adaptively as a function of goal processing and changes in perceptual experience. By allowing a direct comparison of memories with objective records of the timing and content of real-life events, our experimental paradigm opens new avenues for studying the contribution of various situational and individual variables to temporal compression rates in episodic memory.

Notes

1. *It should be noted, however, that event boundaries can either improve or impede memory depending on the nature of information and how it is remembered (for review, see Radvansky, 2012).*
2. *As expected, these two indices of temporal correlation were correlated to each other ($r = -.79, p < .001$). Nevertheless, we report both indices because they provide slightly different perspectives on the temporal compression of memories.*
3. *Note that these moments of prior experience might not necessarily be stored as “snapshots” (although they could be) but might be dynamic, representing short-time slices or segments of prior experience (Conway, 2008, 2009).*

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