Memory editing: the role of temporal discontinuities in the compression of events in episodic memory

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The design of this study, the analysis plan, and all hypotheses were preregistered at https://osf.io/3s46f. All data, analysis code, and research materials are available at https://osf.io/wnpr5/.

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Abstract

Why does it take less time to remember an event than to experience it? Recent evidence suggests that the dynamic unfolding of events is temporally compressed in memory representations, but the exact nature of this compression mechanism remains unclear. The present study tested two possible mechanisms. First, it could be that memories compress the course of events into a sequence of moments or slices of prior experience, while omitting other segments—akin to edited films that give condensed accounts of events using sequences of separate shots (referred to as the *discontinuity hypothesis*). Alternatively, it may be that the entire stream of information is represented, but mentally replayed at a faster speed than the original experience (referred to as the *acceleration hypothesis*). In two preregistered experiments, these hypotheses were tested by comparing mental replay times for continuous movies depicting naturalistic events and edited versions of the same movies in which less informative parts were removed to mimic the presumed structure of memory representations according to the discontinuity hypothesis. We found that memories for videos in which less informative segments were replaced by temporal ellipses (Experiment 1), or by black screens of the same duration as removed segments (Experiment 2), were less compressed and contained a higher density of recalled units than memories for complete videos. These results support the discontinuity hypothesis and suggest that segments of time that are redundant and predictable are omitted in episodic memory, while more informative segments are selectively retained to represent the unfolding of events.

Keywords: Episodic memory, temporal compression, event segmentation, time

Efficient data compression is essential for the functioning of capacity-limited systems such as human memory (Bates & Jacobs, 2020). In the domain of episodic memory, a key question is how dynamic events that unfold over time are stored and retrieved (Baldassano et al., 2017; Conway, 2009; Zacks, 2020). Recent studies have shown that the time needed to recall an event is generally shorter than the actual duration of the corresponding episode, suggesting that the course of events is temporally compressed in memory representations (Bonasia et al., 2016; Chen et al., 2017; Jeunehomme & D'Argembeau, 2019; Michelmann et al., 2019; Faber & Gennari, 2015). This time-compressed replay is a hallmark feature of memory for naturalistic events that has also been observed in non-human primates (Zuo et al., 2020). However, little is known about how the unfolding of events is condensed in memory representations.

Cognitive and neural evidence indicates that the structure of episodic memories depends on event segmentation processes (for reviews, see Brunec et al., 2018; Clewett et al., 2019; Radvansky & Zacks, 2017; Zacks, 2020). In daily life, we encounter a continuous flow of information that we interpret by breaking it down into meaningful units. Changes in various dimensions of ongoing experience (e.g., locations, characters, objects, actions, and goals) trigger the perception of event boundaries (Zacks et al., 2007), which determine the chunking of information into discrete units (Clewett et al., 2019; Radvansky & Zacks, 2017). This structure of event perception has direct consequence for memory: parts of the sensory stream that correspond to event boundaries are better retained (Baird & Baldwin, 2001; Newtson & Enquist, 1976; Swallow et al., 2009) and serve as anchors for memory organization (Dubrow & Davachi, 2013; Horner et al., 2016; Radvansky & Copeland, 2006).

We have recently proposed a cognitive model of memory compression that builds on these event segmentation processes and posits that the temporal compression of naturalistic events occurs because some event segments are omitted, either during encoding or retrieval

(D’Argembeau et al., in press; Jeunehomme et al., 2018; see also Michelmann et al., 2019). The retained segments would be those corresponding to highly informative regions of the stream of activity (corresponding to event boundaries; Baldwin & Kosie, 2021; Zacks, 2020), whereas less informative regions would be discarded, resulting in temporal gaps in event representations. Consequently, the extent of memory compression would depend on the amount of temporal gaps in the representation of the course of events—a possibility that we refer to here as the *discontinuity hypothesis*. Another possibility would be that the entire stream of information is represented, but mentally replayed at a faster speed than the original experience—what we refer to here as the *acceleration hypothesis*. Metaphorically speaking, the discontinuity hypothesis conceives of memories as edited films while the acceleration hypothesis assumes that memories are akin to continuous video recordings played in fast forward mode.

The discontinuity hypothesis arose from the analysis of verbal reports on memory contents. When describing memories of real-life events, people typically report a succession of slices of past experience with temporal discontinuities, as if they were mentally “jumping” from one moment of experience to another without representing everything that happened in between (Jeunehomme et al., 2018; Jeunehomme & D’Argembeau, 2020). It remains possible, however, that the omitted segments were remembered but were not mentioned in the verbal reports. Other evidence in support of the discontinuity hypothesis comes from recent magnetoencephalography and response time data showing that event boundaries serve as steppingstones to skip certain segments during event recall (Michelmann et al., 2019, 2021). However, direct evidence for the role of temporal discontinuities in memory compression is still limited.

The current work aims to test the discontinuity hypothesis by comparing mental replay times for continuous and edited movies depicting naturalistic events. Our goal was to create stimuli that mimic the structure of memory representations assumed by the discontinuity hypothesis, and to investigate the impact of this manipulation on memory compression rates. Film editing techniques use cuts as a tool to effectively summarize the narrative, by leaving out certain parts of the depicted events (Levin & Baker, 2017; Magliano & Zacks, 2011; Schwan & Garsoffky, 2004). For example, one shot might show a person approaching a car and the next shot might show them in the car starting the engine, without the need to show all subevents (e.g., getting into the car) for viewers to understand the scene. We reasoned that if events are similarly condensed in memory representations, edited movies that leave out less informative segments of the sensory stream should be less compressed in memory than intact movies, because the deleted parts in edited movies correspond to segments that would normally be omitted in the memory representations, creating temporal gaps. In other words, the mental replay of an edited video would take proportionally more time than that of an intact video relative to their actual duration. By contrast, if the entire sensory stream is represented in memory, but mentally replayed at a faster speed than the original experience (as per the acceleration hypothesis), and that similar compression rates apply to intact and edited movies, then recall of the two types of videos should take proportionally the same amount of time relative to their actual duration. We conducted two preregistered experiments to test these hypotheses.

Experiment 1

In Experiment 1, participants were asked to mentally replay a series of videos depicting people performing daily life activities. Two versions of the videos were used, in a between-subjects design: half of the participants saw the complete unfolding of the activity (i.e., intact videos), whereas the other half saw videos in which less informative segments of the activity were cut and replaced by temporal ellipses. If the discontinuity hypothesis is correct, memory compression rates (i.e., the time needed to mentally replay the video relative to the actual stimulus duration) should be smaller for edited videos than for intact videos.

Method

Participants. We recruited 40 students aged between 18 and 30 years in each experimental condition (i.e., complete vs edited videos), resulting in a total of 80 participants. This sample size was determined a priori using G*Power 3 (Faul et al., 2007) to have a statistical power of 0.80 (with an alpha of .05, two-tailed) to detect between-group differences with an effect size *d* = 0.60. The effect size was estimated by computing the mean effect size observed in previous studies comparing differences in temporal compression rates across different types of events (Jeunehomme & D'Argembeau, 2019, 2020). We opted for a between-subjects design because presenting both experimental conditions to the same participants could potentially induce inferences on experimenter demands (e.g., participants might come to believe that memories should be shorter for edited than complete videos), which we wanted to avoid. Participants were randomly assigned to one of the two conditions. Following our pre-registered analysis plan, ten participants (six in the complete condition and four in the ellipse condition) were excluded and replaced by other participants. Five participants were excluded because of technical issues with the presentation of videos (i.e., videos were presented slower than their actual duration) and five participants because their mental replay times suggested that they did not respect experimental instructions (i.e., mental replay times < 2 s). The final sample consisted of 80 participants (45 females; mean age = 23 years, *SD* = 3.07). All participants provided written informed consent and the study was approved by the Ethics Committee of the Faculty of Psychology of the University of Liège (ref. 1920-105).

Materials. Five videos depicting a continuous sequence of actions performed by a person during daily life activities (e.g., gardening, grocery shopping) were selected from the studies of Smith et al. (2020, 2021). For each activity, two film versions were used: the complete video and an edited version of the same video. In the edited version, some parts of the movie were cut and replaced by ellipses. For example, the full video about grocery shopping began by showing a person entering the grocery store, walking to the aisles, and then selecting a first item. In the ellipsis version of this video, the action of walking through the aisles was replaced with a temporal ellipsis, so that the video shows the person entering the grocery store and then directly choosing an item from the aisle. The number and placement of ellipses was determined based on a pilot study in which 10 participants (5 females; mean age = 25 years, *SD* = 2.52) had to mentally replay the complete version of the videos and to describe their memories. For each video, actions that were reported by fewer than half of the participants (and thus were presumably not represented during event recall, according to the discontinuity hypothesis) were removed and replaced by ellipses.[1] The number and duration of removed segments are detailed in Table 1 and the stimuli are available on OSF (https://osf.io/wnpr5/). Each removed segment was replaced by an ellipsis consisting of a 1-s (30 frames) black screen, with transitions between the movie and the ellipses being smoothed using a 0.33 second (10 frames) progressive smoothing.

Table 1. Duration of videos in Experiment 1 and number and mean duration of ellipses

	Complete	Ellipsis			
Video	Video duration	Video duration	Number of ellipses	Mean duration of ellipses	Range
Gardening	00:04:51	00:02:28	23	00:00:07	00:00:12
Grocery	00:03:01	00:01:54	10	00:00:08	00:00:12
Video game	00:04:28	00:02:18	12	00:00:12	00:00:27

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[1] Note that segmentation data were available for three of the videos we used (i.e., Gardening, Grocery, and Getting ready; Smith et al., 2020), which allowed us to examine whether the frequency of event boundaries differed between the parts of the videos that were retained or deleted when constructing the edited versions. We found that the mean proportion of event segmentation points (i.e., the frequency of button presses per second) was higher for parts of the videos that were retained (0.31, 95% CI [0.29 – 0.34]) than for parts that were removed (0.22, 95% CI [0.19 – 0.24]) in the edited versions, thereby suggesting that these followed the segmental structure of events.

Printer	00:02:28	00:01:26	9	00:00:08	00:00:11
Getting ready	00:03:33	00:02:22	13	00:00:06	00:00:13

Procedure. In the two experimental conditions, each trial began with the presentation of a fixation cross on the computer screen (for a duration of 3 s), followed by the presentation of a video (see Figure 1). Participant were instructed to watch the video carefully and to pay attention to all actions that the person performs in the video. Once the video was finished, participants had to mentally re-experience the unfolding of the video in as much detail as possible (and not as quickly as possible). In addition, they were instructed to press the "SPACEBAR" to indicate that they started to mentally re-experience the video and once again when they were done, so that the duration of their mental replay was measured. Immediately after the mental re-experience of the video, participants were invited to describe, as accurately and faithfully as possible, all the actions that came to their mind during their mental replay of the video. A field was presented on the computer screen for participants to write down all the actions they remembered. They were asked to write each action on a different line by pressing the "ENTER" key to move from one line to the next. Moreover, they were asked to only report the actions that they had re-experienced during the mental replay phase and no additional action that they might recall during the writing phase. Finally, participants had to press a red button displayed under the writing area to begin the next trial. In the ellipsis condition, two additional instructions were provided. First, participants were instructed to ignore the temporal ellipses during the viewing of the videos. Second, they were asked not to recall (and thus report) the temporal ellipses but only the actions that happened in the videos.

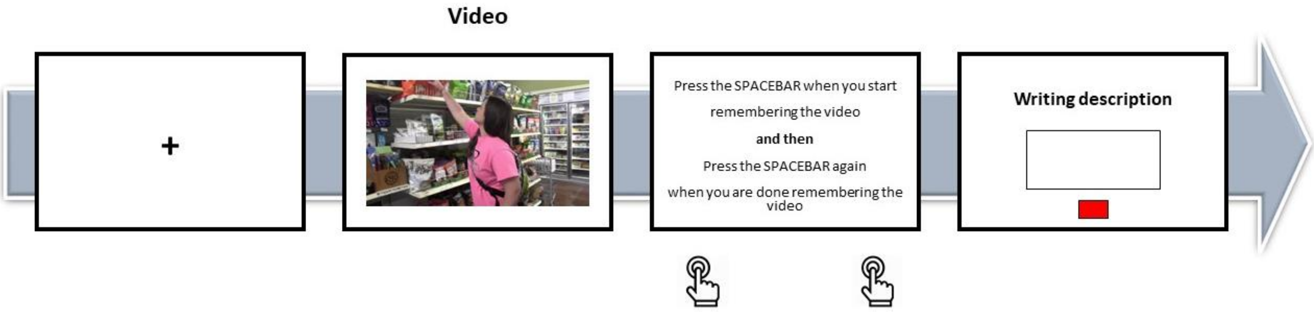

Figure 1. Illustration of the memory task. For each trial, participants first watched a video (either a complete or an ellipsis version). Then, they mentally replayed the video and indicated the start and the end of their mental replay. Finally, they described every action they remembered while mentally replaying the video.

The task was performed individually on the Gorilla online experience platform (https://gorilla.sc/), which provides a reliable video display and high-precision reaction time recording (for evidence supporting the effectiveness of the Gorilla platform in collecting online RT data, see Anwyl-Irvine et al., 2020). All the instructions were given by the experimenter via videoconference.

Before starting the experimental trials, participants completed one practice trial with a different video (either a complete video or a video involving temporal ellipses, depending on the experimental condition), to familiarize them with the entire procedure. This practice trial was followed by a discussion with the experimenter to ensure that participants understood all the instructions before starting the experimental trials. In each condition, the five videos constituting the experimental trials were presented in random order.

Scoring of memory descriptions. When reporting the content of their memories, participants were asked to write each action they recalled on a separate line. When scoring reported actions, the first author thus scored ‘1’ when a line involved an action and ‘0’ otherwise (e.g., when the line referred to descriptions of the environment or persons but did not include an action). Furthermore, when participants inadvertently described two actions on the same line (which was rare), each action was credited with a score of '1'. No partial credit was given and no false recall (i.e., actions that were not represented in the videos) was identified in the descriptions. The number of recalled actions was then tallied for each trial. All memory descriptions were scored by the first author and the reliability of scoring was assessed by asking another trained rater, who was blind to the experimental conditions and hypotheses of the study, to independently assess a random selection of 10% of the trials. The Intraclass Correlation Coefficient (ICC) computed on the number of actions identified for each trial showed an almost perfect agreement between the two raters (ICC= 0.993).

Predictions and statistical analyses. If the discontinuity hypothesis is correct, the following observations should be made when comparing memories for the two types of videos. First, temporal compression rates (i.e., the time needed to mentally replay the video relative to the actual stimulus duration) should be smaller for edited videos than for intact videos. Second, although the total number of recalled actions may be smaller for edited videos than for intact videos (because the edited versions contain fewer actions overall), the density of recalled actions (i.e., the number of actions recalled per unit of time of the actual video duration) should be higher for edited videos than for intact videos because the former include proportionally more informative regions of the sensory stream. Finally, we expected that estimates of the time needed to remember an action would be similar between intact and edited videos; in other words, editing videos by removing less informative segments should affect the rate of temporal compression and density of recalled actions but not the representation of individual actions per se.

Because the distribution of our main measure of temporal compression was significantly skewed, assumptions underlying classical inferential methods were violated. Thus, following our preregistration, 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 precisely, we conducted a series of Yuen's tests for two independent groups using 20% trimmed means and the bootstrap-t method (Wilcox, 2012). 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, 2020). 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 predicted temporal compression rates, we also conducted robust mixed-effects regression analyses. We fitted a robust mixed-effects model with compression rates as outcome and density as predictor, as well as a by-subject and a by-video random intercept. 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 performed using the functions of Wilcox (2012) and the robustlmm package (Bates et al., 2015) implemented in R (R Core Team, 2013).

Transparency and openness. We preregistered the design of this experiment, the analysis plan, and all hypotheses on OSF (https://osf.io/3s46f). We report how we determined our sample size, all data exclusions, all manipulations, and all measures. All data, analysis code, and research materials are available on OSF (https://osf.io/wnpr5/).

Results

In total, the experiment included 400 trials (5 trials for each of the 80 participants). However, 17 trials (10 in the complete condition and 7 from ellipsis condition) were excluded from the analyses because of technical issues with video presentation or no respect of experimental instructions (i.e., trials for which response times were less than 5 seconds, which was considered too fast to correspond to the mental replay of the video; this exclusion criterion was preregistered), leaving 383 trials for the following analyses.

Temporal compression of memory replay. The rate of temporal compression of videos during memory replay was estimated as the ratio of the actual video duration to the duration of its mental replay. Mean compression rates for videos (20% trimmed means, with their 95% CI) in the complete and ellipsis conditions are presented on Figure 2A. Consistent with our prediction, a Yuen's *t*-test showed that temporal compression rates were higher for complete videos than for ellipsis videos, $t = 1.97$, $p = .017$, $\xi = .36$.

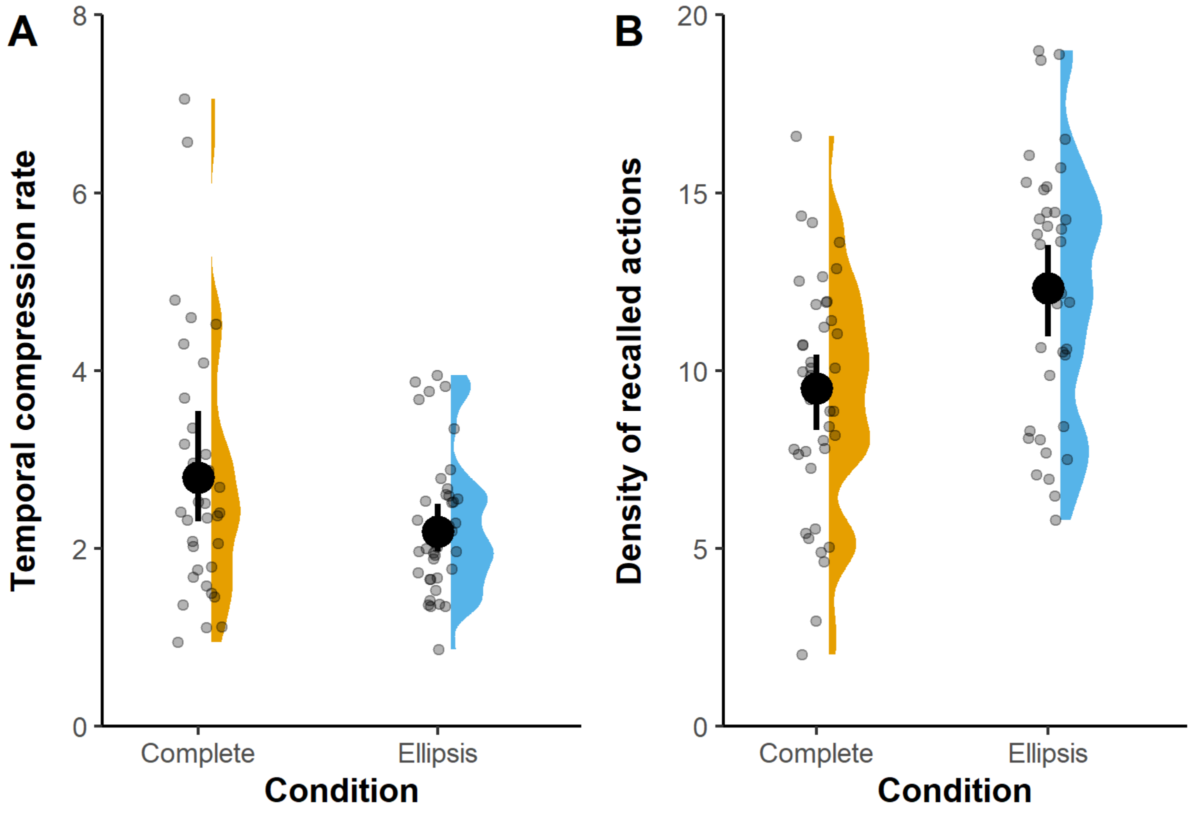

Figure 2. Rates of temporal compression and densities of recalled actions in the complete and ellipsis conditions in Experiment 1. (A) Temporal compression is estimated as the ratio of the video duration to the time needed to mentally re-experience this video. (B) The density of recalled actions corresponds to the number of recalled actions per minute of the video. Raincloud plots show the distribution of the data and point-range plots represent the 20% trimmed means and their 95% robust confidence intervals.

Number and density of recalled actions. On average, participants reported 33.57 actions per video in the complete condition, 95% CI [29.21, 37.12], and 25.87 actions per video in the ellipsis condition, 95% CI [22.92, 28.65]. A Yuen's *t*-test showed that participants recalled more actions for complete than ellipsis videos, $t = 3.14$, $p < .001$, $\xi = .47$.

To assess the density of recalled actions from the videos, we computed the number of reported actions per unit of time (i.e., per minute) of each video. The mean density of recalled actions in the two experimental conditions are shown on Figure 2B. Consistent with our prediction, a Yuen's *t*-test revealed that the density of recalled actions was higher for ellipsis videos than for complete videos, $t = -3.28$, $p = .003$, $\xi = .51$.

We also estimated the time taken by participants to remember each action by dividing the duration of mental replay by the number of recalled actions. On average, participants took 2.85 seconds to remember an action in the complete condition, 95% CI [2.57, 3.19], and 2.77 seconds in the ellipse condition, 95% CI [2.48, 3.06]. A Yuen's *t*-test showed that this difference was not statistically significant, $t = 0.39$, $p = .711$, $\xi = .06$.

Although not part of our preregistered analyses, we also examined to what extent the actions recalled in the complete condition corresponded to parts of the videos that were retained or deleted in the ellipsis condition. On average, 85.9% of recalled actions in the complete condition, 95% CI [84.4%, 87.2%], referred to parts of the videos that were retained in the ellipsis condition, whereas only 14.1%, 95% CI [12.8%, 15.6%], referred to parts that were deleted. A Yuen's *t*-test confirmed that recalled actions in the complete condition referred more frequently to parts of the videos that were also depicted in the ellipsis condition, $t = 74.72$, $p < .001$, $\xi = .93$.

Relationship between temporal compression rates and the density of recalled actions. Previous studies on memory for real-life events have shown that the rate of event compression in memory is inversely related to the density of recalled experience units (Folville et al., 2020; Jeunehomme & D'Argembeau, 2019; Jeunehomme et al., 2020. Although it was not planned in our pre-registered analyses, we examined whether we could replicate this result using video stimuli. We thus conducted a robust mixed-effects regression analysis with compression rates as outcome and the density of recalled actions as predictor (see Methods). We found that the density of recalled actions was a significant predictor of temporal compression rates for both complete videos ($b = -0.13$, $SE = 0.03$, $t = 4.18$, $p < .001$) and ellipsis videos ($b = -0.06$, $SE = 0.02$, $t = 4.09$, $p < .001$)[2].

Discussion

Experiment 1 aimed to test the discontinuity hypothesis by determining whether removing less informative segments of continuous videos depicting daily-life activities reduces temporal compression rates when mentally replaying these videos. As predicted, we found that memories for the ellipsis versions of the videos were less compressed than memories for the complete versions. Furthermore, memories contained a higher density of recalled actions

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[2] It should be noted that the proportion of deleted segments in the edited videos (as measured by the ratio of the duration of the edited version to the duration of the complete version) differed somewhat across videos (i.e., Gardening: .51, Grocery: .64, Video game: .51, Printer: .58, Getting ready: .67). To examine whether this influenced the temporal compression of memories for edited videos, we performed an additional mixed-effects regression analysis, with compression rates as outcome and duration ratios as predictor. We found that duration ratios were a significant predictor of temporal compression rates for ellipsis videos ($b = -2.78$, $SE = 0.72$, $t = 3.87$, $p < .001$). Importantly, however, when adding duration ratios as predictor in the model that included compression rates as outcome and the density of recalled actions as predictor, we found that the density of recalled actions remained a significant predictor of compression rates ($b = -0.06$, $SE = 0.02$, $t = 3.74$, $p < .001$).

(i.e., more actions recalled per unit of time of the actual video duration) in the ellipsis condition than in the complete video condition, and recalled actions in the complete condition mainly referred to parts of the videos that were retained in the ellipsis versions. In line with previous studies (Follville et al., 2020; Jeunehomme & D'Argembeau, 2019; Jeunehomme et al., 2020), the rate of temporal compression during mental replay was predicted by the density of recalled actions. Importantly, however, estimates of the time needed to remember an action were similar in the two conditions, showing that our manipulation influenced the quantity of recalled actions but not the representation of individual actions per se. Overall, these results support the idea that the temporal compression of continuous events in episodic memory occurs, at least in part, through the omission of certain segments of experience, so that the representation of the time course of events contains temporal discontinuities.

Experiment 2

One limitation of Experiment 1 is that videos were shorter in the ellipsis condition than in the complete condition, because some segments were replaced by ellipses of a standard duration of one second. Given recent evidence that temporal compression in episodic memory tends to increase with the length of events (Jeunehomme & D'Argembeau, 2019), the lower compression rates that were observed for the ellipsis versions could be due to their shorter duration rather than the editing manipulation per se. To rule out this possibility, in Experiment 2, we created edited versions of the videos in which the deleted segments of the movies were replaced by black screens of the same duration, so that the total duration of the complete and edited videos was equivalent. As in Experiment 1, we predicted that temporal compression rates would be lower, and that the density of recalled actions would be higher, for edited videos than for complete videos.

Method

Participants. As in Experiment 1, we planned to recruit 80 students aged between 18 and 30 years (i.e., 40 participants in each experimental condition), to achieve a statistical power of 0.80, considering an alpha error of .05 and an effect size of 0.60. Following our pre-registered analysis plan, 10 participants (7 in the complete condition and 3 in the black screen condition) were excluded and replaced by other participants: three participants because of technical issues with video presentation and seven participants because of short mental replay durations (< 2 seconds). The final sample consisted of 80 participants (46 females; mean age = 22 years, *SD* = 3.24 years). All participants provided written informed consent and the study was approved by the Ethics Committee of the Faculty of Psychology of the University of Liège (ref. 1920-105).

Materials and procedure. The experimental procedure was the same as Experiment 1, except that the videos were edited by presenting a black screen of the same duration as deleted segments rather than 1-s ellipses. For example, in the video about grocery shopping, the deleted segment showing a person walking through the aisles that lasted 15 s in the complete video was replaced by a black screen of 15 s in the edited version of the video. As a result, the intact and edited versions had exactly the same duration. The number and placement of black screens in each video were exactly the same as for temporal ellipses in Experiment 1. The stimuli are available on OSF (https://osf.io/wnpr5/).

Scoring of memory descriptions. Participants who viewed the edited videos were instructed to omit the black screens during the memory task. As expected, there was no mention of the black screens in the written descriptions of memories, suggesting that these instructions were correctly followed. All actions reported in the memory descriptions were scored by the first author using the same criteria as in Experiment 1 and the reliability of scoring was assessed by asking another trained rater, who was blind to the experimental conditions and hypotheses of the study, to independently assess a random selection of 10% of the trials. The ICC showed an almost perfect agreement between the two raters (0.998).

Transparency and openness. We preregistered the design of this experiment, the analysis plan, and all hypotheses on OSF (https://osf.io/3s46f). We report how we determined our sample size, all data exclusions, all manipulations, and all measures. All data, analysis code, and research materials are available on OSF (https://osf.io/wnpr5/).

Results

From the 400 trials that were presented, 20 trials (11 from the complete condition and 9 from the black condition) were excluded from the analyses because of technical issues with video presentation or no respect of experimental instructions (response times < 5 seconds), leaving 380 trials for the analyses.

Temporal compression of memory replay. As in Experiment 1, temporal compression rates were estimated as the ratio of the actual video duration to the duration of its mental replay. In the black-screen condition, these estimates were calculated after removing the duration of the black screens from the stimulus duration, so that only the segments when the movie was presented were included in our measurement. Mean compression rates for videos in the complete and black-screen conditions are shown on Figure 3A. A Yuen's *t*-test showed that temporal compression rates were higher for the complete condition than for the black-screen condition, $t = 2.44$, $p = .017$, $\xi = 0.38$.

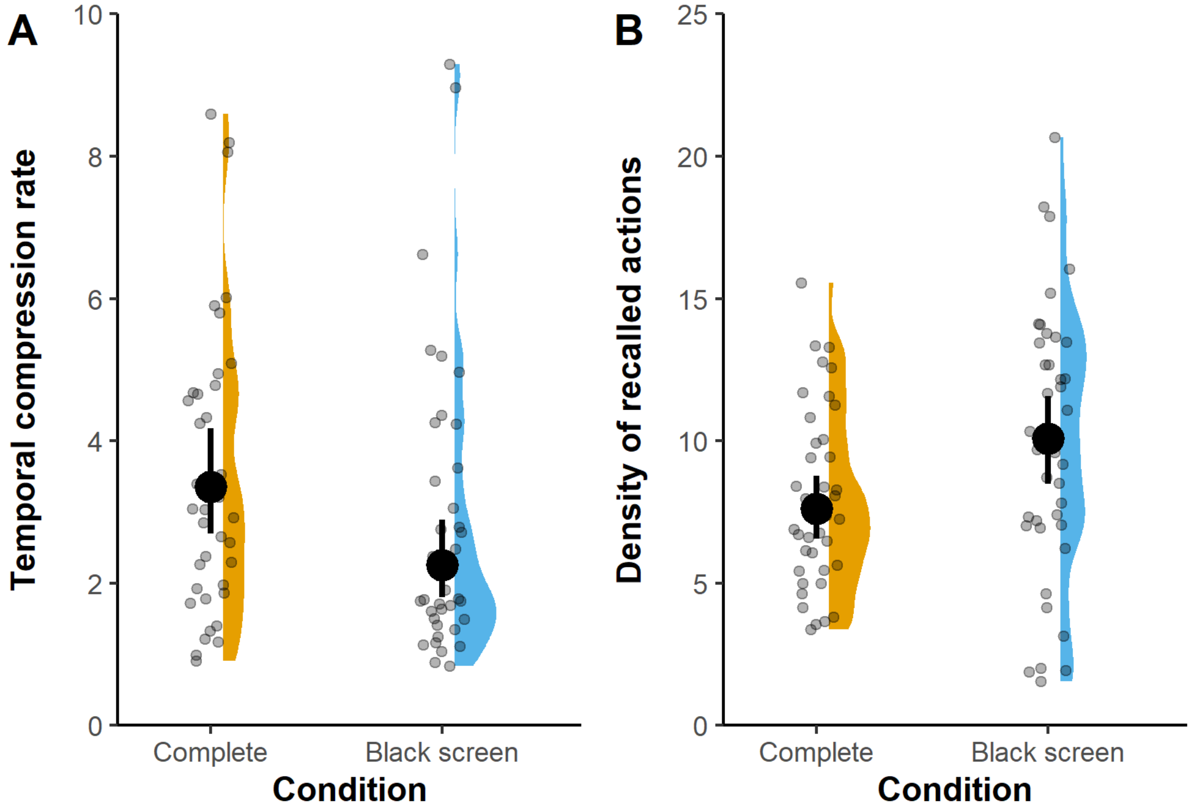

Figure 3. Rates of temporal compression and densities of recalled actions in the complete and black screen conditions in Experiment 2. (A) Temporal compression is estimated as the ratio of the video duration to the time needed to mentally re-experience this video. (B) The density of recalled actions corresponds to the number of recalled actions per minute of the video. Raincloud plots show the distribution of the data and point-range plots represent the 20% trimmed means and their 95% robust confidence intervals.

Number and density of recalled actions. On average participants recalled 27 actions per video in the complete condition, 95% CI [23.27, 31.05], and 21.76 actions per video in the black screen condition, 95% CI [18.77, 24.96]; a Yuen's *t*-test showed that this difference was statistically significant, $t = 2.11$, $p = .033$, $\xi = 0.35$. On average, 86.3% of recalled actions in the complete condition referred the parts of the videos that were depicted in the black screen condition, 95% CI [83.7%, 88.8%], whereas only 13.7% referred to parts that were replaced by black screens, 95% CI [11.2%, 16.3%]. A Yuen's *t*-test confirmed that recalled actions in the complete condition referred more frequently to parts of the videos that were also depicted in the black screen condition, $t = 38.36$, $p < .001$, $\xi = .94$.

The density of recalled actions was estimated as the number of recalled actions per minute of the actual video duration. For the black-screen condition, this estimate was computed after removing the duration of black screens, so that only the segments when the movie was presented were considered. Mean densities of recalled actions in the two experimental conditions are shown on Figure 3B. A Yuen's *t*-test revealed that the density of recalled actions was higher for black-screen videos than for complete videos, $t = - 2.66$, $p = .027$, $\xi = 0.40$.

We also estimated the time taken by participants to remember an action. On average, participants took 3.10 seconds to remember an action in the complete condition, 95% CI [2.73, 3.53], and 3.07 seconds in the ellipse condition, 95% CI [2.62, 3.64], a difference that was not statistically significant according to a Yuen's *t*-test, $t = 0.09$, $p = .808$, $\xi = .01$.

Relationship between temporal compression rates and the density of recalled actions. As in Experiment 1, we also conducted a robust mixed-effects regression analysis to examine whether rates of video compression during mental replay were predicted by the density of recalled actions. We found that the density of recalled actions was a significant predictor of temporal compression rates for both complete ($b = -0.13$, SE = 0.05, $t = -2.88$, $p = .005$) and black screen videos ($b = -0.09$, SE = 0.02, $t = -5.04$, $p < .001$)[3].

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[3] As in Experiment 1, the proportion of deleted segments in the edited videos (i.e., the ratios of the duration of the edited version to the duration of the complete version) was a significant predictor of temporal compression rates for black screen videos ($b = -1.49$, $SE = 0.71$, $t = 2.11$, $p = .037$). However, adding duration ratios as predictor in the model that included compression rates as outcome and the density of recalled actions as predictor

Additional analyses when including the duration of black screens. Our main pre-registered hypothesis was that temporal compression rates would be smaller for edited videos than for complete videos, when excluding the duration of black screens (i.e., when considering only the segments in which the movie was presented). However, we also noted that if the video segments that were replaced by black screens were completely omitted during the mental replay of the intact videos, the compression rates would be similar between the two types of videos when compression is calculated based on the total stimulus duration (i.e., including the segments in which black screens were presented). This was a strong assumption, as it supposed that none of the information presented in the segments corresponding to black screens would be recalled during the mental replay of intact videos. In fact, when the duration of the black screens was included in the calculation of temporal compression, compression rates were higher for the black-screen videos than for the complete videos, $t = 2.07$, $p = .030$, $\xi = 0.38$. In the same vein, the estimated density of recalled actions was now higher for black screen videos than for complete videos, $t = 2.13$, $p = .030$, $\xi = 0.36$. This suggests that although the video segments corresponding to black screens were less likely to be recalled, they were not completely omitted during the mental replay of the intact videos.

Discussion

Experiment 2 replicates the results of Experiment 1 while ruling out the possibility that the observed differences in compression rates and recalled action density between edited and intact videos were due to differences in stimulus duration. As in Experiment 1, we also found

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did not change the effect of the density of recalled actions on compression rates ($b = -0.09$, $SE = 0.02$, $t = 5.04$, $p < .001$).

that the time needed to remember an action was equivalent between the two types of videos and that temporal compression was predicted by the density of recalled actions.

General discussion

Although there is growing evidence that episodic memories represent the dynamic unfolding of events in a condensed form, the exact nature of this compression mechanism remains unclear. To address this question, we investigated whether omitting certain parts of the sensory stream mimics the process by which the course of naturalistic events is temporally compressed in memory representations. We found that memories for videos in which less informative segments were replaced by temporal ellipses (Experiment 1), or by black screens of the same duration as removed segments (Experiment 2), were less compressed and contained a higher density of recalled units than memories for complete videos. This suggests that complete videos were not replayed in their entirety, but that people omitted some video segments when remembering the course of events. In both experiments, we also replicated previous results that the density of recalled moments of experience predicts memory compression rates (Folville et al., 2020; Jeunehomme & D’Argembeau, 2019; Jeunehomme et al., 2021).

These results support the discontinuity hypothesis rather than the acceleration hypothesis as a mechanism for event compression in episodic memory: Memories compress the course of events into a sequence of moments or slices of prior experience, while omitting other segments. In this sense, memories are akin to edited films that give condensed accounts of events using sequences of separate shots, with each shot showing a certain section of space and time, while maintaining a sense of continuity in the unfolding of events (Levin & Baker, 2017; Magliano & Zacks, 2011; Schwan & Garsoffky, 2004). This compression mechanism is possible because naturalistic events contain redundancy—some parts of events are less informative than others. For example, the visual system can use regularities that occur in the spatial structure of natural images to encode inputs in compacted representations (Storrs & Fleming, 2021). In the same vein, the continuous flow of experience is temporally structured, alternating between periods of stability (perceived by observers as events) and periods of change (perceived as boundaries between events) (Zacks et al., 2007; Baldassano et al., 2017). Informational redundancy within events can thus be used to encode experience in a compressed form: Segments of time that are redundant and predictable can be omitted, while processing resources selectively encode informative segments (Baldwin & Kosie, 2021). To further test this hypothesis, it would be interesting in future research to investigate whether the amount of perceptual change in videos depicting naturalistic events (e.g., as quantified by a convolutional neural network) can predict rates of memory compression, as has recently been shown for duration judgments (Roseboom et al., 2019).

An important question is the extent to which the temporal compression of events is a property of episodic memory traces or reflects the selection of stored information during a given retrieval act. The current study does not allow us to draw definitive conclusions in this regard, as we do not have direct access to the representational format of information stored in memory. However, due to the limited capacity of the cognitive system, the continuous flow of sensory inputs cannot be perceived and memorized in an exhaustive way, and compression offers an efficient adaptation to capacity limits (Bates & Jacobs, 2020). Thus, we believe that the observation of temporal discontinuities during event recall reflects, at least in part, the structure of episodic memory traces (i.e., not all segments of past episodes are stored in memory). In support of this view, previous studies have shown that attention is not consistently deployed over the course of dynamic events; people selectively attend to highly informative regions of the sensory stream, while decreasing sampling of content that is highly predictable and thus less informative (Baldwin & Kosie, 2021). For example, when people are allowed to advance at their own pace through slideshows depicting continuous events, they dwell longer on slides depicting event boundaries than within-event contents (Hard et al., 2011; Kosie & Baldwin, 2019). Furthermore, the deletion of movie segments is better detected at event boundaries than within events (Newtson & Engquist, 1976). These and related findings suggest a tendency to optimize attentional resources by selectively sampling highly informative regions of the sensory stream, thereby promoting a deeper encoding of relevant information in memory. It follows that events that are perceived as involving a higher proportion of informative segments should lead to less compressed representations in memory. Of course, this does not preclude the event compression rate from being further modulated according to retrieval demands. For example, there is evidence that when people scan their memory for a particular piece of information, compression rates are higher than when they try to mentally relive the events (Michelmann et al., 2021; see also Bellmund et al., 2020, for a review of evidence suggesting that the flexible adaptation of the speed of memory replay may be supported by the hippocampal-entorhinal region).

Another interesting finding of the present study is that the speed at which individual actions were recalled remained stable, regardless of the nature of the videos; on average, participants took around 3 seconds to mentally re-experience each action depicted in the video. Intriguingly, this duration of recalled units corresponds to the 3-s temporal integration window that has been identified as the ‘subjective present’ in the temporal perception literature (Montemayor & Wittmann, 2014; Pöppel, 1997). This temporal window is thought to be a fundamental component of human cognition in which perceptual information is integrated to create a phenomenally unified representation of the ‘now’ (for a review, see Montemayor & Wittmann, 2014). It is therefore possible that the succession of units of experience reported when recalling the unfolding of a past event corresponds to the sequential reinstatement of some of the units of ‘now’ that were created during the initial experience of this event.

Finally, it should be noted that, in this study, we used movies representing rather common events that have a predictable structure (e.g., steps for grocery shopping). Prior knowledge and experiences, in the form of event schemas or scripts, play an important role in the perception and memory of such events (Gilboa & Marlatte, 2017; Zacks, 2020). Knowledge of predictability structure may in fact optimize information processing by selectively sampling the most relevant parts of the sensory stream (Baldwin & Kosie, 2021), thereby contributing to the compression of events in memory. In future studies, it would be interesting to further investigate this potential role of prior knowledge on event compression rates by manipulating the degree of familiarity or novelty of events.

In summary, the present research provides the first evidence that removing less informative parts of daily life activities mimics the process by which information from the continuous stream of experience is selected for representing the unfolding of events in episodic memory. An important avenue for future research will be to examine the extent to which this compression mechanism is modulated by various event characteristics, such as duration, emotional value, and familiarity.

References

Anwyl-Irvine, A. L., Massonnié, J., Flitton, A., Kirkham, N., & Evershed, J. K. (2020). Gorilla in our midst: An online behavioral experiment builder. *Behavior Research Methods, 52*, 388–407.

Baird, J. A., & Baldwin, D. A. (2001). Making sense of human behavior: Action parsing and intentional inference. In B. F. Malle & L. J. Moses (Eds.), *Intentions an intentionality: Foundations of social cognition* (pp. 193-206). Cambridge, MA: MIT Press.

Baldassano, C., Chen, J., Zadbood, A., Pillow, J. W., Hasson, U., & Norman, K. A. (2017). Discovering event structure in continuous narrative perception and memory. *Neuron*, *95*, 1-13.

Baldwin, D. A., & Kosie, J. E. (2021). How does the mind render streaming experience as events? *Topics in Cognitive Science*, 13, 79–105.

Bates, C., Jacops, R. (2020). Efficient data compression in perception and perceptual memory. *Psychological Review, 127*(5). 891-917.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of statistical software, 67*(1), 1–48.

Bellmund, J. L. S., Polti, I., & Doeller, C. F. (2020). Sequence Memory in the Hippocampal–Entorhinal Region. *Journal of Cognitive Neuroscience, 32*(11), 2056–2070.

Bonasia, K., Blommesteyn, J., & Moscovitch, M. (2016). Memory and navigation: Compression of space varies with route length and turns. *Hippocampus, 12*, 9-12.

Brunec, I. K., Moscovitch, M., & Barense, M. D. (2018). Boundaries Shape Cognitive

Representations of Spaces and Events. *Trends in Cognitive Sciences*, *22*(7), 637-650.

Chen, J., Leong, Y. C., Honey, C. J., Yong, C. H., Norman, K. A. , & Hasson, U. (2017). Shared memories reveal shared structure in neural activity across individuals. *Nat Neurosci, 20*, 115-125.

Clewett, D., DuBrow, S., & Davachi, L. (2019). Transcending time in the brain: How event memories are constructed from experience. *Hippocampus*, *29*(3), 162–183.

Conway, M. A. (2009). Episodic memories. *Neuropsychologia*, *47*(11), 2305-2313.

D'Argembeau, A., Jeunehomme, O., & Stawarczyk, D. (2021). Slices of the past: how events are temporally compressed in episodic memory. *Memory*, DOI: 10.1080/09658211.2021.1896737.

Dubrow, S., & Davachi, L. (2013). The Influence of Context Boundaries on Memory for the Sequential Order of Events. *Journal of Experimental Psychology: General*, *142*(4), 693-700.

Faber, M., & Gennari, S. P. (2015). In search of lost time : Reconstructing the unfolding of events from memory. *Cognition*, *143*, 193-202.

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175-91.

Folville, A., Jeunehomme, O., Bastin, C., & D'Argembeau, A. (2020). The impact of age on the temporal compression of daily life events in episodic memory. *Psychology and Aging*, *35*(4), 484-496.

Gilboa., A., & Marlatte, H. (2017). Neurobiology of schemas and schema-mediated memory.

*Trends in Cognitive Sci*ences, *21*(8), 618-631.

Hard, B. M., Recchia, G., & Tversky, B. (2011). The Shape of Action. *Journal of Experimental Psychology: General, 140*(4), 586-604.

Horner, A. J., Bisby, J. A., Wang, A., Bogus, K., & Burgess, N. (2016). The role of spatial boundaries in shaping long-term event representations. *Cognition, 154*, 151-164.

Jeunehomme, O., & D'Argembeau, A. (2019). The time to remember: temporal compression and duration judgments in memory for real-life events.*Quarterly Journal of Experimental Psychology, 72*, 930-942.

Jeunehomme, O., & D'Argembeau, A. (2020). Event segmentation and the temporal compression of experience in episodic memory. *Psychological Research, 84,* 481-490.

Jeunehomme, O., Folville, A., Stawarczyk, D., Van der Linden, M., & D’Argembeau, A. (2018). Temporal compression in episodic memory for real-life events. *Memory*, *26*(6), 759-770.

Jeunehomme, O., Leroy, N., & D'Argembeau, A. (2020). The temporal compression of events during episodic future thinking. *Cognition,* DOI: 10.1016/j.cognition.2020.104416.

Kosie, J. E., & Baldwin, D. (2019). Attention rapidly reorganizes to naturally occurring structure in a novel activity sequence. *Cognition, 182,* 31-44.

Levin, D. T., & Baker, L. J. (2017). Bridging views in cinema: a review of the art and science of view integration. *Wires Cognitive Science*, *8*(5). e1436.

Magliano, J. P., & Zacks, J. M. (2011). The impact of continuity editing in narrative film on event segmentation. *Cognitive Science, 35,* 1489–1517.

Mair, P., & Wilcox, R. (2020). Robust statistical methods in R using the WRS2 package.

Behavior Research Methods, *52*, 464–488.

Michelmann, S., Hasson, U., & Norman, K. A. (2021). Event boundaries are steppingstones for memory retrieval. PsyArXiv. https://doi.org/10.31234/osf.io/k8j94

Michelmann, S., Staresina, B. P., Bowman, H., & Hanslmayr, S. (2019). Speed of time-compressed forward replay flexibly changes in human episodic memory. *Nature Human Behaviour*, *3* (2), 143-154.

Montemayor, C., & Wittmann, M. (2014). The varieties of presence: Hierarchical levels of temporal integration. *Timing and Time Perception*, *2*, 325-338.

Newtson, D., & Engquist, G. (1976). The perceptual organization of ongoing behavior. *Journal of Experimental Social Psychology, 12,* 436-450.

Pöppel, E. (1997). A hierarchical model of temporal perception. *Trends in cognitive sciences, 1*(2), 56-61.

R Core Team (2013). R: A Language and Environment for Statistical Computing. *R Foundation for Statistical Computing*, Vienna. http://www.R-project.org/

Radvansky, G. A., & Copeland, D. E. (2006). Walking through doorways causes forgetting: Situation models and experienced space. *Memory & Cognition*, *34*(5), 1150-1156.

Radvansky, G. A., & Zacks, J. M. (2017). Event boundaries in memory and cognition. *Current Opinion in Behavioral Sciences*, *17*, 133-140.

Schwan, S., & Garsoffky, B. (2004). The cognitive representation of filmic event summaries. *Applied Cognitive Psychology*, *18*(1), 37–55.

Smith, M. E., Loschky, L. c., & Bailey H. R. (2021). Knowledge guides attention to goal-relevant information in older adults. *Cognitive Research: Principles and Implication*, 6(56), https://doi.org/10.1186/s41235-021-00321-1

Smith, M. E., Newberry, K. M., & Bailey H. R. (2020). Differential effects of knowledge and aging on the encoding and retrieval of everyday activities. *Cognition*, *196*, 104159.

Storrs, K. R., & Fleming, R. W. (2021). Learning about the world by learning about images. *Current directions in psychological science*, *30*(2), 120-128.

Swallow, K. M., Zacks, J. M., & Abrams, R. A. (2009). Event Boundaries in Perception Affect Memory Encoding and Updating. *Journal of Experimental Psychology: General*, *138*(2), 236-257.

Wilcox, R. R. (2012). *Introduction to robust estimation and hypothesis testing*. Waltham, USA: Academic Press.

Zacks, J. M. (2020). Event perception and memory. *Annual Review of Psychology, 71,* 165–191.

Zacks, J. M., Speer, N. K., Swallow, K. M., Braver, T. S., & Reynolds, J. R. (2007). Event Perception: A Mind/Brain Perspective. *Psychol Bull.*, *133*(2), 273-293.

Zuo, S., Wang, L, Shin, J. H., Cai1, Y., Zhang, B., Lee, S. W., Appiah, K., Zhou, Y., Kwok, S. C. (2020). Behavioral evidence for memory replay of video episodes in the macaque. *eLife*. DOI: https://doi.org/10.7554/eLife.54519.