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**Title:**
Reconstructive nature of temporal memory for movie scenes

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**Abstract**
Remembering when events took place is a key component of episodic memory. Using a sensitive behavioral measure, the present study investigates whether spontaneous event segmentation and script-based prior knowledge affect memory for the time of movie scenes. In three experiments, different groups of participants were asked to indicate when short video clips extracted from a previously encoded movie occurred on a horizontal timeline that represented the video duration. When participants encoded the entire movie, they were more precise at judging the temporal occurrence of clips extracted from the beginning and the end of the film compared to its middle part, but also at judging clips that were closer to event boundaries. Removing the final part of the movie from the encoding session resulted in a systematic bias in memory for time. Specifically, participants increasingly underestimated the time of occurrence of the video clips as a function of their proximity to the missing part of the movie. An additional experiment indicated that such an underestimation effect generalizes to different audio-visual material and does not necessarily reflect poor temporal memory. By showing that memories are moved in time to make room for missing information, the present study demonstrates that narrative time can be adapted to fit a standard template regardless of what has been effectively encoded, in line with reconstructive theories of memory.

**Keywords:** episodic memory, memory for time, audio-visual narratives**,** script-based knowledge, event boundaries, memory schema

## 1. Introduction

### 1.1. Memory for the time of movie scenes

The ability to organize our memories by order of occurrence is a distinctive feature of episodic memory (Tulving, 1983; Eichenbaum, & Fortin, 2003). As Tulving (1983) said, “organization of knowledge in the episodic system is temporal: one event precedes, co-occurs, or succeeds another in time. The organization is also relatively loose, in the sense that the initially precisely recorded information about an event can be easily changed or lost”. A range of behavioral (for review, see Friedman, 1993; 2004), neuropsychological (Hirst & Volpe, 1982; Shimamura, Janowsky, & Squire, 1990), brain imaging (St. Jacques, Rubin, LaBar, & Cabeza, 2008; Lehn et al., 2009; Heusser, Poeppel, Ezzyat, & Davachi, 2016) and animal (Skaggs & McNaughton, 1996; Pastalkova, Itskov, Amarasingham, & Buzsáki, 2008) studies have investigated how we make temporal order judgments. Curiously, despite different research methods have been used to study temporal information in memory, only a few works (Jenkins & Ranganath, 2010; Lositsky et al., 2016; Montchal, Reagh, & Yassa, 2019) have employed the method of the horizontal timeline to indicate when a stimulus was exactly presented in the study phase. Such a sensitive behavioral technique is particularly useful for quantifying the distance between the estimated versus the actual time of occurrence. For example, in a recent study by Montchal and colleagues (2019) participants were asked to watch a ~28 min movie and subsequently place the still-frames from the episode on a continuous timeline. They found that behavioral performance was highly precise, with an average error of about 2-3 mins. Another crucial aspect of this study was the use of complex audio-visual material from a commercial TV show (see also Furman, Dorfman, Hasson, Davachi, & Dudai, 2007). Narrative stimuli of this type are particularly interesting as they are composed of a continuous stream of complex visually-rich events (Baldassano et al., 2017), which are temporally dynamic (Ferguson, Homa, & Ellis, 2017) and can “evoke responses that are as ‘juicy’ as the experiences we have in real life” (Zacks, 2014).

### 1.2. Potential role of event segmentation

Which mechanisms are responsible for such accurate temporal judgments? A key role in providing a temporal structure as a basis for driving participants’ responses might be played by event segmentation (Zacks, Tversky, & Iyer, 2001; Zacks, Speer, Swallow, Braver, & Reynolds, 2007). A solid body of research over the years has demonstrated that people spontaneously segment ongoing narratives into sub-parts, i.e. events, with good agreement in the placement of event boundaries across subjects (Newtson & Engquist, 1976; Baldassano et al., 2017).

In particular, the term “event model” refers to the construction and updating of a mental representation of the described situation (Speer, Reynolds, & Zacks, 2007; J. M. Zacks, Speer, Swallow, Braver, & Reynolds, 2007) that guides the online segmentation and affects how experience is encoded in long-term memory (Radvansky &Zacks 2014). An "Event" model can be thought of as a broader type of “situation" model (van Dijk & Kintsch, 1983), as the former is not limited to language processing but includes any representation of events derived from perceptual-motor experience (Radvansky and Zacks 2014).

Event models are characterized by several situational features. People keep track of primary dimensions of the described situation (e.g. spatial locations, causal breaks, etc.), updating their event models when situational dimensions change, as described by the Event Indexing Model (Zwaan et al., 1995).

Event segmentation could play a critical role in temporal memory for at least two reasons. First, event boundaries can be thought of as an overt manifestation of the internal representation of the event structure, which emphasizes causal relatedness. More specifically, the dominant dimension organizing relations between event models in long term memory is their causal connectivity (Radvansky, Copeland & Zwaan, 2005; Radvansky & Zacks, 2017), which also represents a crucial cue for temporal judgments, especially those regarding the ordering of events (Friedman, 1993). Support for this interpretation comes from the finding that sequential recall and temporal order memory are better within two event boundaries than across them (Ezzyat & Davachi, 2011; DuBrow & Davachi, 2013; Horner et al., 2016), suggesting that relations between event models are less well-defined if there is no causal relationship. Thus, a narrative story should be conceived as a chain of meaningful events in which the temporal information tends to be consistent with the cause-and-effect directionality of causal relations.

Second, there is evidence that the information presented in the vicinity of event boundaries is processed more deeply. The Event Segmentation Theory (EST; Kurby & Zacks, 2008) and the broader Event Horizon Model (Radvansky & Zacks, 2017) posit that segmentation is based on the continuous monitoring of a prediction error representing the discrepancy between the forecast of the event model currently activated in working memory and incoming information. Boundaries are placed when prediction error increases, signaling the necessity to update the current event model. As a consequence, the information surrounding the boundary is thought to undergo increased processing and better consolidation in long-term memory (Zacks et al., 2007). Consistently, it has been shown that event segmentation is predictive of later long-term memory (DuBrow & Davachi, 2013; Radvansky & Zacks, 2017). For example, stimuli extracted from event boundaries are better recognized, and described with more details, than those from non-boundaries (Newtson & Engquist,1976; Schwan, Garsoffky, & Hesse, 2000). Importantly, there is some evidence that temporal order memory also improves when surface structure cues (e.g. commercial breaks) are aligned with event boundaries (Boltz, 1992; Schwan, Garsoffky, & Hesse, 2000; Schwan & Garsoffky, 2004). However, no published study, to our knowledge, has investigated whether the proximity to event boundaries is related to the precision of judgments about the time-of-occurrence.

### 1.3. Potential role of script-based prior knowledge

However, event segmentation might be just one of the possible mechanisms that support memory for time. Specifically, we argue that more general information about time patterns might play a pivotal role in memory for time of narrative scenes (Bower, Black, & Turner, 1979; Baldassano, Hasson, & Norman, 2018; Friedman 1993;). Indeed, the 'global coherence' of a narrative is "constructed inferentially through interactions between the information conveyed in the story, and prior knowledge" about schematic script information (Maguire, Frith, & Morris, 1999), which represent typical event sequences "that defines well-known situations" (Schank & Abelson, 1977). Importantly, schemas and scripts convey semantic information of stereotypical situations, rather than unique events. For example, Bransford and Johnson (1972) showed that the possession of a relevant framework, in the form of an explanatory picture, results in increased comprehension and recall of ambiguous story passages. The effect was especially strong when the picture was given before reading the passages, suggesting that readers used such a schema to encode the information in a meaningful way.

The present study focused on the role of a more general kind of prior knowledge compared to contextual information, which we called "script-based prior knowledge" about the typical story components and how narrative events are likely to unfold. These schemas are naturally acquired by multiple presentations with narrative experiences that tend to share a general temporal evolution and are thought to facilitate both comprehension and episodic memory. For example, the related field of "story grammar" (Rumelhart, 1975; Kintsch & van Dijk, 1978; Mandler & Johnson, 1977; Thorndyke, 1977; Stein & Glenn, 1979) has shown that people have little control over the intrusion of schematic knowledge used during recall of narrative material. For instance, study participants are more likely to retrieve an ill-formed story in a canonical order which includes constituents of a story schema and to add portions of the narrative to their recall when a story is told with some of its constituents missing (Mandler & Goodman, 1982). These studies suggest that people have a script-based prior knowledge about how stories are typically organized, despite all the possible variations that could exist in a narrative. Perhaps the most general script for listening to a story or watching a movie is of the kind of ‘beginning-middle-end’ (Cutting, 2016). Accordingly, beginning and end might be considered meaningful reference points on the grounds of a global coherent story (Friedman, 1993). After all, “the “end” of the story is already known at its beginning” (Branigan, 1992), meaning that there is a tacit understanding of how events unfold in a story, and how a story typically begins and ends. According to the Event Horizon Model (Radvansky & Zacks, 2017), event models and event schemas are supposed to work at different levels of memory representation. Specifically, while event models are unique, as they reflect the distinctive properties of individual experiences, event schemas reflect more general properties of repeated experiences. Nonetheless, these two kinds of information interact during encoding and retrieval of long-term memory traces (Mandler, 1978; Rumelhart & Ortony, 1977; Grafman, Partiot, & Hollnagel, 1995; Newberry & Bailey, 2019). In particular, event schemas are thought to be used as building blocks for the construction of event models. For example, they are helpful when someone needs the knowledge to fill in unmentioned but highly likely components for which he/she has a large knowledge base (Radvansky & Zacks, 2014). Moreover, Newberry and Bailey (2019) have demonstrated that event segmentation can be affected by manipulating the type of prior knowledge given before the experiment. Interestingly, Ferguson and colleagues (2017) found that recognition memory for dynamically temporal events was not affected by the disruption of the global structure of the movie. In contrast, we assume that memory for time might be largely affected by significant changes in the narrative discourse.

### 1.4. The current study

The goal of the present study was to investigate whether memory for time is modulated by the spontaneous process of event segmentation and by script-based prior knowledge. In Experiment 1, participants viewed a full episode from the TV series “Sherlock” and were subsequently asked to indicate the time of occurrence of short video clips extracted from the movie using a visual analog scale that represented the movie timeline. We hypothesized that, if participants divide the ongoing narrative into sub-events, they might be more accurate when positioning clips that are closer to event boundaries. Moreover, if the beginning and end are used as reference points based on an underlying movie script, then greater accuracy should be observed for clips extracted from these movie parts. To more directly examine the effect of script-based prior knowledge, in Experiment 2 we removed the end part of the movie from the encoding session. Our rationale was that if observers simply rely on what they have been shown, their judgments of the time of occurrence should follow a pattern comparable to that of Experiment 1. Instead, if they rely on script-based knowledge, they should automatically activate the entire script representation even if the movie was not viewed in full. This automatic activation might affect memory for time performance in a systematic way, reflecting the intrusion of the missing part into the temporal representation of the movie. More specifically, we expected an underestimation of the time of occurrence of the video clips that were close to the cut, due to the inclusion of the unseen part into the temporal representation of the movie. To note, the current manipulation does not affect how the movie is encoded and segmented (Newberry and Bailey, 2019) before the cut, given that participants were not informed about the cut-before-end procedure. Finally, Experiment 3 tested the degree to which the results of Experiment 2 generalize to different audio-visual material (i.e. a stop-motion animated comedy instead of a crime film with real actors).

## 2. Experiment 1

The first experiment investigated the influence of event boundaries and proximity to start/end points on the precision of memory for time of movie clips. At encoding, participants viewed a full episode of the BBC's show "Sherlock", a movie characterized by a strong causal and situational structure. The next day, they were shown 2 secs video clips extracted at different points from either the same or a different episode from the same show. For correctly recognized clips, they were asked to indicate when the event in question occurred on a horizontal timeline that represented the duration of the movie presented at encoding. To test whether memory for time performance was associated with event segmentation, which is a fine index of the temporal structure of the event, and/or with the most basic representation of the temporal structure of a story (beginning, middle, end), we examined whether video clips extracted around event boundaries or closer to the beginning/end of the movie were placed more precisely on the timeline.

### 2.1. Methods

#### *2.1.1. Participants*

Twenty right-handed volunteers (12 females; aged 19–34; mean age: 21.5 years), with no familiarity with the movie show, participated in the study. All were naive as to the purpose of the experiment, reported normal or corrected-to-normal vision, and provided informed consent before the experiment following guidelines set by the Human Studies Committee of G. D'Annunzio Chieti University. The study included an encoding session (duration: approx. 90 mins) followed by a retrieval session (duration: approx. 30 mins). The two sessions were separated by a ~24 hrs interval.

#### *2.1.2. Stimuli and procedure*

The experimental paradigm is illustrated in Figure 1. Both sessions were performed in a darkened testing room. Stimuli were presented on a 17' LCD computer monitor (1024 x 768 pixels, 60 Hz refresh rate) at a distance of ~60 cm. Subjects wore headphones and listened to the audio track dubbed in Italian at a comfortable level (~60 dB).
In the encoding session (**Figure 1A**), a full episode of the BBC television series Sherlock (Season 1, Episode 1, "A study in pink"; duration: 87:30 mins) was presented using VLC media player version 2.20. Participants were instructed to pay attention to the movie but were not informed about the nature of the following tasks.
In the retrieval session (**Figure 1B**), a series of video clips (N = 228, 216 for the main experiment, 12 for practice and instructions) of 2s duration were presented using E-Prime 2.0 software (Psychology Software Tools). The order of the video clips was randomized across subjects. Each trial started with the presentation of a video clip at the center of the screen. Participants were asked to judge whether the clip was seen in the encoding session (old) or not (new) and to report the response as fast and accurately as possible starting from the clip onset. Responses were recorded through a mouse button (index/middle finger of the right hand, respectively). The clip was followed by a red fixation cross (size 0.8° visual angle) until a judgment was given. Old stimuli [N=114 (108+6)] were uniformly sampled every 43.75 secs (this value refers to the center of the clip) from the beginning of the movie. Few of the clips were not presented as they were used in a different test that was performed after the one described here (data not shown). New stimuli [N=114 (108+6)] were selected from another episode of the same show (Episode 2, "The Blind Banker") maintaining the same temporal distance between clips. Following old responses, participants were asked to provide an additional memory for time judgment. A

central horizontal grey line (size: 0.9°x19.8° visual angle), representing the duration of the movie, appeared at the center of the screen. The line was made of 720 consecutive segments, each corresponding to 7.29 secs of the movie. Participants were asked to select a point on the line with a mouse click to indicate the exact moment in the movie from which the clip was extracted. A cursor (arrow pointer) was visible and moved in synchronization with the mouse. The timeline remained on the screen until a judgment was given for a maximum of 10 secs, followed by an intertrial interval (ITI) of 2 secs. No feedback was provided. The instructions made clear that the line represented the duration of the movie that was presented in the encoding session, where the extreme left corresponded to the beginning, and the extreme right corresponded to the end. An experimenter made sure that the subjects understood the instructions during the practice session.


**Figure 1. Experimental Paradigm**
The figure illustrates the structure of the experimental paradigm for the three experiments. **A.** In the encoding phase, participants were presented with an episode from the TV series "Sherlock" (entire episode in Experiment 1, the first 60 mins of the episode in Experiment 2) or the first 60 mins of the movie "Wallace & Gromit: The Curse of the Were-Rabbit" (Experiment 3). **B.** In the retrieval phase, participants were presented with a series of 2 secs video clips, extracted either from the previously encoded movie or from an unseen, related movie, and were asked to perform an item recognition judgment (old/new) followed by the memory for time judgment using a computer mouse. The clip was followed by a red fixation cross until a judgment was given. For clips judged as old, participants were also asked to select a point on a horizontal line to indicate the exact moment in the movie from which the clip was extracted. An ITI of 2 secs with a central fixation cross preceded the next trial. **C.** The position of the event boundaries for each experiment identified by an inter-rater analysis in a group of independent observers. The lines below the boundaries represented the six parts in which the movie was splitted.

A pilot experiment was conducted to identify event boundaries in the movie. An independent group of 20 participants was asked to overtly segment the video based on the following indications (Baldassano et al., 2017): ‘‘Write down the times at which you feel like a new scene is starting; these are points in the movie when there is a major change in topic, location, time, etc. Also, give each scene a short title”. Event boundaries were extracted with a completely data-driven method by using the DBSCAN clustering algorithm (Ester, Kriegel, Sander, & Xu, 1996). After the removal of outlier annotations, the algorithm automatically identified the best number of clusters based on two parameters: number of observations and temporal window. Clusters were identified when choosing a random observation, in the following and preceding 2.5 seconds (temporal window = 5 seconds), at least ten observations were found. The event boundary was obtained by averaging all the observations within each identified cluster. This procedure identified 51 event boundaries that were most characteristic in the group of observers for Experiment 1, while 36 event boundaries were identified for Experiment 2 and 30 boundaries for Experiment 3. (**Figure 1C**).

*2.1.3. Data analysis.*

We first calculated the accuracy of old/new recognition judgments. Subsequent analyses of recognition accuracy were conducted selectively on old clips. To quantify variations of performance as a function of the clip position, we split the movie into six equal parts of ~15 mins and used the movie part as an independent variable in a 1-way repeated-measures analysis of variance (ANOVAs). This arbitrary division was chosen to maximize temporal sampling while still relying on an adequate number of clips in each part (N=18). Tukey HSD Post Hoc tests were used to test differences between pairs of movie parts. We further tested whether recognition accuracy varied as a function of the proximity to event boundaries by conducting a trial-by-trial Spearman Rank Order Correlation Test between the group-level recognition accuracy for each old clip and the corresponding clip distance from: i. the nearest boundary (boundary distance); ii. the end of the movie (clip onset) and iii. either the beginning or the end of the movie (beginning/end distance). To test whether the recognition accuracy was influenced by the number of event boundaries, the correlation analysis was also conducted separately for different movie segments: i. Part 1 and 2 (including 22 boundaries); ii. Part 3 and 4 (14 boundaries) and iii. Part 5 and 6 (15 boundaries).

We then analyzed memory for time judgments after the exclusion of trials associated with mouse clicks outside the timeline. These analyses were restricted to correctly recognized old clips (hits). The precision of memory for time was calculated as the temporal distance, quantified in secs, between the line segment selected by the subject and the correct segment for each trial. The placement error was calculated with respect to the center of each video clip. Two parameters were considered: absolute and relative error. Compared to absolute error, relative error further considers the direction of error (forward or backward) and allows to estimate the presence of a systematic bias. Two ANOVAs assessed the effect of the movie part on absolute and relative distance. Tukey HSD Post Hoc tests were used to test differences between pairs of movie parts. We also conducted a series of one-sample t-tests (two-tailed) with Bonferroni correction to determine if the amount of relative error for each movie part was significantly different from zero across participants, indicating a significant bias.

To test whether the precision of memory for time varied as a function of the temporal properties of the clips, a trial-by-trial Spearman Rank Order Correlation Test was conducted between the group-level absolute error for each clip and the corresponding clip distance from i. the nearest boundary (boundary distance) and ii. either the beginning or the end of the movie (beginning/end distance). The trial-by-trial correlation between the

absolute error and the boundary distance was also performed separately for the three movie segments as in the analysis of recognition accuracy.
Two analyses examined the relationship between item recognition and memory for time performance: i. an overall Spearman Correlation Test between individual subject measures of recognition accuracy and absolute positioning error, and ii. a trial-by-trial Spearman Correlation Test between group-level absolute error and recognition accuracy for each movie clip.
Finally, to assess the memory for the temporal order of the video clips, we conducted a trial-by-trial Spearman Rank Order Correlation Test between the estimated (group-level) and the actual order of the movie clips. The correlation test was conducted for the whole movie and each movie part.

2.2. Results.
The overall level of recognition accuracy was 0.91 ± 0.04 (mean ± SD). The ANOVA yielded a significant main effect of movie part [$F (5, 95) = 11.752$, $p < 0.0001$, $\eta_p^2 = 0.38$]. Post-hoc analyses showed that recognition judgments for clips extracted from Part 3 (0.95 ± 0.06) and 6 (0.91 ± 0.08) were significantly more accurate compared to those extracted from Part 1(0.82 ± 0.12), Part 4 (0.79 ± 0.11) and Part 5 (0.84 ± 0.08, all $p < 0.05$) and that those extracted from Part 2 (0.89 ± 0.09) were significantly more accurate compared to those extracted from Part 4 (all $p < 0.05$). The correlation between recognition accuracy and boundary distance was not significant ($r_s = 0.04$, p = n.s.), also when splitting the whole movie in three segments (Part 1 and 2: $r_s = 0.22$, p = n.s.; Part 3 and 4: $r_s = -0.04$, p = n.s.; Part 5 and 6: $r_s = 0.03$, p = n.s.). Finally, recognition accuracy correlated neither with the beginning/end distance ($r_s = 0.04$, p = n.s.), nor with the end distance ($r_s = -0.13$, p = n.s.), further supporting the absence of a consistent relationship between item recognition performance and the clip position.
Figure 2A shows that subjects distributed their temporal judgments along the entire visual analog scale (**Figure 2A**). The level of absolute and relative error across trials was 583 ± 145 secs and -22 ± 228 secs, respectively (**Figure 2B**). For absolute error, the ANOVA (**Figure 2C, red)** yielded a significant main effect of movie part [$F (5, 95) = 16.71$, $p < 0.0001$, $\eta_p^2 = 0.46$]. Post-hoc analyses showed that clips extracted from Part 1 and 6 were associated with significantly more precise judgments compared to those extracted from Part 2 to 5 (all $p < 0.01$), indicating that clips extracted from the first and the last part of the movie were placed more precisely than middle ones. For relative error, the ANOVA (**Figure 2C, blue**) again revealed a significant main effect of movie part [$F (5, 95) = 4.92$, $p < 0.0005$, $\eta_p^2 = 0.21$]. Post-hoc analyses showed a significant difference between Part 2 and both Part 3 ($p < 0.0005$) and Part 4 ($p < 0.005$). Notably, one-sample t-tests revealed that none of the parts were significantly different from zero (all p = n.s., Bonferroni corrected), a result that indicates the absence of a consistent bias towards over- or under-estimation of memory for time in any part of the movie.
Based on the latter result, the relationship between the precision of memory for time and the temporal properties of the clips was only tested considering absolute error. A significant correlation was found between the boundary distance and the absolute error ($r_s = 0.21$, $p < 0.05$, **Figure 2D**), indicating that the clips that were closer to event boundaries were positioned more precisely than more distant ones. However, we found that the correlation reached the significance level only in the first segment (Part 1-2; $r_s = 0.39$, $p < 0.05$), which was characterized by the highest frequency of boundaries, but not in other segments (Part 3-4; $r_s = 0.09$, p = n.s.; Part 5-6; $r_s = 0.20$, p = n.s.). Importantly, the absolute error also showed a positive correlation with the beginning/end distance ($r_s = 0.62$, $p <$

0.0001, **Figure 2E**), confirming that stimuli extracted from the first and the last part of the movie were positioned with more precision than the middle ones.
Interestingly, we observed a significant negative correlation between mean recognition accuracy and mean absolute error across subjects ($r_s = -0.47$, $p < 0.05$), but not across video clips ($r_s = 0.06$, p = n.s.), indicating a positive relationship between the two indices of episodic memory.
Finally, the inter-trial correlation between the estimated and the actual order of the clips was highly significant ($r_s = 0.94$, $p < 0.0001$). More specifically, a significant correlation in Part 1 ($r_s = 0.72$, $p < 0.001$), 2 ($r_s = 0.72$, $p < 0.001$), 4 ($r_s = 0.76$, $p < 0.0005$) and 5 ($r_s = 0.71$, $p < 0.001$) but not in the remaining parts (**Figure 2F**).

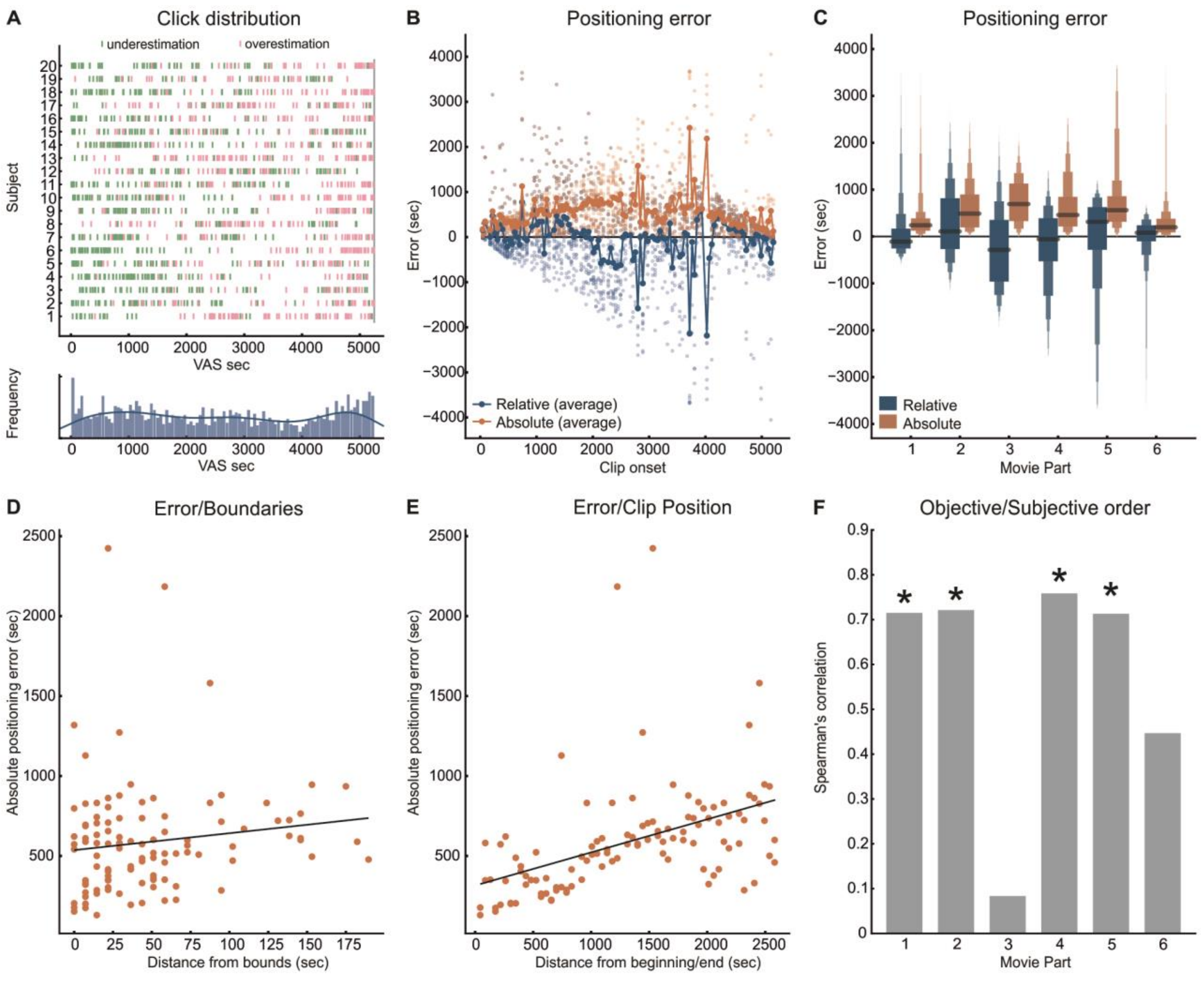


**Figure 2. Results of Experiment 1.**
The figure illustrates the memory for time performance for video clips extracted from the first episode of the TV show “Sherlock”, which was presented in full the day before.
**A.** Click distribution for each subject, with a further indication of the direction of the positioning errors.
**B.** Absolute (red line) and relative (blue line) error, expressed in secs and averaged across subjects, in the positioning of the clips on the visual analog scale as a function of the clip location in the movie. The transparent dots represent individual subject data, For relative errors, positive and negative values indicate over- and underestimation of clip position, respectively.
**C.** Absolute (red) and relative (blue) error as a function of movie part (part duration: ~15 mins). The letter-value plot shows the group mean (black line) and the quantiles of the distribution: , the bigger box represents the second quartile (Q1-Q3), while smaller boxes represent lower order quantiles (octiles, hexadeciles etc.).

**D.** Scatter plot showing the positive relationship between the absolute positioning error, averaged across subjects, and the clip distance from the closest event boundary. For visualization purposes, A regression line was added to the plot to show the linear relationship between the two variables.
**E.** Scatter plot showing the positive relationship between the absolute positioning error and the shortest distance between the clip and either the beginning or the end of the movie.
**F.** Graph representing the correlation between the estimated and the actual order of the video clips. The asterisks indicate the presence of a significant correlation.

## 2.3. Discussion

Compared to the recent reference work by Montchal and colleagues (2019), the results of Experiment 1 indicate a lower precision of memory for time (2-3 mins vs. almost 10 mins in our experiment), a finding that likely reflects also the large difference in movie duration (~28 vs. ~87 mins). Several metrics further indicate that participants were more accurate at judging the temporal occurrence of clips taken from both the beginning and the end part of the movie compared to clips extracted from the middle part. This was expected given that extreme parts are known to be crucial landmarks for temporal judgments (Friedman, 1993). This is true not only because they are consistent temporal properties of our environment (i.e. most of the activities have beginnings and ends), but also because they are fundamental elements in terms of narrative structure (Cutting, 2016). Notably, no clear bias was observed in the direction of errors, suggesting that the observed displacement was not due to a general under- or overestimation of the time of occurrence, but rather represented the expression of inter-individual variability in clip positioning.
Previous research has shown that the event boundaries have a strong effect on memory (Boltz, 1992; Sargent et al., 2013; Flores, Bailey, Eisenberg, & Zacks, 2017), but the degree to which proximity to event boundaries is reflected in fine measures of temporal memory is still unclear. The results of Experiment 1 revealed that memory for time was significantly more precise in the proximity of event boundaries, albeit the effect size of the correlation was relatively small. Such a weak effect could be explained by several factors. The first concerns the sampling of the clips, as we opted for a homogeneous sampling throughout the movie duration rather than a boundary-dependent sampling. It might be possible that superior memory for time manifests only for clips extracted *exactly* at (Netwson & Engquist, 1976), rather than in proximity of event boundaries, in an all-or-nothing manner. Another factor that could have reduced the strength of the association is represented by inter-subject variability in boundary position (Speer et al., 2007, Schwan & Garsoffky, 2008). Specifically, the relationship might be stronger when boundaries are identified by the same subject that performs the memory task. However, testing this hypothesis is problematic. On the one hand, the act of explicit segmentation might represent a confounding factor for subsequent analyses of memory for time. On the other hand, we did not make participants segment the movie after the memory test since there is evidence that segmentation tends to be coarser when events are more familiar (Newtson, Engquist & Bois 1977; Zacks et al., 2001). Finally, the relationship might depend on the frequency of events/boundaries. It has also been shown that it is possible to manipulate the temporal grain of segmentation by asking participants to identify the smallest (fine-grained) or largest (coarse-grained) units that they find natural and meaningful (Radvansky & Zacks, 2014). Partial support for the hypothesis that the relationship depends on the number of events comes from the observation that the effect observed in the present study was only significant in the first movie segment, which was characterized by a higher number of boundaries compared to other segments.
In contrast, there was no effect of boundary distance on item recognition. The absence of such an effect might be due to the high level of recognition accuracy. Indeed, we tested item recognition to make sure that participants positioned clips they recognized, but at the same time, we wanted to maximize the number of correctly recognized trials for a robust

estimation of temporal memory per movie part. In the alternative, as discussed before, it might be possible that better recognition judgments occur only when clips are extracted exactly at event boundaries.
In line with previous studies on temporal memory (Strube & Neubauer, 1988; Wright, Gaskell, & O'Muircheartaigh's, 1997), we found that participants who were better at discriminating old from new clips also showed higher memory for time performance. This finding supports the claim, made by reconstructive theories, that the better we remember, the more information we have to reconstruct the time of occurrence (Friedman, 2004). However, the relationship was not significant when tested at the level of individual clips. This negative finding might be partially explained by the fact that subjects were not asked to position the clips they did not recognize. As a consequence, we could not compare the temporal precision of recognized versus non-recognized clips. However, the presence of a complex, indirect relationship between recognition and memory for time is further suggested by the different effects of clip position (movie part) on these two indices of episodic memory.
Finally, although we found a strong correlation between the estimated and actual order of the clips, the correlation coefficient decreased in correspondence of the middle and the last part of the movie. The latter result is particularly interesting, as it appears at odds with evidence for great precision of memory for time observed in this movie part. This partial dissociation between order memory and temporal precision is consistent with the idea that memory for time is supported by multiple mechanisms, each evolved to serve a specific purpose (Friedman, 1993, 2004).
In general, the present results suggest that boundary distance and distance from extreme points affect temporal memory for video clips extracted from full-length movies. The following experiments aimed at testing more directly the influence of script-based prior knowledge on memory for time of movie scenes.

## 3. Experiment 2

The results of Experiment 1 demonstrate a strong relationship between the precision of memory for time and the proximity to extreme points of the movie. However, while beginning and end points represent basic landmarks of the story macrostructure, they can be also considered boundaries themselves, making it difficult to disentangle the role of event segmentation from script-based prior knowledge. Moreover, beginning/end distance inevitably represents an oversimplification of the concept of script-based prior knowledge. To overcome these limitations, we conducted Experiment 2 as a more selective test of the effect of script-based prior knowledge on memory for time. To this end, we used a "cut-before-end" procedure by only presenting ~2/3 of the movie used in Experiment 1 in the encoding phase of the new experiment. The rationale for the manipulation was that the removal of the end part of the movie should result in a conflict between the representation of what has been seen (the movie fragment) and the more general representation of the movie script, which includes a climax/epilogue part. We hypothesized that the activation of the whole movie script, triggered by the presentation of more than half of the movie, might lead to the automatic incorporation of the missing part into the global coherent representation, resulting in a systematic bias in memory for time. Therefore, we now expected a specific impairment of memory for time characterized by increasing anticipation of clips closer to the missing part of the movie. Of note, the video ended in a fairly abrupt fashion. Since there is no consensus on a procedure to precisely identify the end part of the plot, we opted for a quantitative approach, under the assumption that the last third of a conventional movie should contain the climax and the final resolution of the story.

### 3.1. Methods

*3.1.1. Participants*
Twenty new volunteers (16 females; aged 19-30; mean age: 22.1 years) participated in the study, with the same inclusion criteria of Experiment 1.

*3.1.2. Stimuli and procedure*
Experiment 2 was a replication of Experiment 1. The crucial difference was that participants only watched the first 60 min of the movie. Old stimuli [N=114 (108+6)] were now sampled every 30 secs from the beginning. New stimuli [N=114 (108+6)] were selected from the Episode 2 maintaining the same temporal distance between clips. Finally, the timeline was again made of 720 consecutive segments, but each segment now corresponded to 5 secs of the movie.

*3.1.3. Data analysis*
Data analysis was similar to Experiment 1, but this time the timeline was split into six equal parts of 10 min (vs. ~15 min, Experiment 1). The analysis of recognition accuracy was limited to the effect of the clip position, given our specific interest in memory for time performance. Also, we now investigated the degree of correlation between the absolute (and relative) error and the clip distance from the end of the presented video (clip onset) rather than with the beginning/end distance. Moreover, given that a large number of boundaries was associated with the first 30 mins of the movie, the trial-by-trial correlation analysis between the positioning error and the boundary distance was also performed separately for the first half (part 1-3, approximately corresponding to Part 1-2 of the full movie) and the second half of the presented video.
A further analysis was conducted to directly compare the result of experiments 1 and 2. Firstly, the goodness-of-fit of a linear regression between subjective (line judgment, calculated across subjects) and objective time (actual clip position) was calculated for both experiments. The slope of the regression line (for each subject and experiment) was then compared across experiments by using a two-sample t-test (two-tailed). To test whether the difference between the results of the first and the second experiment was explained by systematic errors occurring at specific points of the movie, a regression line for Experiment 1 was also calculated using only the first 60 mins of the movie.

<u>3.2. Results</u>
Overall item recognition accuracy was 0.88 ± 0.04.The ANOVA yielded a significant main effect of movie part [$F(5, 95) = 16.350$, $p < 0.0001$, $\eta_p^2 = 0.46$]. Post-hoc analyses showed that recognition judgments for clips extracted from Part 3 (0.94 ± 0.06) and Part 4 (0.92 ± 0.08) were significantly more accurate compared to those extracted from Part 1 (0.73 ± 0.19), Part 2 (0.75 ± 0.13), Part 5 (0.78 ± 0.11), and Part 6 (0.77 ± 0.14, all $p < 0.001$), while no significant difference was observed between Part 3 and 4 (p = n.s.).
The qualitative analysis of response distribution indicated a drop in the number of clicks toward the end portion of the visual analog scale (**Figure 3A**). The level of absolute and relative error across trials was 615 ± 268 secs and -465 ± 337 secs, respectively (**Figure 3B**). For absolute error, the ANOVA (**Figure 3C, red**) yielded a significant main effect of movie part [$F(5, 95) = 22.09$, $p < 0.0001$, $\eta_p^2 = 0.53$]. Post-hoc analyses showed that judgments for clips from Part 1 to 3 were significantly more precise compared to those for clips from Part 4 to 6 (all $p < 0.05$). Furthermore, judgments for clips from Part 6 were significantly less precise compared to those from Part 1 to 4 (all $p < 0.05$). For relative error, the ANOVA (**Figure 3C, blue**) again revealed a significant main effect of movie part [$F(5, 95) = 34.09$, $p < 0.0001$, $\eta_p^2 = 0.64$]. Post-hoc analyses showed that judgments for clips from Part 1 to 3 were significantly more precise compared to those for clips from Part

4 to 6 (all $p < 0.005$). Furthermore, Part 6 was significantly different from Part 1 to 4 (all $p < 0.005$). One-sample t-tests revealed that Part 2 ($p < 0.01$) and Part 4 to 6 (all $p < 0.001$) were significantly different from zero. These results indicate the presence of a strong bias towards underestimating the clip position affecting the second half of the video that was presented to subjects.

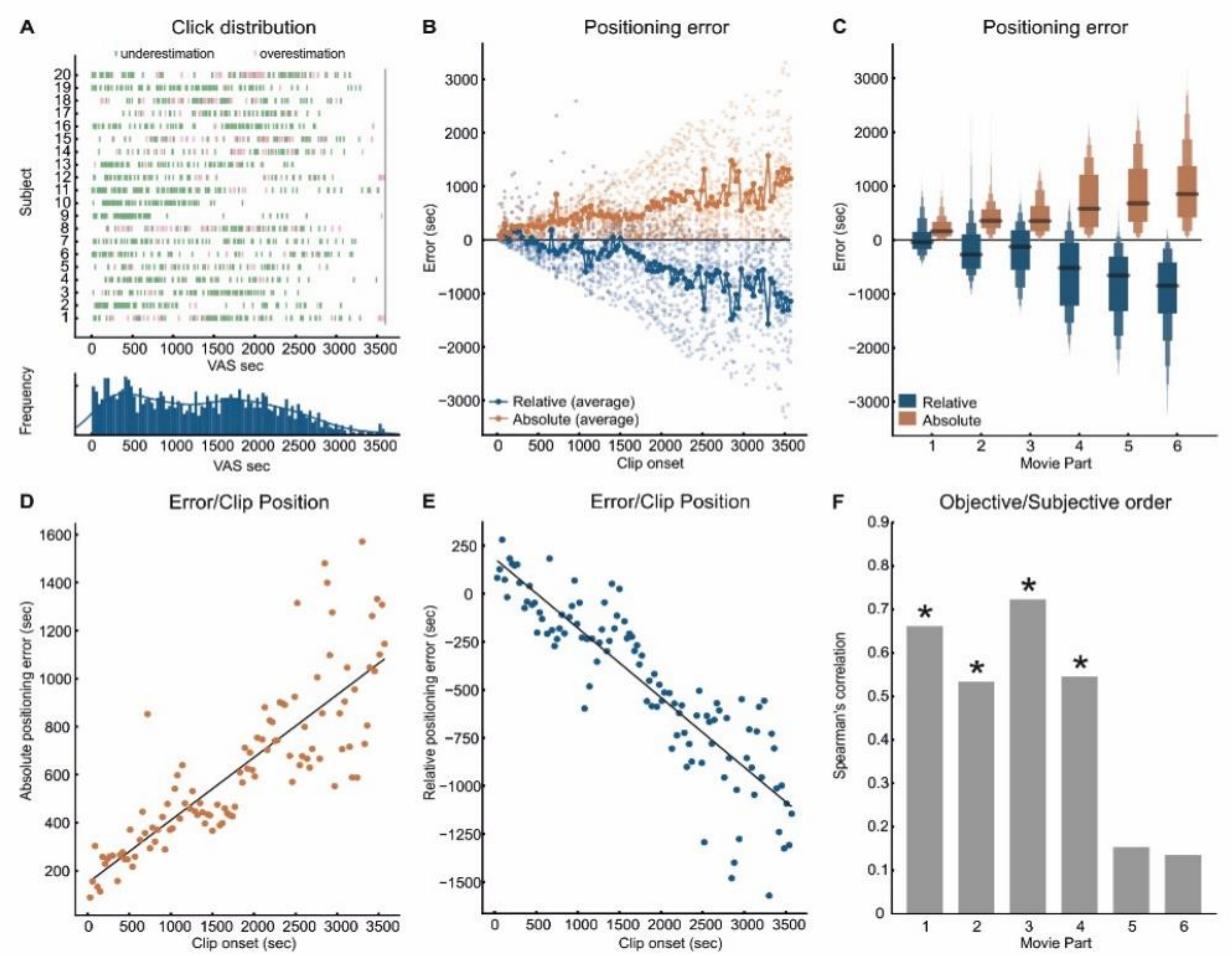


**Figure 3. Results of Experiment 2.**
Memory for time performance in Experiment 2, in which only the first 60 mins of the "Sherlock" episode were presented at encoding.
**A.** Click distribution for each subject.
**B.** Absolute (red line) and relative (blue line) error, expressed in secs and averaged across subjects, in the positioning of the clips on the visual analog scale as a function of the clip's location in the movie.
**C.** Absolute (red) and relative (blue) error as a function of the movie part (part duration: 10 mins).
**D-E.** Scatter plots showing the relationship between the clip distance from the end of the video and both the absolute (D) and the relative (E) positioning error.
**F.** Graph representing the correlation between the estimated and the actual order of the video clips.

The analysis of the inter-trial correlation between the precision of memory for time and boundary distance now indicated the absence of a significant correlation ($r_s = 0.16$, p = n.s.). However, when the correlation test was performed separately for the two halves of the presented video, we observed a significant correlation within the first ($r_s = 0.30$, $p < 0.05$) but not the second half ($r_s = 0.05$, p = n.s.) of the video, indicating that segmentation affected memory for time only in the movie segment that contained more boundaries. Crucially, clips that were closer to the last part of the video were strongly associated with both increased error (positive correlation between absolute error and clip onset, $r_s = 0.88$,

$p < 0.0001$, **Figure 3D**) and increased level of underestimation (significant negative correlation between relative error and clip onset, $r_s = -0.91$, $p < 0.0001$, **Figure 3E**). To test the consistency of the underestimation bias across individuals, the presence of a correlation between relative error and clip position was tested in each subject. The Spearman Rank Order correlation was significant ($p<0.001$) in 18/20 subjects.

Finally, the analysis of the inter-trial correlation between estimated and actual order of the clips revealed the presence of a very strong correlation ($r_s = 0.96$, $p < 0.0001$, **Figure 4F**). Importantly, there was a significant correlation between estimated and actual order for clips extracted from Part 1, ($r_s = 0.66$, $p < 0.005$), Part 2 ($r_s = 0.53$, $p < 0.05$), Part 3 ($r_s = 0.72$, $p < 0.001$) and Part 4 ($r_s = 0.55$, $p < 0.05$), but not from Part 5 ($r_s = 0.15$, p = n.s.) and Part 6 ($r_s = 0.14$, p = n.s.).
The comparison across Experiments 1 and 2 revealed that the relationship between subjective and objective time at the group level was well explained by linear regression ($R^2 = 0.91$ and 0.92 for Experiments 1 and 2, respectively, **Figure 4A**). The t-tests comparing the regression slopes (numbers below or above 1 indicate underestimation or overestimation of clip positioning, respectively) derived from individual subject fitting across experiments (**Figure 4B**) revealed a significant difference ($p < 0.0001$) between the experiments (Experiment 1: $b = 0.94 \pm 0.17$; Experiment 2: $b = 0.63 \pm 0.19$), also when the regression slope for Experiment 1 was calculated using only the first 60 minutes of the movie ($b = 0.83 \pm 0.17$, $p < 0.005$).

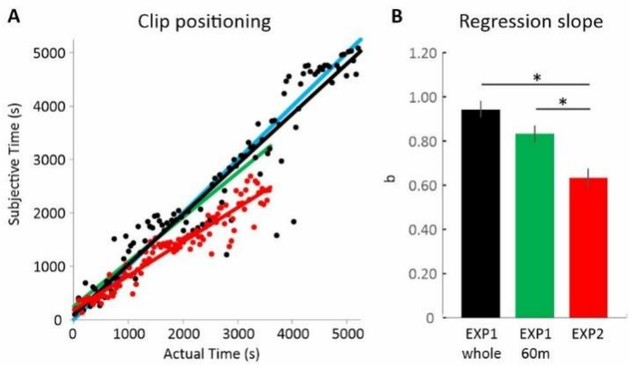


**Figure 4. Comparison of Experiments 1 and 2.**
The figure compares memory for time performance between Experiments 1 and 2.
**A.** The plot shows the clip positioning (y-axis) as a function of the actual position on the visual analog scale (x-axis) for Experiment 1 (black dots) and 2 (red dots) with the corresponding linear regression lines. The light blue line indicates the ideal performance. The green line refers to the regression line calculated using only the first 60 mins of the movie in Experiment 1. While no specific bias was observed in Experiment 1, increasing underestimation as a function of time was evident in Experiment 2. **B.** A direct comparison of the regression slope across experiments. Error bars indicate SEM. Horizontal lines indicate a significant difference across conditions (p<0.005).

## 3.3. Discussion

The results of Experiment 2 indicate that memory for time of movie scenes is profoundly altered when participants are not presented with a full movie in the encoding session. In contrast with the results obtained in Experiment 1, the absolute error now increased as a function of the proximity to the missing part of the movie. This effect was caused by an increasing bias towards the underestimation of the time of occurrence for movie clips of increasing onset that was consistent across participants. Moreover, the absence of systematic effects in Experiment 1 rules out the possibility that this bias, which affects clips to be positioned on the right side of the timeline, is associated with the responding hand. The bias produces by the "cut-before-end" procedure is also evident when comparing the subjective positioning versus the objective time across experiments and cannot be easily explained by a systematic error occurring in specific points of the movie. Interestingly, the relationship between proximity to event boundaries and precision of memory for time was still present in the first half of the video but was not observed in the second half, replicating the results of Experiment 1.

Taken together, the results of Experiments 1 and 2 suggest that memory for time of movie scenes relies on a general, higher-order representation of the entire movie script which guides the memory judgments beyond what has been effectively encoded. Put differently, participants did not appear to make judgments that are based on what they effectively watched, but rather on a general movie script that was automatically activated based on the seen movie fragment. Of note, the last part of the video was associated not only with the largest absolute and relative error but also with the highest level of temporal disorganization. This finding might suggest that the bias might not represent a uniform compression of time but rather a more general disorganization of the temporal representation. This and other effects associated with the cut-before-end procedure were further investigated in Experiment 3.

## 4. Experiment 3

Experiment 3 was a replication of Experiment 2, except that participants were presented with a new movie with several different features compared to the one employed in Experiment 1-2. We now presented the first 60 mins of "Wallace & Gromit: The Curse of the Were-Rabbit" (2005). While Sherlock is a crime film with a contemporary setting and real actors, Wallace & Gromit is a stop-motion animated comedy in which characters, objects, and background are made of plasticine clay. Despite these differences, the two movies have a similar total duration (87 vs. 80 mins, respectively) and are both based on a conventional script with a strong causal/situational structure that broadly includes four acts (setup, complication, development, and climax; see Cutting, 2016). The rationale of the experiment was to test whether the systematic bias associated with the encoding of an interrupted movie was also observed for a very different movie, which nonetheless shares a conventional script structure, and whether such a bias was again associated with a decrease of order memory performance.

### 4.1. Methods

#### *4.1.1. Participants*

Fifteen new volunteers (10 females; aged 20-30; mean age: 22.7 years) participated in the study with the same inclusion criteria of Experiment 1-2.

#### *4.1.2. Stimuli and procedure*

Experiment 3 was a replication of Experiment 2. The difference was that participants viewed only the first 60 min of "Wallace & Gromit: The Curse of the Were-Rabbit" (2005). Old stimuli [N=114 (108+6)] were taken from the presented video and sampled every 30 secs from the beginning of the movie. New stimuli [N=114 (108+6)] were selected from two short films "A grand day out" (1989) and "A close shave" (1995) that share characters, objects, and background with the presented movie. The timeline was made of 720 consecutive segments, each corresponding to 5 secs of the movie. An independent group of 20 participants identified event boundaries in the movie with the same instruction as in experiment 1. This procedure identified 35 boundaries in total and 28 boundaries for the presented video (16 in the first and 12 in the second half of the video; **Figure 1C**).

*4.1.3. Data analysis*
Data analysis was the same as in Experiment 2.

4.2. Results
Overall item recognition accuracy was 0.93 ± 0.05. The ANOVA yielded a significant main effect of movie part [$F(5, 70) = 3.9183$, $p < 0.005$, $\eta_p^2 = 0.22$]. Post-hoc analyses showed that recognition judgments for clips extracted from Part 2 (0.96 ± 0.05) were significantly more accurate compared to those extracted from Part 4 (0.84 ± 0.19) ($p < 0.005$). There was no significant difference in recognition accuracy for clips extracted from Part 1(0.88 ± 0.12), Part 3 (0.90 ± 0.10), Part 5 (0.88 ± 0.14), and Part 6 (0.92 ± 0.09) (p = n.s.). Clicks were distributed fairly homogeneously along the visual analog scale, apart from the very last part (**Figure 5A**). The level of absolute and relative error across trials was 443 ± 87 secs and -42 ± 223 secs, respectively (**Figure 5B**). For absolute error, the ANOVA (**Figure 5C, red**) yielded a significant main effect of movie part [$F(5, 70) = 3.03$, $p < 0.05$, $\eta_p^2 = 0.18$]. Post-hoc analyses showed that the only significant difference was between Part 1 and 3 ($p < 0.05$). For relative error, the ANOVA (**Figure 5C, blue**) revealed a significant main effect of movie part [$F(5, 70) = 15.84$, $p < 0.0001$, $\eta_p^2 = 0.53$]. Post-hoc analyses showed that judgments for clips from Part 5 and 6 were significantly less precise compared to those for clips from Part 1 to 4 (all $p < 0.05$). A significant difference was also observed between parts 5 and 6. One-sample t-tests revealed that a significant deviation from zero was only present in Part 6 ($p < 0.0001$). Therefore, the analysis of relative error confirms the presence of a bias that specifically affects clips extracted from the last part of the presented video.
As in Experiment 2, clips that were closer to the last part of the presented video were associated with increased absolute error (significant positive correlation between absolute error and clip onset, $r_s = 0.27$, $p < 0.005$, **Figure 5D**) and increased level of underestimation (significant negative correlation between relative error and clip onset, $r_s = -0.56$, $p < 0.0001$, **Figure 5E**). Tests conducted in each individual indicated a significant ($p<0.01$) correlation in 10 /15 subjects. However, the strength of the correlation was lower than that observed in the previous experiment. The analysis of the inter-trial correlation between the absolute error and the boundary distance indicated the absence of a significant correlation ($r_s = - 0.10$, p = n.s.). The same result was obtained when splitting the video in the first ($r_s = - 0.18$, p = n.s.) and the second half ($r_s = - 0.06$, p = n.s).
The analysis of the correlation between estimated and actual order of the clips revealed once more the presence of a very strong correlation ($r_s = 0.95$, $p < 0.0001$). There was a significant correlation between estimated and actual order for clips extracted from Part 1 ($r_s = 0.68$, $p < 0.005$), Part 2 ($r_s = 0.65$, $p < 0.005$), Part 3 ($r_s = 0.72$, $p < 0.001$), but not from Part 4 ($r_s = 0.42$, p = n.s.) and Part 5 ($r_s = 0.11$, p = n.s.). However, the correlation coefficient was highest in the final part of the video (Part 6: $r_s = 0.88$, $p = 0.0001$, **Figure 5F**), in which the position bias was detected.

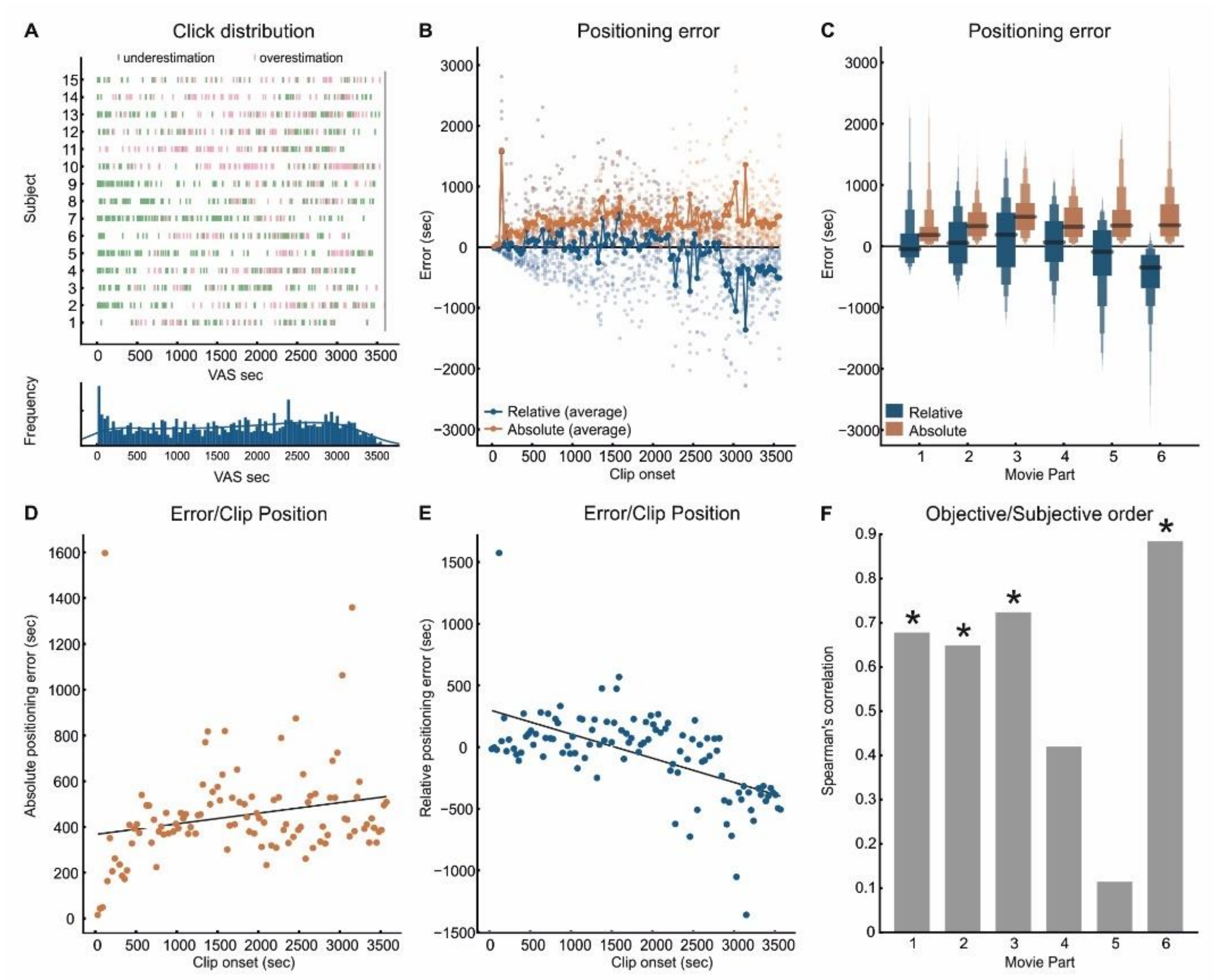


**Figure 5. Results of Experiment 3.**
Memory for time performance for video clips extracted from the movie “Wallace & Gromit: The Curse of the Were-Rabbit”, of which only 60 mins were presented the previous day (Experiment 3).
**A.** Click distribution for each subject.
**B.** Absolute (red line) and relative (blue line) error, expressed in secs and averaged across subjects, in the positioning of the clips on the visual analog scale as a function of the clip position in the movie
**C.** Absolute (red) and relative (blue) error as a function of the movie part (part duration: 10 mins).
**D-E.** Scatter plot showing the relationship between the clip onset and both the absolute (D) and the relative (E) positioning error.
**F.** Graph representing the correlation between the estimated and the actual order of the video clips.

## 4.3. Discussion

Differently from Experiment 2, in which a significant trial-by-trial correlation was observed between the absolute and relative error, the results of Experiment 3 indicate an interesting divergence between the two indices of performance. Specifically, the pattern of absolute error appears to partly resemble that of Experiment 1, although errors did not significantly diminish in the last part of the presented video. Instead, the clear underestimation effect observed for clips belonging to the last part of the presented video, expressed by the relative error, is highly reminiscent of the pattern observed in Experiment 2, albeit observed in a narrower temporal window. Of note, the independence between the two indices of performance suggests that the cut-before-end manipulation in this experiment is specifically associated with a temporal biasing effect rather than with a general drop of memory for time performance. Importantly, despite the different genre, content, editing, directing style, etc of the movie presented in Experiment 3 vs. 2, the replication of a systematic bias for clips that were closer to the missing part of the movie is again consistent with the hypothesis that knowledge of the movie script affects memory for time and allows to generalize the results to different contexts.

Notably, this time there was no significant correlation between absolute error and boundary distance. This finding provides support to the hypothesis that the effect of boundaries on memory for time depends on the granularity of event segmentation, given that the video was segmented in fewer events compared to that used in Experiment 1 and 2. Differently from experiment 2, we also observed a strong correlation between the estimated and the actual order of the clips in the last part of the presented video. This result demonstrates that the underestimation bias is not necessarily associated with a general disorganization of the temporal representation. In other words, it seems that subjects moved back the sequential chain of clips of the final part of the video in an orderly fashion.

## 5. General discussion

The present study aimed to investigate the mechanisms underlying memory for time of movie scenes. Specifically, we examined whether performance in a timeline positioning task was modulated by spontaneous event segmentation and script-based prior knowledge (Experiment 1). When participants encoded a full movie, they were more precise at judging the time of occurrence of clips extracted from the beginning and the end parts compared to middle ones, and that of clips that were closer to event boundaries. We then manipulated the length of the presented movie, under the hypothesis that watching a large fraction of a movie that follows a conventional script would automatically activate the entire corresponding script representation, and this would in turn affect memory for time judgments (Experiment 2). Consistent with the hypothesis, we found that participants manifested a systematic bias in memory for time when only 2/3 of the movie was presented. This bias consisted of an increasing underestimation of the time of occurrence for clips that were closer to the end of the presented video. A similar underestimation of clip position was observed when participants watched a very different movie (Experiment 3), suggesting that the effect is not limited to a specific movie/script. The results of the last experiment further indicate that the underestimation bias is not necessarily associated with a general disorganization of the temporal representation.

### 5.1. Better memory for time at extreme points of the movie

Better performance for extreme points of the timeline in Experiment 1 was expected based on the notion that the opening and the closing acts are crucial moments within a narrative and their temporal position might be remembered more accurately.

It could be claimed that the beginning/end effect found in Experiment 1 (U-shape function) was simply based on well-known primacy/recency biases in memory (i.e., people tend to better recall earliest and latest items compared to middle items; Talmi, Grady, Goshen-Gottstein, & Moscovitch, 2005). There is evidence suggesting that these serial effects are not restricted to situations involving immediate free recall of lists of stimuli (Ebbinghaus, 1885/1913; Glanzer & Cunitz, 1966; Murdock, 1974) but can be observed also in other contexts, such as in paradigms involving thought retrieval (Stawarczyk & D'Argembeau, 2019). By the same logic, the flow of thoughts might be considered somewhat akin to the sequence of discrete events perceived during movie watching. However, three arguments argue against a typical primacy/recency effect in this context. First, encoding and retrieval sessions in Experiment 1 were separated by a ~24 hrs interval, suggesting that task performance was exclusively based on long-term memory.

Second, no recency effect was observed in Experiment 2, where, in contrast, memory trials from the last part of the presented video were associated with the worst level of performance. At first glance, this can seem counterintuitive. We all tend to think that the first and the last parts of activities will be better remembered, at the very least because they constitute crucial landmarks of a given experience. This common view is also supported by studies on autobiographical memory. For instance, Robinson (1986) found that remembering life events relies on temporal referents deriving from the beginnings and ends of one's work calendar, like a scholastic semester or a sport season. Furthermore, other indices of memory for time performance are more accurate when events occur in the proximity of key temporal landmarks (Friedman, 2004). However, our results suggest that people were not using the end of the video as the *real* movie end (see section 5.3 below). Third, although the "stream of consciousness" (James, 1890) can be coherently organized around a chain of thoughts that follows a trajectory, we do not know whether it shares the same inherent structure of a narrative story. Specifically, it has been proposed that movies are generally structured around a set of four-acts: setup, complication, development, and climax, with possible additional prologue and epilogue (Cutting, 2016; Thompson, 1999; Bordwell, 2006). Interestingly, this kind of "story grammar" (Rumelhart, 1975; Kintsch, Mandel, & Kozminsky, 1977; Mandler & Johnson, 1977; Thorndyke, 1977; Stein & Glenn, 1979; Thorndyke & Yekovich, 1980) is relatively invariant across different stories and has very similar structural characteristics compared to many other types of narratives (i.e. oral histories, folktales, novels, plays, manga). Taken together, these results suggest that participants only treated the beginning and the end of the presented video as temporal landmarks when congruence could be found with an existing script. In this regard, we might use the term "*schematic* recency/primacy effects" to refer to long-term memory effects that depend on the matching between the activity and the underlying event schema.

5.2. The role of event boundaries

Although the effect of proximity to boundaries observed in Experiment 1 and 2 was not particularly robust, it nonetheless indicates a link between spontaneous event segmentation and memory for time performance and supports the idea that the automatic parsing of the cinematic flow into meaningful events affects memory for time (Boltz, 1992; Zacks, Speer, Vettel, & Jacoby, 2006; Swallow, Zacks, & Abrams, 2009; Zacks, Speer, & Reynolds, 2009; Radvansky & Zacks, 2017). The Event Segmentation Theory (Zacks, Speer, Swallow, Braver, & Reynolds, 2007) proposes that, during ongoing comprehension, our perceptual system sets up a working memory representation of the current event which is specifically updated at event boundaries. Accordingly, near-boundaries stimuli are thought to receive extra processing that leads to information being recalled more efficiently, eventually resulting in higher recognition memory performance (e.g. Newtson & Engquist, 1976) and more detailed recall (Schwan, Garsoffky, & Hesse, 2000; Swallow, Zacks, & Abrams, 2009). The present results extend previous research by showing that proximity to event boundaries also results in more accurate judgments about the time of occurrence. Notably, clips positioned around event boundaries were positioned with higher accuracy on the timeline even in absence of explicit perceptual cues (e.g. *cuts*, commercial breaks, etc.) that are known to strengthen the placement of boundaries (Boltz, 1992; Schwan, Garsoffky, & Hesse, 2000). Moreover, while prior studies have used short videos of everyday events (Schwan & Garsoffky, 2004) or ~50-min films (Boltz, 1992), we found a temporal effect at a longer timescale.

However, a similar relationship was not observed in Experiment 3 and was not present for the second part of the video presented in Experiment 1 and 2. A possible explanation for this apparent discrepancy is that the effect of segmentation on memory for time depends

on the number of boundaries/events in the story. According to this view, the overall null effect in Experiment 3 would be due to an insufficient number of boundaries compared to Experiments 1 and 2. Likewise, in Experiments 1 and 2 a significant relationship was only observed for the segment of the video that contained the largest number of boundaries/events. There is some evidence in the literature that more event boundaries can improve memory performance (Newtson, 1973). For instance, Boltz (1992) found that the effect of commercial breaks on recall performance varied as a function of the number of commercial breaks at boundaries. Similarly, Pettijohn and colleagues (2016) showed that increasing the number of event boundaries increased the memory benefit.
Taken together, our findings suggest that the presence of more boundaries, which indicates the parsing of information in different sub-events, facilitates the formation of a temporal representation of the story in long-term memory, which is essential for judgments of the time of occurrence. What remains unclear is whether the crucial factor is the actual number of events in the audiovisual material or the level of granularity chosen by the observer, which might also change through the course of the movie. To disentangle the two possibilities, future experiments should explicitly manipulate the instructions about the granularity of segmentation of the same movie.

5.3. The role of script-based knowledge

By showing a robust underestimation effect on the last part of the video when the end part of the movie is removed from the encoding session, the results of Experiment 2 further indicate that temporal memory for complex audio-visual information depends on script-based prior knowledge about the global schema of the story. In accordance with reconstructive theories of memory (e.g., Bartlett, 1932; Ross, 1989; Loftus, 1993; Conway & Pleydell-Pearce, 2000), we suggest that participants automatically reconstructed the position of the events by relying on a general script-based prior knowledge of conventional stories. More specifically, the reconstructive model of memory for time (Friedman, 1993) posits that different aspects of episodic memory are combined with general knowledge of time patterns and conventional locations in time to infer when the event has probably occurred.
Moreover, our results are consistent with previous research that has employed material, such as stories/movies of routine events (e.g. eating at the restaurant), which are considered the quintessence of the script-based cognition. These studies have shown that when participants are required to recall routine events narrated in the story, they are more likely to adapt their responses as a function of an existing script, and distort the order of events to fit their memories to a stereotypical scheme (Abbott, Black, & Smith, 1985; Bower, Black, & Turner, 1979; Bower & Clark-Meyers, 1980; Migueles & García-Bajos, 2012). Regarding our experiment, it is possible that, if tested with a different temporal task (for instance, ordering a set of pictures extracted from the movie), people would be less likely to exhibit such a robust memory distortion. We also do not know whether such a global representation is always activated when making a temporal judgment on narrative material and the degree to which participants are aware of this bias. A similar effect was replicated in Experiment 3, although in this case the underestimation bias was observed without a concomitant decline in general performance. This finding suggests that the effect cannot be explained by basic attentional factors (i.e. general increase in temporal confusion, see also section 5.5 below) but rather with the structure of the associated memory representation. Notably, the amount of the observed underestimation effect sensibly diverged across the two experiments (~17 mins vs. ~7 mins), a result that could be explained by differences in the plots leading to more or less variability across viewers (Hasson, Nir, Levy, Fuhrmann, & Malach, 2004). Alternatively, the difference could be due

to a difference in the degree to which the two movies adhere to a standard script, which eventually affects the strength of expectations about the missing part.

### 5.4 Memory for time and item recognition

In studies of memory of news or autobiographical events, temporal accuracy is usually associated with how well the participants remember the event (Strube & Neubauer, 1988; Wright, Gaskell, & O'Muircheartaigh's, 1997). This finding fits with reconstructive theories of memory for time that posit that contextual information associated with an event is used to infer when the event has occurred (e.g. Friedman, 2004). The significant correlation between overall item recognition and memory for time performance across subjects observed in Experiment 1 provides further support to this interpretation.

However, several results from the present study suggest that the relationship between recognition and memory for time is not straightforward. First, the relationship was not significant when assessed at the level of individual clips. Moreover, item recognition was not affected by proximity to boundaries or by clip position in the same manner as memory for time. This apparent discrepancy might have several explanations, partially associated with our study design. Specifically, item recognition performance was generally very high, with less variability compared to memory for time. Memory for time was only assessed for clips judged as old, a fact that prevented a direct contrast between correctly and incorrectly recognized pictures. Lastly, to obtain a meaningful index of item recognition accuracy, performance for each clip was averaged across subjects, thereby losing control over inter-subject variability.

Alternatively, the pattern of results might indicate that memory for time is associated with the amount of information that can be recollected about that item and not simply with a mere sense of familiarity with the item, which is enough to drive item recognition judgments (Tulving, 1985).

### 5.5 Memory for time and order memory.

Across the three experiments, we found a robust correlation between the estimated and the actual order of the clips. The presence of a gross relationship was expected given that narrative stories are intrinsically ordered in a sequential/causal fashion. At the same time, however, the level of precision of temporal order was surprising, considering that participants were not asked to judge the relative time of two items (e.g. recency judgments; Friedman, 1993; DuBrow & Davachi, 2013) but instead to position the clips with respect to a global pattern, with no feedback about previously positioned clips. Moreover, some findings from the present study indicate relative independence between time-of-occurrence and order memory judgments. In the last part of the movie presented in Experiment 1, high temporal precision was accompanied by low order performance. Conversely, in the last part of the presented video in Experiment 3, temporal order was preserved vis-a-vis a significant underestimation bias. Thus, the sequence of events in the temporal representation of the movie appears similar to a flexible chain that can be either simply compressed (Experiment 3) or twisted (Experiment 2) by the influence of a higher-order schema. In general, the relative independence between the two indices of performance is consistent with the view that memory for time cannot be explained by a single mechanism (Friedman 1993, 2004). Instead, different mechanisms appear to explain performance in task tapping on different aspects (position, order) of memory for time.

### 5.6 Limitation and open questions

One limitation of the current study is that it did not directly investigate the types of situational change that contribute to event segmentation. According to the Event Indexing

Model (Zwaan et al, 1995), people monitor situation continuity during online comprehension by keeping track of at least five dimensions (i.e. time, space, causality, intentionality, characters). The identification of event boundaries results from processing changes in these features (Magliano, Miller, Zwaan, 2001; Zacks, Speer, Swallow, Maley, 2010; Cutting & Iricinschi, 2015 ). Our approach was instead to directly obtain event boundaries in an independent sample, based on the rationale the placement of boundaries should reflect the overt manifestation of the monitoring of the different situational dimensions. Nonetheless, it would be interesting to identify effective ways to directly associate variability in these dimensions with variability in memory for time.
Another limitation pertains to the cut-before-end procedure. Our arbitrary choice to cut the last thirty minutes of the movie resulted in an abrupt interruption of the story. While we opted for a quantitative approach, systematic manipulation of the missing part would provide information about how much movie is necessary to activate the script.
Other questions remain open from the current research. Here we try to outline the ones that seem most important to us. First, it would be interesting to manipulate the delay between encoding and retrieval and investigate whether the underestimation bias crucially depends on memory consolidation (van Kesteren, Ruiter, Fernández, & Henson, 2012; Ghosh & Gilboa, 2014; Runyan, Moore, & Dash, 2019).
A further issue concerns the degree to which the systematic bias generalizes to different modalities (e.g. audio narratives). Specifically, we might speculate that this kind of schema constitutes a parsimonious, uniquely human device that allows the effective transmission of knowledge (Colby, 1965).
Finally, by manipulating the degree to which the storyline follows a conventional trajectory, it would be possible to test whether the “well-formedness” of the movie (Rumelhart, 1975) is a necessary factor for the systematic bias to occur.

## 6. Conclusions

The present study reveals that memory for time of movie scenes depends both on event segmentation and on script-based prior knowledge. As with Bartlett’s Indians and ghosts who ended up conforming to a more rational scheme, we found that also narrative time tends to be “stretched”, normalized, and adapted to a standard narrative template. Consequently, memories are moved on time to make room for missing information.

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