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The time to remember: Temporal compression and duration judgements in memory for real-life events

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Abstract

Recent studies suggest that the continuous flow of information that constitutes daily life events is temporally compressed in episodic memory, yet the characteristics and determinants of this compression mechanism remain unclear. This study examined this question using an experimental paradigm incorporating wearable camera technology. Participants experienced a series of real-life events and were later asked to mentally replay various event sequences that were cued by pictures taken during the original events. Estimates of temporal compression (the ratio of the time needed to mentally re-experience an event to the actual event duration) showed that events were replayed, on average, about eight times faster than the original experiences. This compression mechanism seemed to operate by representing events as a succession of moments or slices of prior experience separated by temporal discontinuities. Importantly, however, rates of temporal compression were not constant and were lower for events involving goal-directed actions. The results also showed that the perceived duration of events increased with the density of recalled moments of prior experience. Taken together, these data extend our understanding of the mechanisms underlying the temporal compression and perceived duration of real-life events in episodic memory.

Keywords
Episodic memory; temporal compression; time estimation; wearable camera; goals

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Introduction

Our daily life is made of a continuous flow of events and experiences. Episodic memory retains traces of these events, allowing us to mentally re-experience the past (Tulving, 2002). Memories are not literal records of past episodes, however, but instead summary representations of our prior experience. Notably, events may be summarised in the form of short-time slices of experience (Conway, 2009). On this view, an episodic memory may consist of a succession of moments of prior experience (Anderson & Conway, 1993) that represents the remembered event in a temporally compressed way. This process may account for the fact that remembering an event typically takes less time than the actual duration of the past episode. To date, however, the characteristics and determinants of this temporal compression mechanism remain unclear.

Initial evidence on the temporal compression of information in episodic memory has come from studies on spatial navigation. Animal research has shown that place cells in the rodent hippocampus re-express firing sequences corresponding to recent spatial experience 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). Recent studies indicate that a similar compression mechanism occurs during spatial memory replay in humans. Bonasia, Blommesteyn, and Moscovitch (2016) found that the time taken to mentally navigate familiar routes is shorter than the time it would take to walk these routes (with the rate of temporal

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compression varying with route length and number of turns). In the same vein, Arnold, Iaria, and Ekstrom (2016) demonstrated that the mental simulation of routes within a recently learned virtual environment occurs at a faster speed than the actual navigation of these routes. While these studies provide evidence that past experiences are recapitulated in a compressed form, they are limited to spatial representations and have not directly investigated factors that could explain how different types of events are compressed in episodic memory.

To address this question, we recently 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 (Jeunehomme, Folville, Stawarczyk, Van der Linden, & D'Argembeau, in press). Participants were then asked to mentally replay these events in as much detail as possible while describing everything that came to their minds during the recall process. Recall protocols showed that past events were remembered as a succession of moments of prior experience that represented the unfolding of events in chronological order. Participants were then asked to select the picture taken by the camera that best corresponded to each moment of past experience they recalled. This allowed us to compute an estimation of the temporal compression of events in memory by measuring the density of recalled moments of experience per unit of time of the actual events. The results showed that past events were remembered in a temporally compressed way and that rates of temporal compression were not constant but varied depending on the nature of remembered events. More specifically, the density of recalled moments of experience was about three times higher when remembering goal-directed actions compared to spatial displacements, and was also slightly higher when remembering spatial displacements compared to events involving few actions or spatial displacements.

These findings suggest that the rate of temporal compression in episodic memory is adaptively modulated to maintain goal-relevant information. According to Conway (2001, 2009), one of the main functions of episodic memory is to keep records of recent actions and action outcomes, thus providing a means to check on progress with current goals and plans. Therefore, events may be retained as a function of the goal structure of an experience: information about goal-directed actions may be sampled at a higher rate, thus leading to a lower temporal compression. An important limitation of our previous study, however, is that temporal compression rates were estimated indirectly on the basis of verbal descriptions of remembered events. More specifically, the temporal compression of events in memory was estimated by computing the density of recalled moments of experience and the time separating these moments in terms of the actual event duration. These indices reflected the presence of temporal "gaps" or discontinuities between recalled moments of prior experience but did not take into account the duration of the recalled moments themselves. Our previous measure of temporal compression was thus imperfect because recalled moments may consist of dynamic short-time slices of past experience (Conway, 2008, 2009), which duration might vary depending on the nature of remembered events. Furthermore, another limitation of our previous study is that verbal reports may not have captured all recalled information, which might to some extent have biased estimates of temporal compression.

Considering these limitations, the first aim of this study was to replicate our previous finding that temporal compression rates in episodic memory are influenced by the nature of remembered events (in particular by goal-directed actions), using a more direct and reliable measure of temporal compression. To achieve this aim, we used a mental replay task inspired by previous studies on the temporal compression of spatial routes (Arnold et al., 2016; Bonasia et al., 2016). More specifically, we measured the time needed for participants to mentally replay a series of past events (without providing concurrent verbal reports) and estimated temporal compression rate for each event as the ratio of replay duration to the actual event duration. In line with our previous study, we predicted that the rate of temporal compression would be lower for events involving goal-directed actions than for events that do not require particular actions (other than spatial displacements). Furthermore, we also expected that the temporal compression of information might be lower for spatial displacements than for moments happening at a fixed location, as the former would presumably involve greater perceptual change (see Faber & Gennari, 2015).

As mentioned above, the mechanisms of compression of events in episodic memory remain unclear. One possibility is that events are compressed in memory because of temporal discontinuities in remembered events (i.e., people might "jump" from one recalled moment to the next without remembering what happened between successive moments), in which case temporal compression should be mainly predicted by the density of recalled moments of experience per unit of time of the actual event. Another, not necessarily mutually exclusive, possibility would be that the compression of information also occurs at the level of recalled moments; depending on their level of detail, these moments might be replayed more or less quickly than the original experiences. To test these possibilities, immediately after each trial we asked participants to verbally describe everything they remembered during their mental replay, such that we could investigate to what extent the rate of temporal compression in episodic memory depends on the density of recalled moments of experience and amount of recalled details within each moment.

The second aim of this study was to investigate to what extent retrospective duration judgements of daily life events depend on recalled moments of past experience. Numerous theoretical models have been developed to account for the encoding and remembering of past event duration (for review, see Block & Zakay, 1997, 2008). Memory-based models propose that retrospective duration judgements are based on the properties of remembered events (Block & Reed, 1978; Ornstein, 1969; Poynter, 1983). Among these models, an interesting theoretical approach for understanding how the duration of daily life events is retrospectively estimated comes from the contextual-change hypothesis (Block, 1982; Block & Reed, 1978). According to this view, retrospective duration judgements depend mainly on the retrieval of contextual information experienced during an interval. More precisely, the perceived duration of an event lengthens as a function of the amount of contextual changes (i.e., changes in environmental elements and/or internal states) that are stored in memory and available at the time of the duration judgement.

In line with this hypothesis, there is evidence that perceptual or contextual changes during encoding influence retrospective judgements about temporal duration (Faber & Gennari, 2015), order (DuBrown & Davachi, 2013; Horner, Bisby, Wang, Bogus, & Burgess, 2016), and proximity (Ezzyat & Davachi, 2014). However, most studies on retrospective duration judgements focused on very short durations (i.e., typically no more than a few seconds) using laboratory stimuli such as sounds, words, or symbols (Block & Reed, 1978; Brown, 1985; Ornstein, 1969; Poynter, 1983; for review, see Block, Hancock, & Zakay, 2010). To date, very few studies have examined retrospective duration judgements for naturalistic events (e.g., Brunec, Ozubko, Barense, & Moscovitch, 2017; Yarmey, 2000) and no study has directly investigated the link between retrospective duration estimates and the amount of recalled information about daily life activities. In this study, we sought to determine whether duration judgements are predicted by the density of recalled moments of prior experience and the level of detail of each moment. Based on the contextual-change hypothesis (Block, 1982; Block & Reed, 1978), we predicted that estimates of temporal duration would increase with the density of recalled moment of prior experience.

In summary, the first aim of this study was to investigate the nature and determinants of the temporal compression of real-life events in episodic memory using a measure of compression rates that does not rely on verbal descriptions of remembered events. Furthermore, we also sought to examine to what extent retrospective duration judgements of real-life events depend on the properties of remembered events, such as the density and level of detail of recalled moments of prior experience.

Method

Participants

We initially planned to recruit 34 undergraduate students aged between 18 and 30 years to take part in this study. This sample size was defined a priori using G*Power 3 (Faul, Erdfelder, Lang, & Buchner, 2007) to achieve a statistical power of 80%, considering an alpha of .05 and a medium within-subject effect size ($d = 0.5$). Four participants were excluded and replaced by other participants for the following reasons: one participant because of a malfunction of the wearable camera and three participants because they guessed that their memory would be tested. The final sample consisted of 34 participants (19 females; mean age = 23 years, $SD = 2.53$ years). 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. The first phase was an adapted version of the walk on the university campus used in Jeunehomme et al. (in press), which required participants to perform a series of daily life activities at different locations while their experience was recorded using a wearable camera. The second phase consisted of a memory task in which participants were required to mentally re-experience different parts of the walk and to provide estimates of the events' duration.

Walk on campus phase. Participants were invited to perform a series of activities at different locations on the campus of the University of Liège (see Figure 1). The entire set of events involved a series of goal-directed actions (e.g., posting a letter) and a series of spatial displacements that did not involve particular actions other than walking from a place to another (e.g., going from the cafeteria to the laboratory); these two types of events were presented in alternate order (see Figure 1). One event that involved no or few actions and no change in spatial location was also included (i.e., sitting at a table in the cafeteria). The succession of events was as follows: participants were first instructed to leave the laboratory and to go to the campus newsstand to buy a daily newspaper. After having purchased the newspaper, they had to go to the Speech and Language Therapy Service to post a letter in a particular mailbox. Then, they had to go to a cafeteria to buy a drink of their choice, after which they chose a table inside the cafeteria to sit down and drink their beverage. Finally, they had to return to the laboratory to bring the camera back to the experimenter. Before starting the walk, participants were given the letter that they should post as well as €5 for purchasing the newspaper and the drink.

During the entire walk, participants wore an Autographer (OMG Life Ltd.) tied around their neck. The Autographer

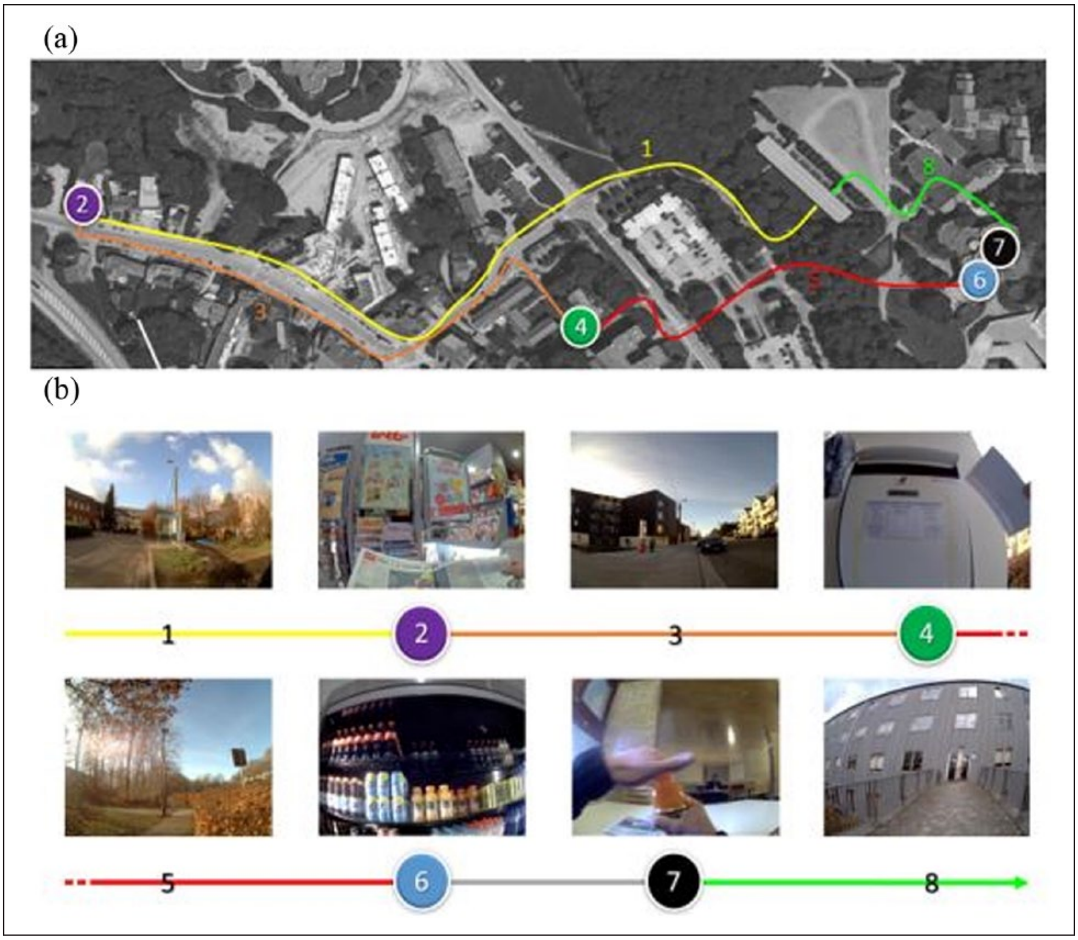

Figure 1. Overview of the walk on the campus of the University of Liège. (a) Locations in which activities were performed (colour circles) and paths taken to go to these locations (colour lines). (b) Examples of pictures taken by the wearable camera during the different activities and paths of the walk.

is a small wearable camera that automatically and silently takes a continuous set of pictures from the first-person perspective, with a fisheye lens (angle of view of 136°). This device has been used in previous studies investigating memories for real-life events (for review of the usefulness of wearable cameras for the investigation of memories for real-life events, see Allé et al., 2017; Chow & Rissman, 2017; Silva, Pinho, Macedo, & Moulin, 2018).

To cover the entire walk as fully as possible, the camera was set to use the fastest capture rate (approximately ten pictures per min). Participants were not informed that their memory for the walk would be subsequently tested; they were told that the purpose of the study was to evaluate 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. Immediately after having completed the walk, participants were instructed to rate 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*).

Memory task. Immediately after the walk on campus phase, participants received an unexpected memory task in which they had to mentally re-experience different parts of the walk and to provide estimates of their duration. Each experimental trial began with the presentation of a fixation cross on the computer screen for a duration of 1 s. Then, a pair of pictures that had been taken by the Autographer during the walk was presented on the screen (see Figure 2). The pictures presented on the left and right of the screen corresponded, respectively, to the beginning and end of an event experienced during the walk (a white arrow presented between the two pictures indicated their chronological order). For each pair of pictures, participants were first instructed to identify the corresponding part of the walk and then to close their eyes and to press the spacebar

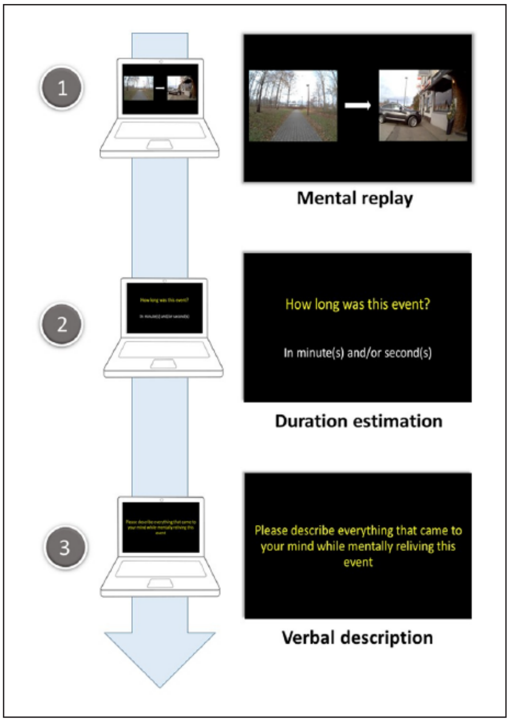

Figure 2. Illustration of the memory task. For each trial, participants first mentally replayed the event and rated their feeling of re-experience (1). Then, they provided an estimation of the actual duration of the event and rated their confidence in their judgement (2). Finally, they verbally described everything they remembered while mentally replaying the event (3).

as soon as they began to mentally re-experience the event. More specifically, they were instructed to try to mentally re-experience everything that happened from the moment corresponding to the picture presented on the left of the screen until the moment corresponding to the picture presented on the right. Participants were told that their task was to try to mentally relive all elements they had experienced during this event (e.g., objects and people in the environment, actions, and thoughts), in as much detail as possible. As soon as they had mentally relived the entire event (i.e., until the moment corresponding to the picture presented on the right), participants were instructed to press the spacebar again and to open their eyes. Then, they rated their feeling of re-experiencing the event (from 1 = *not at all*, to 7 = *completely*), estimated the actual duration of the event, in min and/or s, and rated their confidence in their duration estimation (from 1 = *not at all confident*, to 7 = *completely confident*).

Finally, participants were invited to verbally describe, as accurately and precisely as possible, everything that came to their mind when mentally replaying the event. They were told to only report elements they had previously re-experienced and not additional elements they might remember during the verbal description of their mental experience. Nevertheless, if they reported an additional element, they were instructed to specify to the experimenter that the described element was new and not previously re-experienced; these additional elements were not taken into account in the subsequent analyses. Verbal reports were recorded using a digital audio recorder.

In total, participants performed eight trials, which corresponded to the eight parts of the walk (see Figure 1) and were presented in random order. The task was programmed and presented using Open Sesame 3.1.2 software (Mathôt, Schreij, & Theeuwes, 2012). Before starting the experimental trials, participants first had to complete one practice trial, with a different pair of pictures (corresponding to the inside of the laboratory building), to familiarise them with the entire procedure. This practice trial was followed by a discussion with the experimenter to ensure that participants had understood all instructions before starting the experimental trials. After all trials had been completed, participants were debriefed and asked whether they had expected that their memory for the walk would be tested.

Scoring of recall content. As in our previous study (Jeunehomme et al., in press), verbal reports describing the mental re-experience of events consisted of a succession of moments of past experience (here referred to as "experience units") that represented the unfolding of the events in chronological order. For example, a typical verbal description started by "I left the building and turned right" (first experience unit), "then I saw a men with a yellow jacket" (second experience unit), "then, I walked along the parking" (third experience unit), and so on. The segmentation of verbal reports in distinct experience units was performed by the first author based on indications of transitions or temporal discontinuities between reported moments of experience. For example, transitions from one remembered moment of past experience to another could be indicated by verbal indicators (such as "then," "next," and "after that") or by a moment of silence. Transitions between experience units also often involved significant changes in actions, environmental elements, and/or thoughts (e.g., "I saw a poster on the door [of the campus newsstand]," followed by "Once out of the campus newsstand, I was surprised to see a group of older people"). In most cases, this segmentation procedure was evident. Nevertheless, to assess its reliability, another trained rater independently segmented a random selection of 20% of verbal reports. The Intraclass Correlation Coefficient (ICC) computed on the number of experience units identified within verbal reports showed an almost perfect agreement between the two raters (ICC = 0.98).

Each experience unit was itself composed of one or several pieces of information (here referred to as "unit components") describing various aspects of this moment of past experience, such as people, objects, mental states, and actions. To assess the content of these experience units, we used the coding scheme developed by Jeunehomme et al. (in press). Unit components were classified according to five mutually exclusive categories (i.e., person, object,

Table 1. Descriptions and examples of scored unit components.

Component categories	Description and examples
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"). *Examples: I saw a woman; I saw a group of people.*
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"). *Examples: I saw a car; the sun was shining.*
Thought	Description of a thought, mental state or judgement *Examples: I thought that I have to finish a school work tonight; I was lost in my thoughts; She seemed upset.*
Action with interaction	Description of an action performed by the participant involving a direct interaction with an object or a person. *Examples: I took the money from my pocket; I asked her where I can find the newspaper.*
Spatial movement	Description of a movement of the body in the environment. *Examples: I walked to the cafeteria; I turned left.*
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. *Examples: He wore black glasses; I had a stomach ache.*
Spatial detail	Description of a detail replacing the spatial context of an object or a person. *Examples: The drinks were on my right; A man walked in front of me.*
Comment	Explanations or clarifications that do not in themselves describe the past experience. *Examples: I always take a coffee in the morning.*

Table 2. Characteristics of the walk on campus.

	Trimmed mean	95% CI
Attention to the external environment	4.59	[4.09, 5.09]
Task-unrelated thoughts	3.72	[3.09, 4.32]
Attitude and behaviours	5.86	[5.23, 6.45]

CI: Confidence interval

thought, action with interaction, and spatial movement), with two additional categories providing specific information or details about the appearance or location of a person or object (i.e., perceptual details and spatial details; see Table 1 for descriptions and examples of each category). Information that did not describe moments of past experience was classified as comments. The content of all experience units was scored by the first author and the second trained rater scored a random selection of 20% of experience units to assess the reliability of the coding scheme. There was a strong agreement between the two raters for all categories of unit components (for persons, ICC = 0.84; for objects, ICC = 0.75; for thoughts, ICC = 0.73; for actions with interaction, ICC = 0.84; for spatial movements, ICC = 0.83; for perceptual details, ICC = 0.77; and for spatial details, ICC = 0.75).

Statistical analyses

Because the distribution of our measure of temporal compression was substantially skewed, we used robust statistical methods to analyse 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; Erceg-Hurn & Mirosevich, 2008; Wilcox, 2012). More specifically, we conducted a series of robust repeated-measures analysis of variances (ANOVAs) using the 20% trimmed means and 2,000 bootstrap samples, as recommended by Field and Wilcox (2017). We also conducted robust regression analyses to investigate predictors of temporal compression rates. For these latter analyses, we fitted robust multilevel models (random intercept models with trials as level 1 units and participants as level 2 units) to take the hierarchical structure of the data into account (Goldstein, 2011). An alpha level of .05 was used for all analyses. All descriptive statistics refer to the 20% trimmed means and their 95% confidence intervals (CIs) calculated using the percentile bootstrap method (with 2,000 bootstrap samples; Wilcox, 2012).

Results

The average time to complete the entire walk was 26.04 min, 95% CI [24.98, 27.40]. Participants reported having (moderately) paid attention to the external environment, experienced some task-unrelated thoughts, and behaved in a natural way (see Table 2), suggesting that their experience was similar as in naturally occurring daily life events.

Temporal compression of past experience during mental replay

The first aim of this study was to estimate the temporal compression of past experience in episodic memory using a

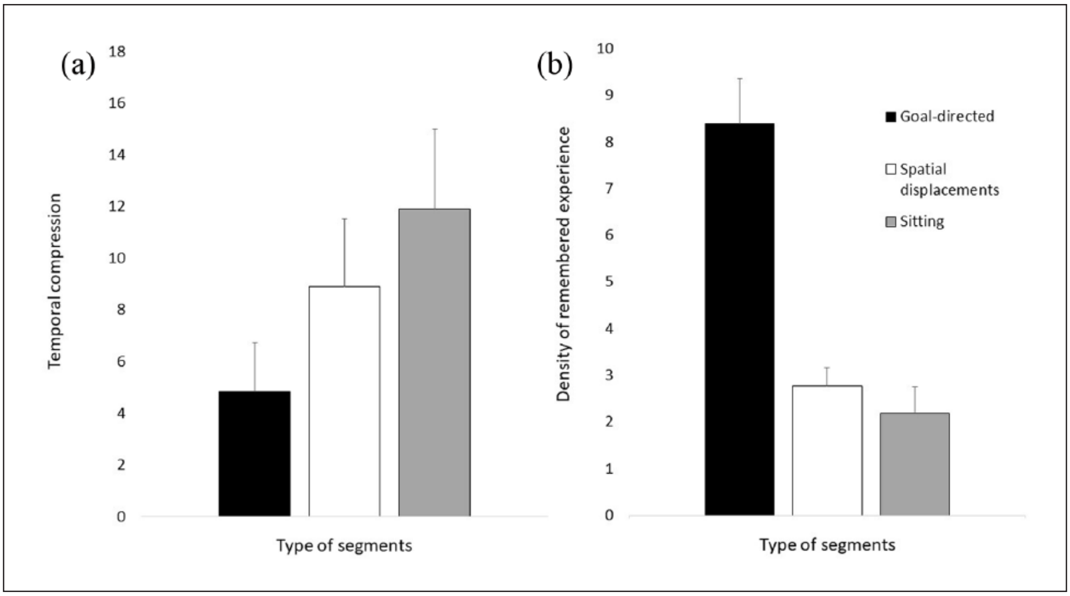

Figure 3. Rates of temporal compression and density of experience units during the mental replay of the three types of segments. (a) Temporal compression is estimated as the ratio of the actual duration of an event to the time needed to mentally re-experience this event. (b) The density of experience units corresponds to the number of recalled units per min of the actual event. Error bars represent 95% robust confidence intervals.

measure of temporal compression that does not rely on verbal reports. For each trial, the duration of the mental re-experience of the event was determined based on the button press that participants made when starting and ending their mental replay, and the actual duration of the event was computed by calculating the time separating the two pictures representing its beginning and end. Then, the temporal compression rate in episodic memory was estimated as the ratio of the actual duration of the event to the duration of its mental replay. The mean ratio indicated that, on average, participants mentally replayed events about 8.16 times faster than the actual event duration, 95% CI [6.64, 10.40].

Next, we sought to replicate our previous finding that temporal compression rates are influenced by the nature of remembered events and, in particular, their goal relevance. To this end, we computed temporal compression rates separately for three kinds of segments of the walk, which varied according to whether or not they involved goal-directed actions and spatial displacements. Goal-directed segments involved performing particular goal-directed actions while spatial location remained relatively stable (i.e., posting the letter, buying the newspaper at the newsstand, and buying the drink at the cafeteria; see colour circles 2, 4, and 6 on Figure 1, respectively). Spatial displacement segments involved changes in spatial location with no particular action to perform other than walking (i.e., going from one place to another; see colour lines 1, 3, 5, and 8 on Figure 1). Finally, the sitting segment involved no or few particular actions (other than drinking the beverage or reading the newspaper) and no change in spatial location (i.e., sitting at the table in the cafeteria; see colour circle 7 on Figure 1). For each type of segments, we computed the ratio of the actual segment duration to the time taken to mentally re-experience it.

A robust one-way repeated-measures ANOVA showed that the temporal compression of past experience in memory significantly differed as a function of segment types, F_t=19.16, F_{Crit}=7.83, p<.01 (see Figure 3a). Post hoc tests showed that goal-directed segments were less compressed in memory than both spatial displacement, $\widehat{\Psi}$ =−3.96, 95% CI [−5.51, −2.41], and sitting, $\widehat{\Psi}$ =−7.96, 95% CI [−$\widehat{\Psi}$ 10.31, −3.61], segments. Although spatial displacements tended to be less compressed than sitting segments, the difference between trimmed means was not statistically significant, $\widehat{\Psi}$ =−3.00, 95% CI [−6.12, 0.11]. Taken together, these results are consistent with our previous findings suggesting that the rate of temporal compression of experience in episodic memory depends on goal-directed actions.

Density and components of recalled experience units

When verbally describing the content of their mental replay, participants reported a succession of moments of past experience—here referred to as experience units (see Methods). On average, participants reported 9 experience units per trial, 95% CI [7.61, 9.88]. To assess the density of recalled experience units during mental replay, we computed the number of reported experience units per unit of time of the actual event. On average, participants recalled 2.70 experience units per min of the actual event, 95% CI [2.38, 3.03].

Table 3. Mean number of components recalled per experience unit.

	Trimmed means	95% CI
People	0.14	[0.12, 0.17]
Objects	0.35	[0.32, 0.38]
Thoughts	0.17	[0.15, 0.21]
Actions with interaction	0.14	[0.11, 0.17]
Spatial movements	0.49	[0.46, 0.51]
Perceptual details	0.03	[0.02, 0.04]
Spatial details	0.10	[0.09, 0.13]
Comments	0.13	[0.11, 0.15]

A robust one-way repeated-measures ANOVA showed that the density of recalled experience units differed between the three types of segments, $F_t = 105.72$, $F_{Crit} = 12.82$, $p < .001$ (see Figure 3b). Post hoc tests showed that participants recalled more experience units per minute of the actual events for goal-directed segments than both spatial displacement, $\widehat{\Psi} = 5.64$, 95% CI [4.26, 7.01], and sitting, $\widehat{\Psi} = 6.21$, 95% CI [4.67, 7.75], segments. There was no significant difference in the density of recalled experience units between spatial displacement and sitting segments, $\widehat{\Psi} = 0.58$ [95% $CI = -0.24$, 1.39]. Overall, then, the pattern of results was similar as for our measure of temporal compression, showing that the density of retrieved moments of past experience was strongly modulated by goal-directed actions.

We also examined the kinds of information recalled within experience units—here referred to as unit components (see Methods). On average, participants reported 1.77 components per experience unit, 95% CI [1.71, 1.83], and the mean numbers of the different types of components are presented on Table 3. Because the spatial and perceptual categories referred to additional information about other components (e.g., the spatial location of an object or a person), we did not include them in the following analysis investigating the prevalence of components. A robust one-way repeated-measures ANOVA yielded a significant effect of component categories, $F_t = 50.08$, $F_{Crit} = 8.15$, $p < .001$, showing that some categories of components were more frequent than others. Post hoc tests revealed that spatial movements were the most frequent components (ps < .05 for all pair-wise comparisons), followed by objects, which were more frequent than actions with interaction, thoughts, and people (ps < .05). Thoughts, actions with interaction, and people were reported with similar frequency (ps > .05).

Relationship between temporal compression rates and recalled moments of experience

The above analyses showed that the temporal compression of events and the density of recalled moments of experience followed similar patterns of variation across the three types of events. Next, we sought to investigate whether the rate of temporal compression in episodic memory was related to the density and level of detail of recalled moments of experience on a trial-by-trial basis. To examine this question, we conducted robust multilevel modelling. First, we fitted a random intercept-only model on temporal compression rates; this model showed that 62% of the total variance in compression rates was due to within-participants differences (i.e., variation among events), whereas 38% of the total variance was due to between-participants differences. Next, we added the density of recalled experience units and number of components within experience units as predictors in the model. This revealed that the density of experience units was a significant predictor of temporal compression rates ($\beta = -0.25$, $SE = 0.02$, $z = 10.98$, $p < .001$). On the other hand, the number of components retrieved within experience units did not significantly predict temporal compression ($\beta = -0.04$, $SE = 0.02$, $z = 1.68$). These results thus suggest that temporal compression rates in episodic memory depend on the density of recalled moments of past experience, but not on the amount of details recalled within each moment.

Retrospective duration judgements

Our next goal was to investigate whether retrospective judgements of event duration are predicted by the density and level of detail of recalled moments of past experience. To this end, we computed the duration judgement ratio for each trial (i.e., the ratio of the duration estimate to the actual duration of the event), a standard measure used in most studies of duration judgements (see Block et al., 2010). A duration judgement ratio higher than 1 means that participants overestimated the actual duration of the event whereas a ratio lower than 1 means that the actual event duration was underestimated; a ratio of 1 indicates an accurate estimation. The average duration judgement ratio was 1.07, 95% CI [0.98, 1.20]. A robust multilevel regression analysis with the duration judgement ratio as outcome variable and the density of recalled experience units and number of components within experience units as predictors showed that duration estimates increased significantly with the density of recalled experience units ($\beta = 0.43$, $SE = 0.04$, $z = 9.86$, $p < .001$), whereas the number of components retrieved within experience units was not a significant predictor ($\beta = -0.04$, $SE = 0.05$, $z = 0.83$). This suggests that the perceived duration of past events is affected by the density of recalled moments of experience, but does not depend on the level of detail of these experience units.

We also examined whether participants' confidence in their duration estimate was related to judgement accuracy. To this end, we computed an error score for each trial by taking the absolute value of the difference between the estimated and actual duration, divided by the actual event duration. This score thus indicated the proportion of error in duration estimation (irrespective of whether duration was over- or underestimated) relative to the actual duration of the event. A robust multilevel regression analysis using this measure as outcome variable indicated that judgement accuracy was not significantly related to confidence ratings ($\beta = 0.03$, $SE = 0.04$, $z = 0.66$).

Influence of path duration and Euclidean distance on memory for spatial displacements

In another set of analyses, we examined factors that could modulate the temporal compression of spatial displacements in episodic memory. Previous research has shown that compression rates in the mental replay of familiar routes are influenced by route length, such that longer routes are more compressed (Bonasia et al., 2016). Considering that people encode both path and Euclidean distances during spatial navigation (e.g., Howard et al., 2014), here we examined the influence of both dimensions on temporal compression rates and duration judgements for spatial displacements (see colour lines on Figure 1). We found that the actual time taken to travel the paths (an estimate of route length) was a significant predictor of temporal compression rates when remembering ($\beta = 0.20$, $SE = 0.02$, $z = 8.18$, $p < .001$) but did not influence duration judgement ratios ($\beta = 0.03$, $SE = 0.06$, $z = 0.49$). In the same vein, the Euclidean distance between the start and end locations predicted temporal compression in memory ($\beta = 0.18$, $SE = 0.03$, $z = 6.62$, $p < .001$) but was unrelated to duration judgement ratios ($\beta = 0.03$, $SE = 0.06$, $z = 0.59$). The respective influence of path lengths and Euclidean distances on spatial memory compression could not be disentangled in this study because these two dimensions were highly correlated ($r = 0.85$).

Subjective re-experience of past events

Finally, we performed an exploratory analysis to investigate to what extent the subjective feeling of re-experiencing past events depended on recalled moments of past experience. We investigated this question by performing a robust multilevel regression analysis with ratings of feeling of re-experience as outcome variable and the density of recalled experience units and number of components retrieved within units as predictors. We found that the density of experience units was a significant predictor of the feeling of re-experience ($\beta = 0.21$, $SE = 0.05$, $z = 4.16$, $p < .001$), whereas the number of components retrieved within experience units did not significantly predict this feeling ($\beta = 0.01$, $SE = 0.05$; $z = 0.20$). This finding suggests that the subjective sense of re-experiencing a past event depends on the amount of retrieved moments of experience rather than the level of detail of these moments.

Discussion

Our daily life is made of a continuous flow of events and experiences. Episodic memory allows us to mentally re-experience these events in a temporally compressed way, but the nature and determinants of this compression mechanism are not fully understood. Here, using a more direct measure of temporal compression that does not rely on verbal reports, we replicated our previous finding that rates of compression depend on the nature of remembered events. More specifically, we found that the temporal compression of events was on average two to three times lower when these involved goal-directed actions compared to other kinds of activities (i.e., spatial displacements or staying in a particular place with few actions to perform). Furthermore, our results showed that the rate of temporal compression depended on the density of recalled moments of past experience rather than the amount of recalled details within each moment. Another goal of this study was to investigate the basis of retrospective duration judgements for daily life events. We found that the perceived duration of events increased with the density of recalled moments of prior experience, but was not related to the level of detail of these moments. When looking specifically at memory for spatial displacements, we found that path durations and Euclidean distances significantly predicted temporal compression rates when remembering but were unrelated to retrospective duration accuracy. Finally, our results showed that the subjective sense of re-experiencing the past was predicted by the density of recalled moments of prior experience.

This study shows that the continuous flow of information that constitutes daily life events is somehow compacted in memory, such that prior experiences are mentally replayed at a faster rate than the original events. A fundamental question is, therefore, how does this temporal compression of experience in episodic memory operate? Together with our previous study (Jeunehomme et al., in press), the present results provide some clues to answering this question. First, we found that rates of temporal compression were predicted by the density of recalled moments of experience per unit of time of the actual event. Second, our previous study indicated that recalled moments of experience were frequently separated by dozens of seconds in terms of the actual event duration. Taken together, these findings support the view that past events are represented in episodic memory as a succession of moments or slices of prior experience (Conway, 2009) that are separated by temporal discontinuities. When remembering a past event, people may "jump" in their mind from one moment of experience to another, such that there are temporal "gaps" in their memory (i.e., portions of past experience that are not represented). Verbal reports on the content of participants' mental replay clearly illustrate this phenomenon. For example, in this study, a participant described having a mental image of arriving in front of the campus newsstand, then an image of picking the daily newspapers inside the campus newsstand, followed by an image of paying the newspaper to the seller; these three successive moments of past experience were separated by a temporal gap of several seconds in the actual event. Overall, then, our results converge on the conclusion that the temporal compression of experience in episodic memory occurs, at least in part, because of the introduction of temporal discontinuities in the representation of the flow of events. Rates of temporal compression may depend on the duration of these discontinuities between remembered moments of prior experience, such that longer temporal gaps would lead to a greater compression of events.

While the density of remembered moments was a significant predictor of the temporal compression of events, the amount of details recalled within each moment was unrelated to compression rates. This suggests that the compression of events in episodic memory mainly operates on the construction of the sequence of experience units that constitute memories (i.e., by the introduction of temporal discontinuities between recalled moments) rather than on the remembered units themselves. However, it should be noted that the time needed to mentally replay each moment of prior experience was not measured in this study, so it cannot be totally excluded that the compression mechanism operates in part at this level (e.g., moments could be mentally replayed more or less quickly depending on the nature of the remembered events). More generally, the exact nature of the experience units that constitute memories for real-life events remain to be determined. According to event-segmentation theory (Zacks, Speer, Swallow, Braver, & Reynolds, 2007), significant changes in perceptual and conceptual features are used by people to interpret and segment the continuous stream of experience into distinct events (Kurby & Zacks, 2008; Zacks, Speer, Swallow, & Maley, 2010). Moments of past experience that form the units of memories could be created as a result of this segmentation of ongoing experience into separated events and sub-events. These experience units may consist in integrated representations of sensory-perceptual, cognitive, and affective processes that occurred at a given moment in the past (Baddeley, 2000). A question that remains to be investigated, however, relates to the temporal structure of experience units. Are these like "snapshots" of the past or are they more dynamic and temporally extended, representing short-time slices of prior experience (Conway, 2008, 2009)? Of course, these two possibilities are not necessarily mutually exclusive and it could be that episodic memories include both kinds of representational format.

An important finding of this study is that temporal compression rates in episodic memory are not constant but seem to be adaptively modulated to maintain goal-relevant information (see also Jeunehomme et al., in press). Such variations in temporal compression across events could in part be due to the grain size of event segmentation. Several studies have indeed shown that people segment ongoing experience in more or less fine-grained events, which influences the encoding and organisation of information in episodic memory (DuBrown & Davachi, 2013; Ezzyat & Davachi, 2011; Horner et al., 2016; Pettijohn, Thompson, Tamplin, Krawietz, & Radvansky, 2016; Swallow, Zacks, & Abrams, 2009). Therefore, it could be that goal-directed actions are interpreted in terms of finer sub-events (e.g., action units; Hard, Recchia, & Tversky, 2011), such that they are encoded at a higher rate and thus less temporally compressed in memory. More generally, the finding that compression rates are lower for goal-directed actions supports the view that an important function of episodic memory is to keep records of actions and action outcomes, providing a means to check on recent progress with current goals and plans (Conway, 2008, 2009).

We initially expected that compression rates in episodic memory would also depend on the amount of perceptual changes within events (Faber & Gennari, 2015). To test this hypothesis, we compared temporal compression rates for events involving spatial displacements versus events that did not involve spatial displacements (as well as no or few goal-directed actions). Although the difference was in the predicted direction (i.e., lower compression rates for spatial displacements), it was not statistically significant. In hindsight, this result could be explained by the use of the "sitting" event as a comparison condition. Although we expected that the sitting event would involve fewer perceptual changes than spatial displacements, we had no control on the actual amount of changes in this condition. An examination of the pictures taken during this event and of the verbal reports on memory contents revealed that perceptual changes were actually quite frequent (e.g., seeing people passing by, hearing conversations, and so on). Therefore, the sitting event was clearly an imperfect comparison condition for assessing the influence of perceptual changes on temporal compression. Future studies using events that are better controlled for the amount of perceptual changes should thus be conducted to shed further light on this possible determinant of the rate of temporal compression of daily life events in episodic memory (for evidence that perceptual changes influence temporal compression in memory for animations in the laboratory, see Faber & Gennari, 2015).

Another goal of this study was to investigate to what extent retrospective duration judgements of daily life events are influenced by recalled moments of past experience. Assuming that the experience units that constitute episodic memories are formed as a result of changes in ongoing experience (e.g., changes in actions, perceptual information, or internal states), the present result that retrospective duration judgements depended on the density of recalled moments of past experience (rather than the amount of details within each moment) is consistent with the contextual-change hypothesis proposed by Block and Reed (1978). Indeed, on this view, the perceived duration of an event is based on the amount of changes in prior experience that are accessed in memory. Our findings are also in line with previous studies showing that the segmentation of ongoing experience into distinct events influences retrospective judgements about various temporal aspects of events (DuBrown & Davachi, 2013; Ezzyat & Davachi, 2014; Faber & Gennari, 2015). Notably, Faber and Gennari (2015) found that animations that were constituted of more sub-events were judged longer, despite the fact that the actual event duration remained constant. In the same vein, it could be that when remembering real-life events, the amount of available moments of prior experience in memory is used as an index for making duration judgements: a higher density of recalled moments per unit of standard time would lengthen the perceived duration of events.

Focusing more specifically on spatial displacements, we found that temporal compression rates when mentally replaying routes increased with the actual travel time and Euclidian distance between start and end locations. These findings are consistent with a previous investigation showing that compression rates of familiar routes are modulated by route length (Bonasia et al., 2016). There is evidence that path and Euclidean distances are represented separately during navigation (e.g., Howard et al., 2014), but this study did not allow to disentangle the influence of these two types of distances on spatial memory compression because they were highly correlated. This issue could be investigated in future studies by selecting specific combinations of goal locations and detours to design a walk that would minimise the correlation between Euclidean and path distances (see Howard et al., 2014).

Although not the primary aim of this study, we also explored to what extent the feeling of mentally re-experiencing past events depended on the density and level of detail of recalled moments of prior experience. We found that the feeling of re-experience increased with the density of recalled moments but was unrelated to the number of components retrieved within each moment. This finding suggests that the temporal structure of memories, and in particular the rate of sampling of successive moments of past experience, plays an important role in the subjective sense of remembering. When the rate of sampling of experience in episodic memory increases, the temporal gaps between remembered moments of prior experience are shorter, which may, in turn, contribute to an increased immersive feeling and the subjective sense that one is reliving the past.

This study opens avenues for future research on temporal compression in episodic memory. Notably, our data indicate that there are substantial individual differences in temporal compression rates and it would be interesting to investigate to what extent these differences are related to cognitive abilities that are known to play an important role in memory for real-life events, such as visual imagery (e.g., Sheldon, Amaral, & Levine, 2017; Vannucci, Pelagatti, Chiorri, & Mazzoni, 2016). Indeed, it could be that individual differences in visual imagery influence, at least in part, the speed of mental replay. Our findings also raise the question of how event features may influence temporal compression rates. This study involved rather mundane events that happened in a familiar context (i.e., the university campus) and it would be interesting to investigate whether and how compression rates vary as a function of various event dimensions, such as their emotionality, novelty/familiarity, and personal significance. Another important research question would be to determine whether temporal compression rates can be controlled during retrieval or whether they depend on automatic processes. This issue could be investigated, for example, by using a divided attention procedure at retrieval (e.g., Craik, Govoni, Naveh-Benjamin, & Anderson, 2006). Furthermore, if it appeared that temporal compression can be volitionally modulated during retrieval, it would be important to understand the mechanisms and functions of this type of memory control.

In summary, by examining the length of mental replay of real-life events in relation to the actual event duration, the present research provides more direct evidence that episodic memory represents past events in a temporally compressed way. Importantly, the rate of temporal compression of events is not constant but seems to vary adaptively to maintain goal-relevant information. Our results also demonstrate that temporal compression rates, duration judgements, and the subjective sense of re-experience depend on the density of recalled moments of past experience rather than the richness of their content. Taken together, these findings expand our understanding of how daily life experiences are temporally compressed in episodic memory by showing that past events are represented as a succession of moments of prior experience with varying temporal discontinuities between remembered moments. The density of remembered moments in turn influences the perceived duration of events and the subjective feeling of re-experiencing the past.

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