The temporal compression of events during episodic future thinking

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Abstract

While the cognitive and neural mechanisms that underlie episodic future thinking are increasingly well understood, little is known about how the temporal unfolding of events is represented in future simulations. In this study, we leveraged wearable camera technology to examine whether real-world events are structured and compressed in the same way when imagining the future as when remembering the past. We found that future events were simulated at proportionally higher speed than past events and that the density of experience units representing the unfolding of events was lower for future than for past episodes. Despite these differences, the nature of events influenced compression rates in the same way for past and future events. Furthermore, the perceived duration of both types of events depended on the density of represented experience units. These results provide novel insight into the mechanisms that structure the unfolding of events during future simulations.

Keywords: episodic memory, episodic future thinking, temporal compression, time estimation, wearable camera.

1. Introduction

The ability to mentally simulate future scenarios—referred to as *episodic future thinking*—is a key feature of the human cognitive system that plays important roles in decisions and actions (Suddendorf & Corballis, 2007). To simulate future possibilities, we need to represent events as unfolding over time, as if pre-playing the situation in our mind. However, despite important progress in understanding the cognitive and neural mechanisms that underlie episodic future thinking (Schacter et al., 2017), little is known about how the temporal course of events is represented in future simulations. The aim of this study is to investigate whether real-world events are structured and compressed in the same way when imagining the future as when remembering the past.

Recent studies have shown that episodic memories represent prior experiences in a compressed form, such that the time it takes to remember an event is typically shorter than the actual duration of the past episode (Bonasia et al., 2016; Jeunehomme & D'Argembeau, 2019; Michelmann et al., 2019; Wang & Gennari, 2019). The course of events is represented as a succession of moments or slices of prior experience (referred to as *experience units*) that includes temporal discontinuities: some segments of prior experience are not represented during memory replay (Jeunehomme et al., 2018). The density of recalled experience units notably depends on event segmentation processes (Zacks, 2020); events that are perceived in terms of finer sub-events are encoded with a higher density of information and thus are less compressed in memory (Faber & Gennari, 2015; Jeunehomme & D'Argembeau, 2020).

Simulating future events relies on many of the same cognitive and neural processes as remembering past events (D'Argembeau, in press; Schacter et al., 2012), but little is known about the temporal structure of episodic future thoughts. The evidence suggests that people organize event details in chronological order both when remembering past events and when imagining future events (Anderson et al., 2015). In terms of event compression, a recent study showed that the mental simulation of routes in a virtual environment occurred at about 2-3 times the speed it took to actually navigate these routes (Arnold et al., 2016). However, it remains unclear whether this compression mechanism generalizes to real-world events and simulations other than spatial navigation. Furthermore, it is unknown whether the unfolding of events is structured and compressed in the same way when remembering the past and imagining the future.

In the present study, we compared the temporal structure of real-world events in episodic memories and episodic future thoughts by measuring the time needed for participants to mentally re-experience or pre-experience a series of daily life activities, while the actual duration of events was measured with wearable camera technology (Chow & Rissman, 2017). Verbal reports on the content of memories and future simulations were also collected. This allowed us to estimate event compression rates (i.e., the ratio of the actual event duration to the duration of mental replay/preplay), as well as the density of recalled/imagined moments of experience per unit of time of the actual event duration (Jeunehomme & D'Argembeau, 2019).

We tested two competing hypotheses on how rates of event compression compare between episodic memories and future simulations. A first possibility is that the unfolding of experience is structured and compressed in the same way when representing past and future events, given that episodic remembering and future thinking largely rely on common processes (Schacter et al., 2012). Suggestive evidence for this hypothesis comes from a study showing that people generate event details as fast for future as for past events (Anderson et al., 2015). However, another possibility is that events are more compressed when imaging the future than when remembering the past: people may only use essential information for representing the course of future events (e.g., scripts of action sequences), whereas memories may include more incidental details. In general, future simulations are less detailed than memories (e.g., Addis et al., 2008; D'Argembeau & Van der Linden, 2004), suggesting that fewer experience units may be used to represent the unfolding of events.

To further investigate the mechanisms underlying future event compression, we also assessed whether the nature of events affects compression rates in the same way when remembering the past and imagining the future. Previous studies have shown that prior experiences are less compressed when they involve specific actions compared to spatial displacements with no action to perform except walking (Jeunehomme & D'Argembeau, 2019, 2020). If similar mechanisms underlie the temporal structure of episodic memories and future thoughts, this difference in compression rates should also occur when simulating future events.

Finally, another aim of this study was to examine the extent to which future event compression impacts duration judgments. There is substantial evidence that retrospective duration judgements depend essentially on the retrieval of contextual elements: the perceived duration of a past event increases with the number of contextual changes that are remembered (Block & Zackay, 1996; Faber & Gennari, 2015; Jeunehomme & D'Argembeau, 2019). On the other hand, the process by which people estimate the duration of future events has received less empirical attention (e.g., Burt & Kemp, 1994; Hinds, 1999). According to Roy et al. (2005), expected duration judgments rely on information stored in memory; it follows that any variable affecting retrospective duration judgements should similarly affect predictions of future durations. Therefore, we predicted that for both past and future events, estimated durations would increase with the density of experience units representing the unfolding of events.

2. Method

2.1. Participants

Thirty-two young adults (17 females; mean age = 28 years, *SD* = 4.37) took part in this study (for justification of sample size, see Supplementary Material).

2.2. Materials and procedure

All participants received a memory task and a future simulation task. In the memory task, they first experienced a series of events and then mentally re-experienced these events. In the future simulation task, they first mentally simulated a series of events and then accomplished these events. Two sets of events were used, each involving a series of actions in which participants interacted with people and objects, and a series of spatial displacements that did not involve particular action other than walking from a place to another (see Figure 1). The assignment of each set of events to the memory and future simulation tasks and the order of presentation of the tasks were counterbalanced across participants. For both sets of events, the actual duration of actions and spatial displacements was recorded using a wearable camera (see Supplementary Material).

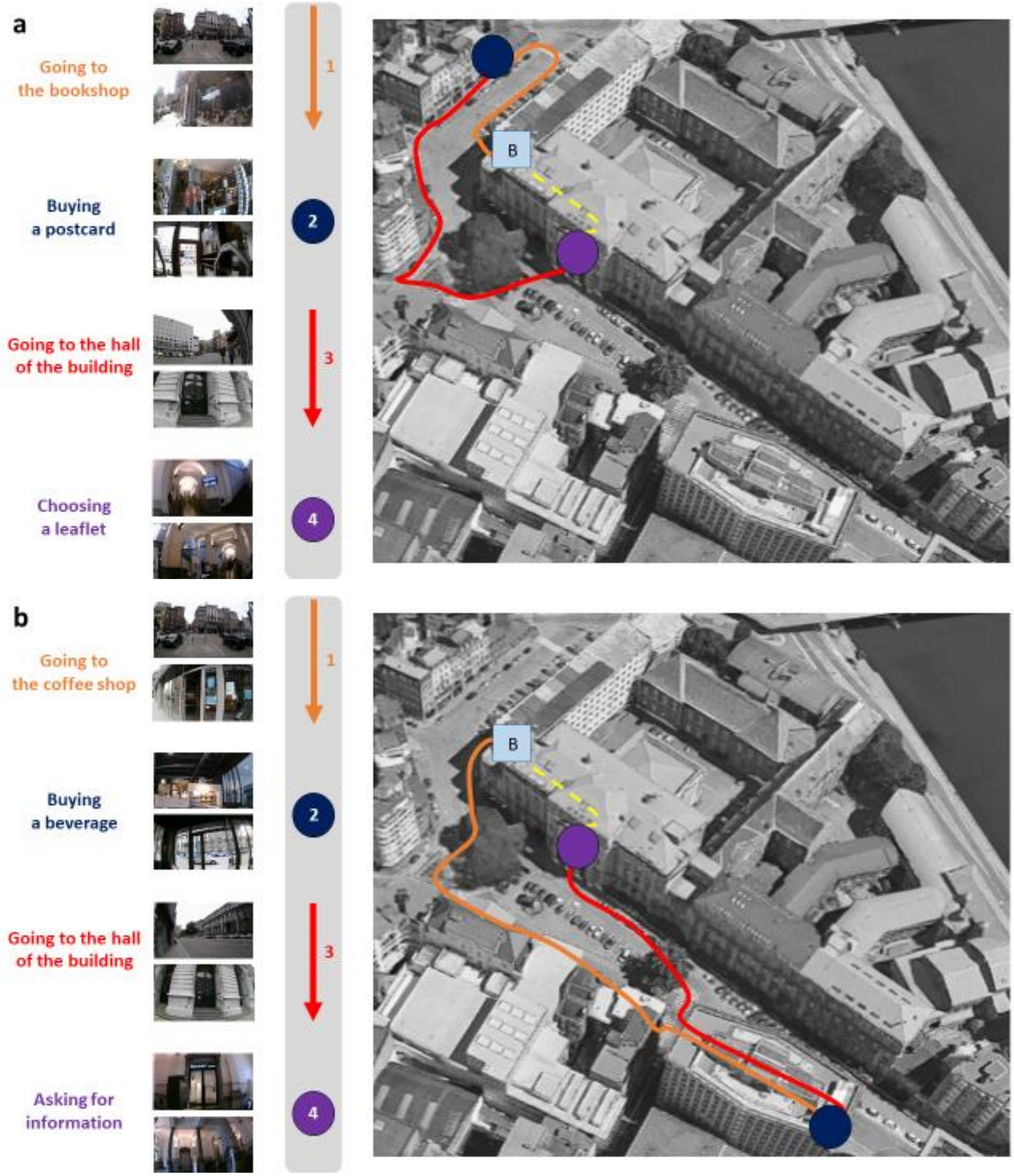

Figure 1. Overview of the two sets of events. (a) In the first set of events, participants were first instructed to leave the laboratory (B square) and to go to the bookstore to buy a postcard (participants were given 2 euros for purchasing the postcard). After having purchased the postcard, they had to go to the hall of the University building to choose a leaflet on the display stands; the leaflets depicted activities that could be done in Liège (e.g., museum visits, festivals or concerts) and participants were instructed to choose an activity they would like to carry out in a near future. Finally, they had to return to the laboratory to bring the camera back to the experimenter. (b) In the second set of events, participants were first instructed to leave the laboratory and to go to a coffee shop to purchase the beverage of

their choice that they were instructed to take away (participants were given 3 euros for purchasing the beverage). Then, they had to go to the reception office at the entrance of the University building to ask information about the closing time of the building. Finally, they had to return to the laboratory to bring the camera back to the experimenter. For each set of events, locations in which actions were performed are indicated by color circles and paths taken to go to these locations are indicated by color lines. Examples of pictures (taken by the wearable camera) indicating the beginning and end of each event are shown on the left.

The time needed by participants to remember or simulate events was assessed as follows: a pair of pictures representing the beginning and end of an event was presented and participants had to mentally re-experience or pre-experience the unfolding of the event in as much detail as possible; the duration of their mental replay/preplay was measured (see Figure 2). Then, participants rated the subjective characteristics of their mental representation (see Supplementary Material), estimated the actual duration of the event, and verbally described everything that came to their mind when replaying/preplaying the event.

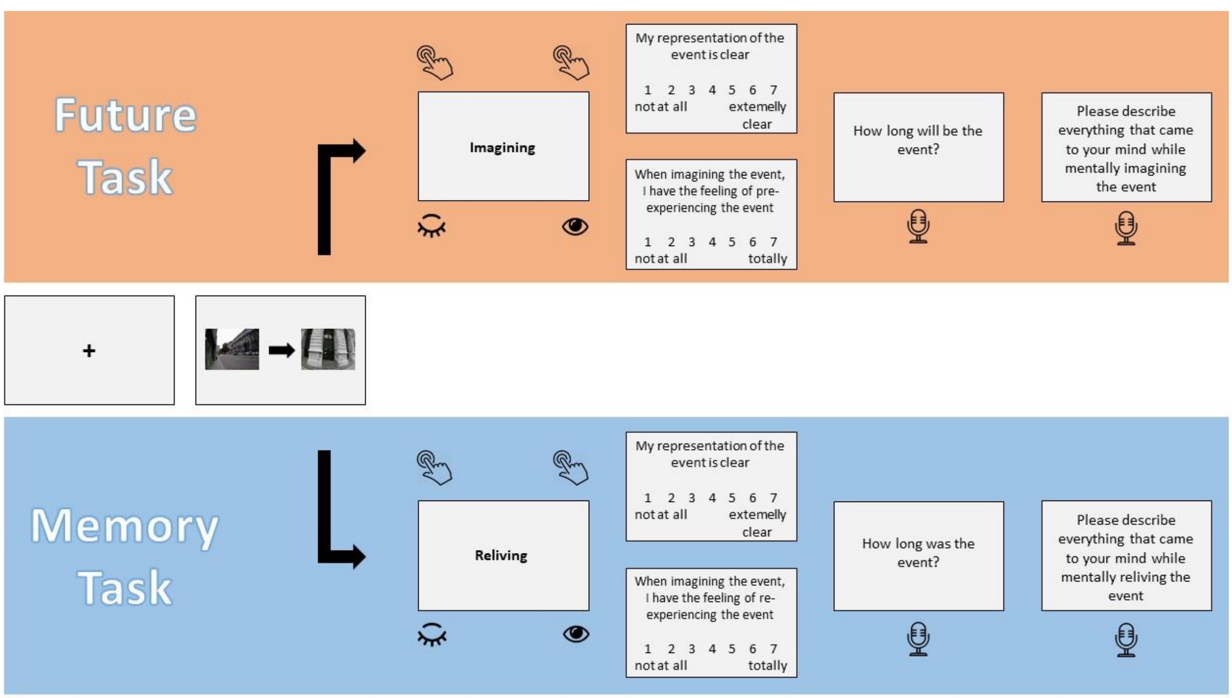

Figure 2. Illustration of the memory and future simulation tasks. On each trial, participants first had to mentally replay/preplay the unfolding of each event, from the moment corresponding to the picture shown on the left of the screen to the moment corresponding to the picture shown on the right of the screen. Participants had to close their

eyes to mentally represent the unfolding of the event and indicated the beginning and end of their mental replay/preplay with a key press. Then, they rated the subjective characteristics of their mental representation (vividness and feeling of pre-experience/re-experience) and provided an estimation of the actual duration of the event (in minutes and/or seconds). Finally, they verbally described everything that came to their mind when they mentally represented the unfolding of the event.

2.3. Scoring of verbal reports

Verbal reports describing the content of mental replay/preplay consisted of a succession of moments or slices of experience (referred to as *experience units*) that represented the unfolding of events. For each event, the number of reported experience units was assessed; transitions between experience units were identified on the basis of verbal indicators (e.g., “then”, “next”, “after that”) and moments of silence (for more detail, see Supplementary Material).

2.4. Statistical analyses

Data were analyzed using robust statistical methods (Field & Wilcox, 2017) because the assumptions underlying classical inferential methods (normality and homoscedasticity) were violated for our main measures of interest (see Figures 3-4). All descriptive statistics refer to the 20% trimmed means and their 95 % confidence intervals (for more detail, see Supplementary Material).

3. Results

3.1. Temporal compression of events

On average, each event actually took about 1-2 minutes to unfold, with no difference between past and future events (see Supplementary Material). The rate of temporal compression of events during episodic remembering and future thinking was estimated as the ratio of the actual event duration to the duration of its mental replay/preplay. Mean compression rates for past and future events that involved actions and spatial displacements are shown on Figure 3. A robust two-way repeated-measures ANOVA revealed a main effect of temporal direction, Q = 3.92, p = .048, showing that temporal compression was lower for past than future events (ξ = 0.23). The effect of the type of events was also significant, Q = 4.53, p = .034, showing that actions were less compressed than spatial displacements (ξ = 0.28). The interaction between the temporal direction and type of events was not significant, Q = 0.66, p = .418.

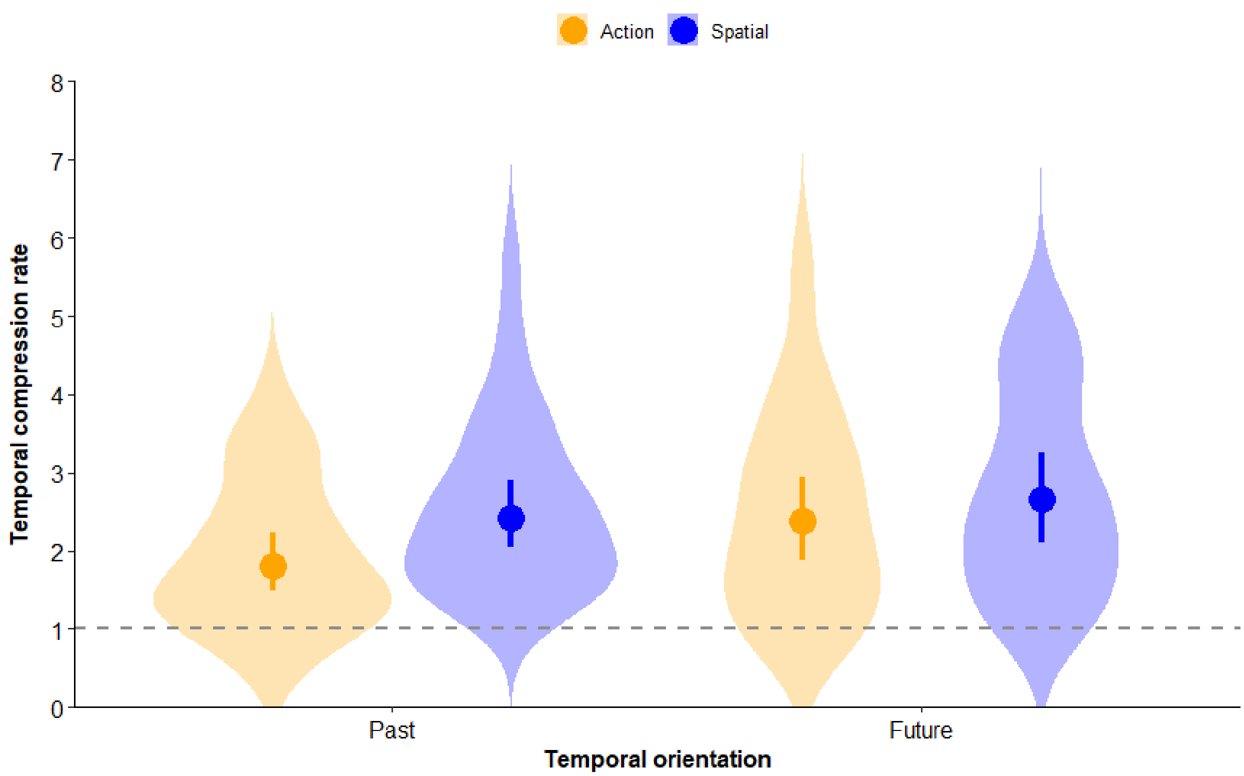

Figure 3. Temporal compression rates as a function of the temporal orientation (past vs. future) and type (actions vs. spatial displacements) of events. The rate of temporal compression is estimated as the ratio of the actual event duration to the time needed to mentally re-experience or pre-experience the event. Violin plots show the distribution of the data and point-range plots represent the 20% trimmed means and their 95% robust confidence intervals. The dashed line indicates a compression rate of 1 (i.e., the duration of mental replay/preplay coincides with the actual event duration).

3.2. Density of experience units

Verbal reports on the content of memories and future thoughts consisted of a succession of experience units that represented the unfolding of events. For each event, we estimated the density of recalled/imagined experience units as the number of experience units reported per minute of the actual event duration (see Figure 4). A robust two-way repeated measures ANOVA revealed a main effect of temporal direction, $Q = 11.99$, $p < .001$, showing that past events were described with a higher density of experience units than future events ($\xi = 0.65$). Moreover, events that involved specific actions were associated with a higher density of experience units than events that involved spatial displacements, $Q = 26.66$, $p < .001$, $\xi = 0.79$. No significant interaction was found, $Q = 2.26$, $p = .133$.

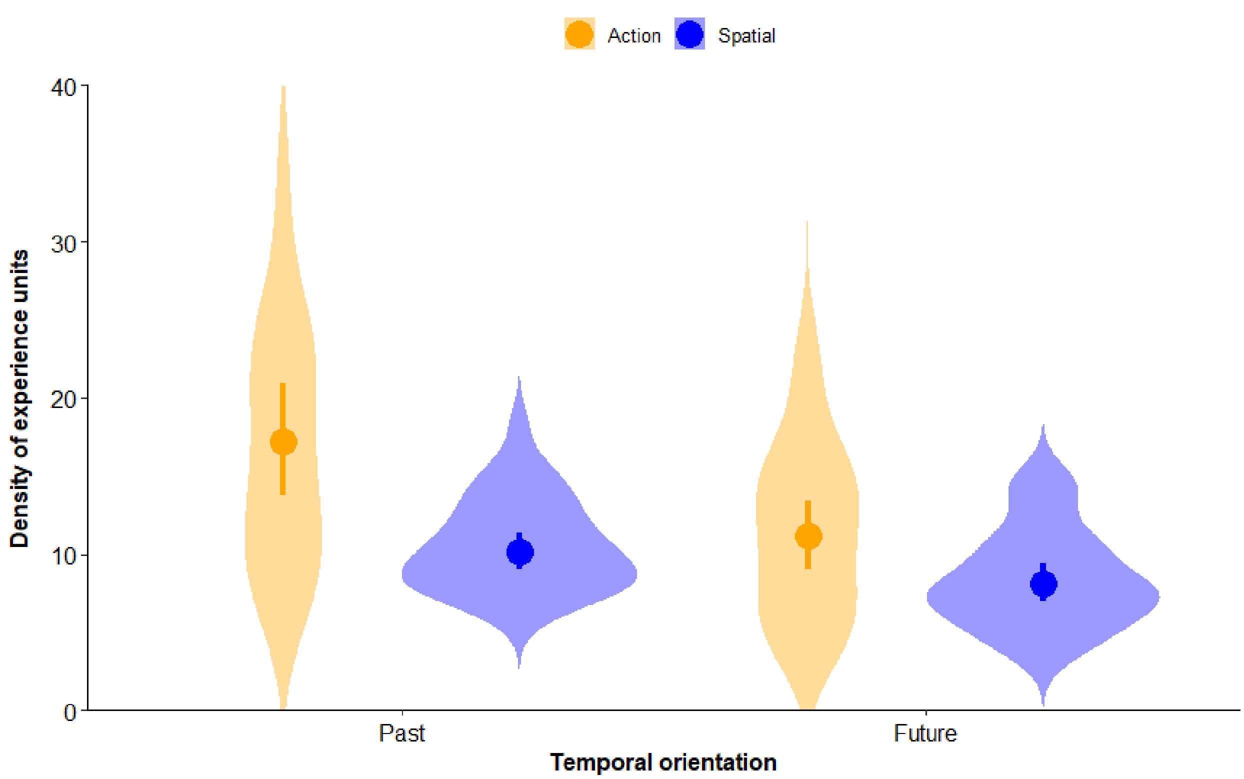

Figure 4. Density of experience units as a function of the temporal orientation (past vs. future) and type (actions vs. spatial displacements) of events. The density of experience units corresponds to the number of recalled/imagined units per minute of the actual event. Violin plots show the distribution of the data and point-range plots represent the 20% trimmed means and their 95% robust confidence intervals.

Next, we conducted a robust multilevel regression analysis to determine whether rates of event compression were predicted by the density of experience units contained within memories and future thoughts. When fitting regression models separately for past and future events, we found that the density of experience units was a significant predictor of compression rates for both memories ($b = -0.06$, $SE = 0.009$, df=24.74, $t = 6.34$, $p < .001$) and future thoughts ($b = -0.14$, $SE = 0.02$, df=24.74, $t = 8.48$, $p < .001$). Interestingly, however, a regression model that included both the temporal direction of events and the density of experience units as predictors revealed a significant interaction between the two predictors ($b = -0.08$, $SE = 0.02$, df=154.38, $t = 5.09$, $p < .001$), indicating that the negative relationship between the density of experience units and event compression rates was stronger for future than past events (Figure 5). This suggests that it took proportionally more time to represent an experience unit when simulating future events than when remembering past events (see Supplementary Material).

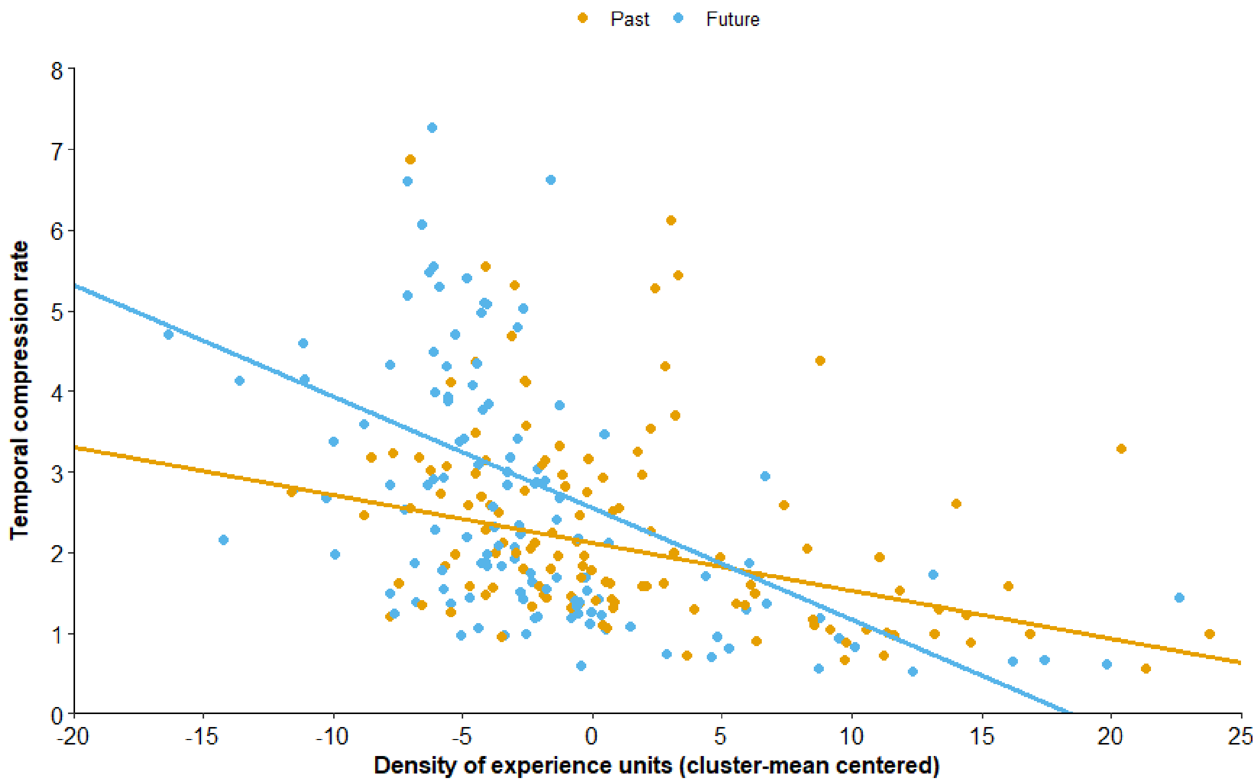

Figure 5. Relationship between temporal compression rates and the density of experience units for past and future events. The regression lines represent the fixed effect of the density of experience units on compression rates in robust multilevel regression analyses (for detail, see Supplementary Material).

3.3. Duration judgments

Retrospective and expected duration judgments were analyzed using the duration judgement ratio (i.e., the ratio of the duration estimate to the actual duration of the event; Block et al., 2010). As shown on Figure 6, participants tended to overestimate the duration of actions, whereas they provided relatively accurate estimations for spatial displacements. A robust two-way repeated measures ANOVA yielded a main effect of temporal orientation, $Q = 5.06$, $p = .025$, showing that estimated durations were higher for future than past events ($\xi = 0.21$), and a main effect of the type of events, $Q = 16.35$, $p < .001$, showing that estimated durations were higher for actions than spatial displacements ($\xi = 0.42$). No significant interaction was found, $Q = 0.01$, $p = .966$.

Robust multilevel regression analyses with the duration judgment ratio as outcome variable and the density of experience units as predictor indicated that duration estimates increased with the density of experience units, for both past (*b* = 0.04, *SE* = 0.01, df=17.06, *t* = 4.38, *p* < .001) and future (*b* = 0.08, *SE* = 0.02, df=26.84, *t* = 3.63, *p*=.001) events. This effect did not interact with temporal orientation (*b* = 0.018, *SE* = 0.013, df=240.69, *t* = 1.41, *p*=.16).

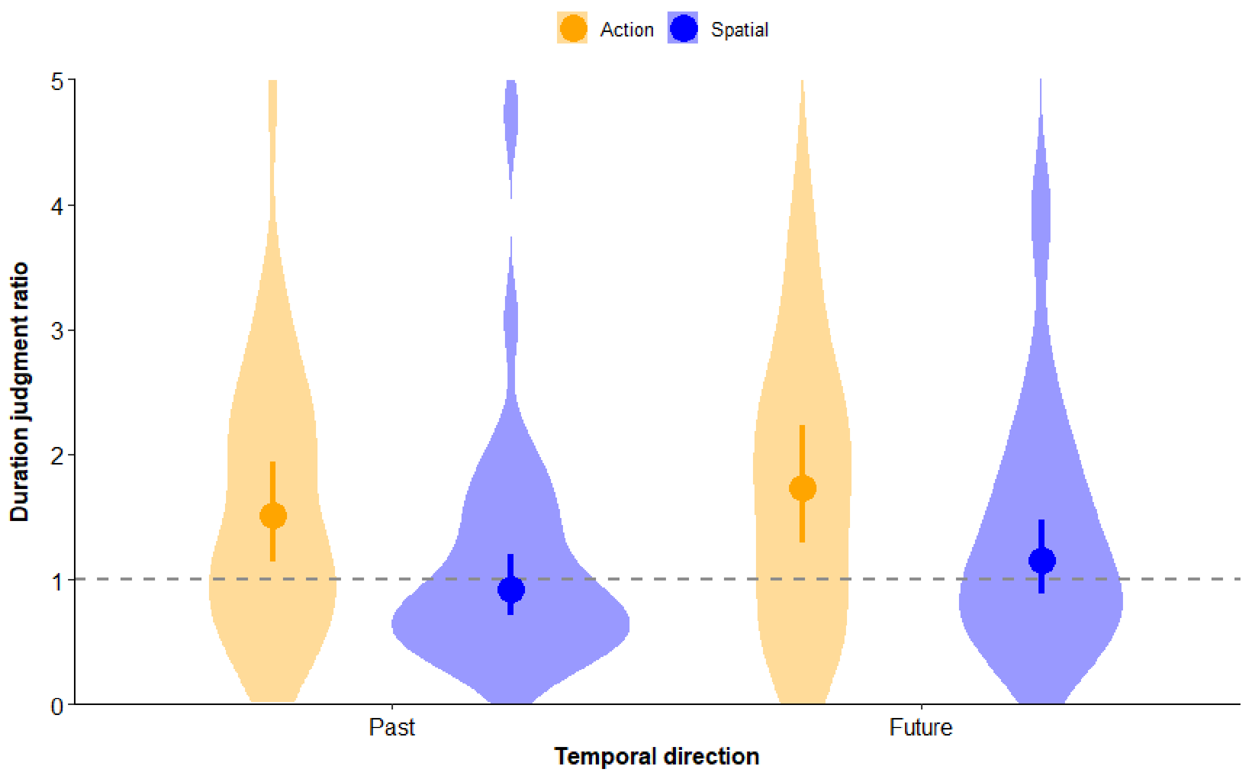

Figure 6. Duration judgment ratio (i.e., estimated duration/actual event duration) as a function of the temporal orientation (past vs. future) and type (actions vs. spatial displacements) of events. A duration judgement ratio higher than 1 means that the duration of the event is overestimated, whereas a ratio lower than 1 means that the duration of the event is underestimated; a ratio of 1 indicates an accurate estimation. Violin plots show the distribution of the data and point-range plots represent the 20% trimmed means and their 95% robust confidence intervals. The dashed line indicates a duration judgment ratio of 1 (i.e., accurate estimation).

4. Discussion

This study provides the first evidence that the unfolding of real-world events is temporally compressed in future simulations, thus extending previous results on the simulation of routes in a virtual environment (Arnold et al., 2016). Another contribution of this study is to show that there are both similarities and differences in the temporal structure and compression of episodic memories and episodic future thoughts. Although events were simulated at proportionally higher speed when imagining the future than when remembering the past, the nature of events influenced compression rates in the same way for past and future events.

While the exact mechanism of event compression is not fully understood, previous studies suggest that the time-compressed replay of prior experience occurs, at least in part, because of temporal discontinuities in the representation of the unfolding of events: some moments of prior experience are not remembered, as if people mentally jumped from one moment of experience to another without representing what happened in between (Jeunehomme et al., 2018; Jeunehomme & D'Argembeau, 2019). The magnitude of event compression may depend on the length of these temporal gaps when representing the course of events or, reciprocally, on the density of remembered experience units per unit of time of the actual event duration (Jeunehomme & D'Argembeau, 2020). The present results suggest that basically the same compression mechanism operates when simulating future events. In fact, it has been argued that episodic memories and future thoughts rely on the same simulation system, which draws on elements from prior experiences and schemas to (re)construct event representations (Addis, 2020). Following this view, our finding that compression rates were higher when simulating future events may reflect differences in the balance of different forms of underlying contents: compared to memories, future thoughts involve fewer experiential details and a greater reliance on schemas to represent the course of events. We also found that the density of experience units predicted compression rates to a greater extent for future than past events, suggesting that it takes proportionally more time to represent an experience unit when simulating future events. This may reflect differences in the associative history of constituent details: remembering involves the reinstatement of previously associated details, whereas imagination requires the creation of novel configurations of details, which places higher demands on the simulation process (Addis, 2020). As a result, the fluency or ease of event simulations is higher when remembering than when imagining (Michaelian et al., 2020).

Despite these differences in the temporal resolution of memories and future thoughts, compression rates and the density of experience units were modulated by the nature of events (i.e., actions vs. spatial displacements) in the same way for past and future episodes. Relative to spatial displacements, actions are more likely to be segmented in fine-grained subevents, leading to the formation of more experience units to represent the event's unfolding and thus lower event compression rates (Jeunehomme & D'Argembeau, 2020). Our results suggest that this effect of event segmentation on the temporal structure of mental representations (Clewett et al., 2019; Zacks, 2020) is similar when remembering past events and simulating future events, providing further support to the view that memory and imagination involve fundamentally the same mechanism (Addis, 2020). Compression rates might notably depend on changes in the structure of events that lead to incremental versus global updating of event models (Bailey & Zacks, 2015; Curiel & Radvansky, 2014). Event models represent information along various dimensions such as persons, objects, actions, and spatial location. Changes in these dimensions can result in incremental updating (when the current event model is altered to accommodate new information) or global updating (when a new event model is created) of event models. One possibility is that events are less compressed when the succession of experience units represents incremental changes, such that there is more continuity in the representation of events. For example, the higher density of experience units when representing actions might reflect incremental updating in the event model (e.g., a succession of actions involving the same entities in the same location), whereas transitions between experience units when representing spatial displacements might more frequently involve global updating (e.g., mental jumps from one location to another). From a functional perspective, representing actions at a finer resolution may enhance the effectiveness of planning, thereby promoting more effective decision making and implementation intention (Baumeister et al., 2016; Gollwitzer, 1999; Taylor et al., 1998).

Another goal of the present study was to investigate possible differences between retrospective and expected duration judgments and to determine the extent to which duration estimates are influenced by the density of recalled/imagined moments of experience. Overall, our results are consistent with previous studies showing that for short time intervals (i.e., less than 5 minutes), the duration of naturalistic events tends to be overestimated (for a review, see Roy et al., 2005). This was especially the case for events that involved actions, whereas spatial displacements were relatively well estimated. Duration estimates were on average higher for future than past events but for both types of events perceived duration depended on the density of recalled/imagined experience units. These findings are not only consistent with the contextual-change hypothesis, according to which the duration of a past event is estimated on the basis of the amount of changes that are accessed in memory (Block & Reed, 1978), but also provide novel evidence that a similar mechanism underlies expected duration judgments (i.e., people use imagined experience units as an index for predicting the duration of future events).

5. Conclusions

Episodic future thinking would not be functional if we spent endless time simulating events in our mind. To be adaptive, episodic simulations need to represent events at a faster rate than the actual duration of experience. Our results suggest that this temporal compression mechanism operates in basically the same way—by representing events as a succession of discrete moments of experience that includes temporal discontinuities—when remembering the past and imagining the future, although compression rates vary with the nature and temporal orientation of events. A question for future research is whether event compression rates can be flexibly modulated as a function of goals and task context.

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Supplementary Material

Supplementary details on the method

Sample size. An a priori power analysis using G*Power 3 (Faul, Erdfelder, Lang, & Buchner, 2007) indicated that 26 participants were needed to achieve a statistical power of 80% to detect differences in compression rates between actions and spatial displacements, considering an alpha of .05 and the effect size (d = 0.58) obtained in Jeunehomme and D'Argembeau (2019). To have an equal number of participants in all conditions of presentation of the tasks for proper counterbalancing (see below), this number was increased to 32 participants. Six participants were excluded and replaced by other participants for the following reasons: one participant because of a malfunction of the wearable camera, two participants because they guessed that their memory would be tested, and three participants because of non-completion of experimental instructions (i.e., taking the wrong path or forgetting to perform a specific action). The final sample thus consisted of 32 participants (17 females; mean age = 28 years, SD = 4.37 years). All of them provided written informed consent and the study was approved by the local ethics committee.

Materials and procedure. During the two sets of events, participants wore a YoCam (Mofily®; http://www.getyocam.com/), which is a small wearable camera with a 140° angle of view lens that we configured to take a video with a resolution of 720 pixels at 30 frames per second. This device allowed us to record a continuous video of all events experienced by the participants, from a first-person perspective. Before experiencing each set of events, participants were instructed to respect the order of activities and to behave as naturally as possible, while at the same time avoiding to obstruct the lens of the camera.

To avoid the intentional encoding of the events in the memory task, participants were not informed that their memory would be subsequently tested. We used a cover story explaining that the purpose of the study was to evaluate the quality of the video taken by the YoCam when performing various actions in different environments (indoor and outdoor) for a subsequent study investigating activities of university students in their daily life. At the end of the experiment, participants were informed that the real aim of the study was to investigate their memory for experienced events and they were asked whether they had guessed that their memory would be tested.

For both the memory and future thinking tasks, participants had to mentally represent the unfolding of events that were cued by pictures representing the beginning and end of the events. For the memory task, these pictures were extracted from the video recorded when participants experienced the events. For future events, the pairs of pictures were selected from the experience of a pre-test participant and were the same for all participants. For each participant, care was taken to select pictures of past events that matched the pictures used for future events (e.g., a picture representing the door of the bookstore), such that the moments representing the beginning and end of each event were equivalent for past and future events. For both types of events, participants were instructed to try to mentally represent everything that happened or might happen 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. They were told that their task was to try to mentally re-experience or pre-experience the unfolding of events (including elements such as objects and people in the environment, actions, and thoughts) in as much detail as possible.

Immediately after their mental replay/pre-play, participants rated the vividness of their mental representation (from 1 = not at all, to 7 = extremely vivid) and their feeling of re-experiencing/pre-experiencing the event (from 1 = not at all, to 7 = completely). Then, they were instructed to report everything that went to their mind while mentally replaying/pre-playing the event. They were told to only report elements that went to their mind during their mental replay/pre-play; if an additional element came to their mind while verbally describing the event, they could mention it but had to specify that this element was new (i.e., was not part of their mental replay/pre-play). These additional elements were not taken into account in the subsequent analyses.

The two tasks were programmed and presented using Open Sesame 3.1.2 software (Mathôt, Schreij, & Theeuwes, 2012). In total, participants performed four trials in the memory condition and four trials in the future simulation condition, which corresponded to the two sets of four events (see Figure 1a, b in the main manuscript). The order of the memory and future simulation phases were counter-balanced across participants. Within each phase, trials were presented in random order. For both the memory and future simulation phases, participants completed one practice trial with a different pair of pictures (corresponding to the inside of the laboratory building) in order to familiarize them with the entire procedure before starting the experimental trials.

Finally, immediately after having completed the two phases, participants had to complete a questionnaire that assessed their familiarity with each location and path they visited during the experiment (from 1 = not familiar, to 7 = very familiar).

Scoring of recalled/imagined contents. Verbal reports describing the mental re-experience or pre-experience of events consisted of a succession of moments of experience (here referred to as *experience units*) that represented the unfolding of events in chronological order (Jeunehomme et al., 2018, Jeunehomme & D’Argembeau, 2019, 2020). For example, a typical verbal description of past experience units started by “*I left the university building and turned right*” (first experience unit), "*then I saw a red car and a blue car on the parking*" (second experience unit), "*then, I walked along the building*" (third experience unit), and so on. Similar verbal descriptions also characterized imagined future events, for example: "*I imagine that I will leave the coffee shop and turn left*" (first experience unit), "*then I will probably see a man in front of the building*" (second experience unit), "*then, I will cross the pedestrian crossing*" (third experience unit), and so on.

Verbal reports of past and future events were segmented in distinct experience units by the first author based on indications of transitions or temporal discontinuities between reported moments of experience. For example, transitions from one remembered/imagined moment of past/future experience to another could be identified on the basis of verbal indicators (such as "*then*", "*next*", "*after that*") or moments of silence. Transitions between experience units often involved significant changes in actions, environmental elements, and/or thoughts (for example, "*I saw a student with a red bag in the hall* [of the university building]" followed by "*Once out of the building, I turned right while thinking of the way I should go to the bookstore*").

Each experience unit could include one or several pieces of information (here referred to as *unit components*) describing various aspects of this moment of past or future 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. (2018) and used in recent studies on temporal compression in episodic memory (Jeunehomme & D'Argembeau, 2019, 2020). More precisely, unit components were classified according to five mutually exclusive categories (i.e., person, object, thought, action with interaction, and spatial movement), with two additional categories coding for the presence of specific information about perceptual or spatial aspects of persons or objects (i.e., perceptual details and spatial details; see Table S1 for descriptions and examples of each category). Reported information that did not describe moments of past or future experience were classified as comments.

For past events, we verified the accuracy of reported information (thanks to the video taken by the wearable camera) and did not find any false memory in the recall protocols. However, a few components could not be verified because they involved elements outside the field of view of the camera.

All verbal reports were scored by the first author and the reliability of scoring was assessed by asking another trained rater to independently assess a random selection of 20% of events. The Intraclass Correlation Coefficient (ICC) computed on the number of experience units identified within verbal reports showed excellent agreement for both past events (ICC= 0.94) and future events (ICC= 0.95). ICCs for all categories of unit components constituting past events (persons, ICC = 0.75; objects, ICC = 0.72; thoughts, ICC = 0.71; actions with interaction, ICC = 0.79; spatial movements, ICC = 0.79; perceptual details, ICC = 0.85; and spatial details, ICC = 0.74) and future events (persons, ICC = 0.83; objects, ICC = 0.80; thoughts, ICC = 0.82; actions with interaction, ICC = 0.86; spatial movements, ICC = 0.79; perceptual details, ICC = 0.74; and spatial details, ICC = 0.70), showed good to excellent agreement (Cicchetti, 1994).

Table S1. Descriptions and examples of 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 judgment *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 color), 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 moments of experience *Examples: I always take a coffee in the morning.*

Statistical analyses. Because the assumptions underlying classical inferential methods were violated for our main measures of interest, we used robust statistical methods to analyze the 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 two-way repeated-measures ANOVAs using the 20% trimmed means. Effect sizes were estimated using the explanatory measure of effect size ξ: values of 0.10, 0.30, and 0.50 correspond to small, medium, and large effect sizes, respectively (Mair & Wilcox, 2019). These analyses were performed using the functions of Wilcox (2012) implemented in R (R Core Team, 2013). All descriptive statistics refer to the 20% trimmed means and their 95 % confidence intervals calculated using the percentile bootstrap method (with 2000 bootstrap samples; Wilcox, 2012).

To investigate the extent to which the density of experience units predicts temporal compression rates and event duration judgments, we conducted robust linear multilevel regression analyses. We fitted robust multilevel models (with trials as level 1 units and participants as level 2 units) with a by-subject random intercept and random slope; the random effects structure was simplified by removing the random effects correlation because otherwise the model failed to converge (Barr, Levy, Scheepers, & Tily, 2013). The density of experience units was cluster-mean centered (i.e., centered around each subject's own mean) to obtain an unbiased estimate of the within-subject association between the predictor and the outcome. These analyses were conducted using the package robustlmm in R (Koller, 2016). An alpha level of .05 was used for all analyses. The data of this study are available on OSF (https://osf.io/uny8r/).

Supplementary results

Actual duration of events in the past and future conditions. The average time (20% trimmed mean) taken by participants to perform actions was 1.17 min, 95%CI [0.93 – 1.45], in the past condition and 1.13 min, 95% CI [0.92 – 1.38], in the future condition, with no significant difference between the two temporal orientations, Yuen's $t = 0.19$, $p = 0.849$. Similarly, the average time needed to complete spatial displacements did not significantly differ between the past (20 trimmed mean = 1.52 min, 95% CI [1.40 – 1.66]) and future (20% trimmed mean = 1.54 min., 95% CI [1.41 – 1.70]) conditions, $t = 0.29$, $p = 0.777$.

Time to represent experience units within memories and future simulations. As indicated in the main text, the significant interaction between temporal direction and the density of experience units in predicting temporal compression rates suggests that it took proportionally more time to represent an experience unit when simulating future events than when remembering past events.

To further investigate this possibility, we estimated the duration of experience units within memories and future simulations by dividing the time it took to remember or imagine an event by the number of reported experience units. A Yuen's *t*-test for trimmed means showed that past experience units (20% trimmed mean = 2.77 seconds, 95% CI [2.33 – 3.22]) were shorter than future experience units (20% trimmed mean = 3.43 seconds, 95% CI [2.88 – 3.94]), $t = -3.73$, $p = .001$, $\xi = .33$.

Controlling for the effect of location familiarity on event compression rates. A robust two-way (type x set of events) repeated-measures ANOVA showed that the location of events was more familiar for spatial displacements than for actions, $Q = 39.89$, $p < .001$; there was no main effect of the set of events, $Q = 0.03$, $p = .853$, and no interaction, $Q = 0.93$, $p = .335$. To investigate whether differences in event compression rates between actions and spatial displacements were due to these differences in location familiarity, we conducted a multilevel regression analysis with compression rates as outcome variable and the type of events and familiarity of location as predictors. This analysis showed a significant effect of location familiarity (indicating that event compression rates decreased with increasing familiarity; $b = -0.11$, $SE = 0.05$, df = 214.02, $t = 2.38$, $p < .05$), but the effect of the type of events (actions vs. spatial displacements) remained significant ($b = 0.71$, $SE = 0.15$, df = 49.36, $t = 4.60$, $p < .001$); there was no interaction between location familiarity and the type of events ($b = -0.05$, $SE = 0.10$, df = 235.12, $t = 0.53$, $p = .60$).

Components within experience units. The average numbers of the different types of unit components reported for past and future events are presented on Figure S1. A robust two-way (temporal orientation x types of unit components) repeated-measures ANOVA yielded a main effect of temporal orientation, $Q = 18.28$, $p < .001$, and a main effect of the type of unit components, $Q = 247.79$, $p < .001$. Furthermore, the interaction was also significant, $Q = 12.40$, $p < .001$. Follow-up comparisons (using Yuen's *t*-tests) revealed that past events involved more persons ($t = 4.00$, $p < .001$, $\xi = .69$), thoughts ($t = 5.66$, $p < .001$, $\xi = .68$), and perceptual details ($t = 2.56$, $p = .019$, $\xi = .39$) than future events, whereas future events involved more spatial movements than past events ($t = 3.94$, $p < .001$, $\xi = .56$). There was no difference between past and future events for objects ($t = 0.24$, $p = .810$, $\xi = .04$), actions with interaction ($t = 0.65$, $p = .520$, $\xi = .14$), spatial details ($t = 0.44$, $p = .665$, $\xi = .08$), and comments ($t = 0.21$, $p = .836$, $\xi = .03$).

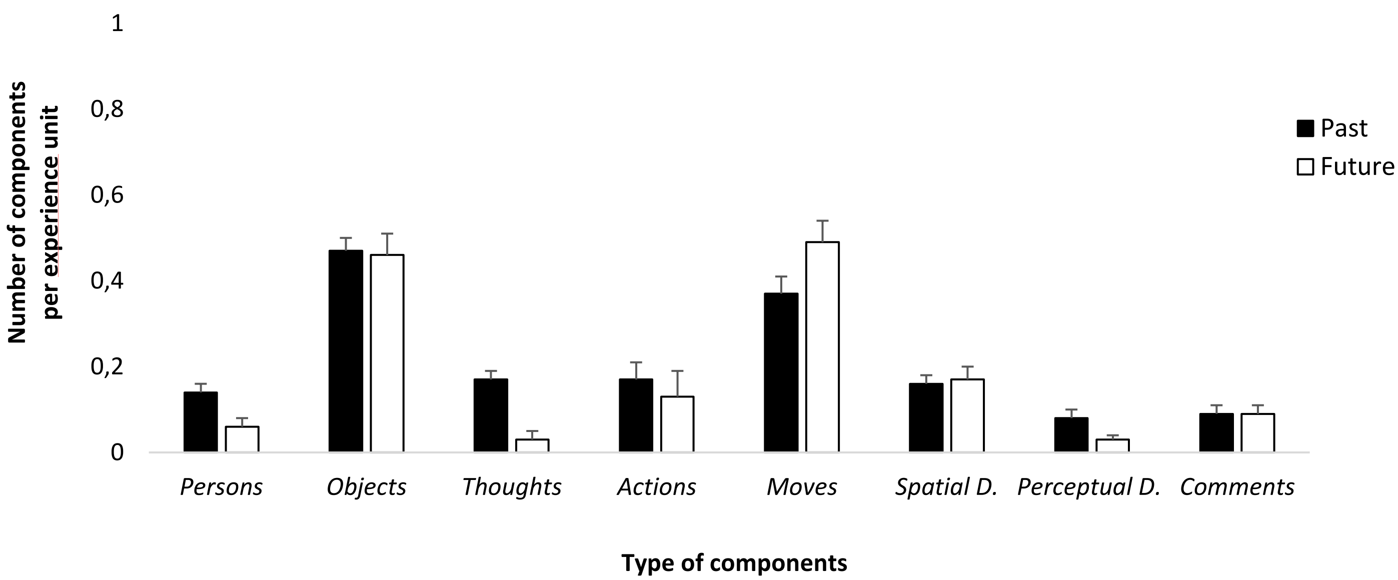

Figure S1. Number of components per experience unit describing past and future events. Bars represent the 20% trimmed means and error bars represent robust 95% CIs.

We also investigated whether the number of components reported per experience unit predicted event compression rates within memories and future thoughts. To do so, we conducted a robust multilevel regression analysis, with temporal compression rates as outcome variable and the density of experience units and temporal orientation of events as predictors. The effect of temporal orientation was significant (*b* = 0.46, *SE* = 0.16, df = 31.56, $t = 2.93$, $p < .01$), showing that compression rates were higher for future than past events, but the effect of unit components was not significant (*b* = 0.32, *SE* = 0.25, df = 213.87, $t = 1.26$, $p = .21$), and there was no interaction between temporal orientation and unit components (*b* = -0.51, *SE* = 0.41, df = 205.33, $t = 1.25$, $p = .21$).

Vividness and feeling of (p)re-experience. Although not the primary aim of the present study, we also examined whether the vividness of mental representations and the subjective feeling of re-experiencing or pre-experiencing events differed depending on temporal orientation and the nature of events. A robust two-way repeated-measures ANOVA revealed that the vividness of remembered events was higher than the vividness of imagined future events, $Q = 25.65$, $p < .001$, $\xi = .53$ (see Table S2). The main effect of the type of events was not significant, $Q = 0.45$, $p = .504$, but there was a significant interaction between temporal orientation and the type of events, $Q = 12.49$, $p < .001$, showing that when events involved a specific action to accomplish, the vividness of event representations was higher for past than future events ($t = 6.91$, $p < .001$, $\xi = .64$), whereas no significant difference was found between past and future events that involved a spatial displacement ($t = 1.74$, $p = .098$, $\xi = .32$).

As for the feeling of (p)re-experience, a robust two-way repeated-measures ANOVA showed a main effect of temporal orientation, $Q = 15.10$, $p < .001$, $\xi = .49$, no main effect of the type of events, $Q = 0.88$, $p = .347$, and a significant interaction between the temporal orientation and type of events, $Q = 4.34$, $p = .037$. For both actions and spatial displacements, the feeling of re-experience was higher than the feeling of pre-experience, but the interaction indicated that this difference was higher for actions (t = 4.08, p < .001, ξ = 46) than spatial displacements (t = 2.48, p = .023, ξ = 29).

Table S2. Subjective characteristics of past and future event representations

	Past		**Future**	
	Actions	***Spatial displacements***	***Actions***	***Spatial displacements***
	Trimmed mean [95% CI]	*Trimmed mean [95% CI]*	*Trimmed mean [95% CI]*	*Trimmed mean [95% CI]*
Vividness	4.09 [4.50 – 5.30]	4.32[3.93 – 4.83]	3.53 [3.10 – 4.00]	3.90 [3.60 - 4.18]
Feeling of mental time travel	4.58 [4.15 - 5.10]	4.18 [3.75 - 4.58]	3.60 [3.18 – 4.10]	3.68 [3.35 - 4.13]

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