Current Research in Behavioral Sciences 6 (2024) 100145



Contents lists available at ScienceDirect

Current Research in Behavioral Sciences

journal homepage: www.elsevier.com/locate/crbeha



Discrete memories of a continuous world: A working memory perspective on event segmentation

Berna Güler [a,*], Zeynep Adıgüzel [c], Bilge Uysal [b], Eren Günseli [a]

[a] Department of Psychology, Sabancı University, Istanbul, Turkey
[b] Donders Institute for Brain, Cognition and Behaviour, Radboud University, Nijmegen, Holland
[c] Department of Psychology, Koç University, Istanbul, Turkey

ARTICLE INFO

Keywords:
Event segmentation
Event boundary
Episodic memory
Attention
Working memory

ABSTRACT

We perceive the world in a continuum but remember our past as discrete episodic events. Dominant models of event segmentation suggest that prediction errors or contextual changes are the driving factors that parse continuous experiences into segmented events. These models propose working memory to hold a critical role in event segmentation, yet the particular functioning of working memory that underlies segmented episodic memories remains unclear. Here, we first review the literature regarding the factors that result in the segmentation of episodic memories. Next, we discuss the role of working memory under two possible models regarding how it represents information within each event and suggest experimental predictions. Clarifying the contributions of working memory to event segmentation is important to improve our understanding of the structure of episodic memories.

1. Introduction

Our perceptual experience of the external world is continuous. Yet, recent studies show that we segment this ongoing perception into meaningful memory events, a phenomenon referred to as *event segmentation* (Kurby and Zacks, 2008). Imagine someone asked you how your day was. You would be likely to remember a morning routine event, a commute event, a work event, a lunch break event, etc. Event segmentation plays important roles in many aspects of memory such as the formation and structuring of episodic memories (Swallow et al., 2009), online memory updating (Kurby and Zacks, 2008), and enhancing memory over long delays (Flores et al., 2017). It contributes to perceiving and understanding others' actions, while also organizing our own actions (Hard et al., 2011). Encountering event boundaries keeps people away from mind-wandering (Faber et al., 2018) and increases the effectiveness of cognitive control (Reimer et al., 2015). It uniquely predicts how well events are remembered even after controlling for general cognitive abilities (Sargent et al., 2013). Thus, event segmentation is a building block of episodic memory, and it has many consequences on various cognitive mechanisms. In this paper, we will review what event segmentation is, why event segmentation occurs, and how event segmentation structures memories, with a focus on the role of working memory (WM).

WM is the active mental workspace that allows holding task-relevant information and rules (Baddeley, Alan, 1986; Cowan, 1988; Engle, 2001), performing mental operations (Axmacher et al., 2007), and guiding behavior (Postle, 2015; Woodman et al., 2007). Although it is often considered as the brief representation of information until long-term memory consolidation takes place, WM is involved in storing information retrieved from LTM (Fukuda and Woodman, 2017). Moreover, some studies suggest WM can be unconscious (Barton et al., 2022; Soto et al., 2011; Velichkovsky, 2017). Thus, a more tangible definition of WM could be neurally active representations instead of conscious storage of task-relevant information over brief intervals (Awh and Vogel, 2020; Kamiński et al., 2017; Scotti et al., 2021; Vogel and Machizawa, 2004). Moreover, the concept of cortical reinstatement, originally associated with WM tasks, has been observed during episodic memory retrieval and at event boundaries. This suggests that WM activation goes beyond traditional working memory tasks and is relevant to a broader range of cognitive processes, a concept that will be explored in the forthcoming review paper.

* Corresponding author at: Orta mahalle, Üniversite caddesi, No:27 Tuzla, 34956 Istanbul, Turkey.
E-mail address: berna.guler@sabanciuniv.edu (B. Güler).

https://doi.org/10.1016/j.crbeha.2023.100145
Received 30 December 2022; Received in revised form 18 December 2023; Accepted 21 December 2023
Available online 28 December 2023
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2. What is event segmentation?

Event segmentation is the process of mentally segmenting ongoing activity into units called events that define a specific time period in a particular context. The crucial changes in this ongoing activity usually mark the end of one event and the beginning of another, which is referred to as an *event boundary*. These changes can be perceptual such as changes in movement (Hard et al., 2006), location (Lawrence and Peterson, 2016; Radvansky et al., 2010; Radvansky and Copeland, 2006), time (Ezzyat and Davachi, 2011; Speer and Zacks, 2005; van de Ven et al., 2022), or conceptual, such as changes in the goal of the actor (Huff et al., 2012), task rules (Wang and Egner, 2022) and causal relations of the situation (Pettijohn and Radvansky, 2016). A perceived event boundary results in the segmentation of an event such that a new event starts upon the detection of an event boundary.

Although event boundaries are often associated with relatively major perceptual changes mentioned above, smaller changes in an event also create sub-events within an event. Event segmentation is suggested to have a hierarchical structure that consists of events in various temporal grains: fine-grained events are smaller units that eventually constitute coarse-grained events (Richmond et al., 2017). For example, consider having breakfast as the coarse-grained event, then taking the cereal box out of the cabinet, taking the milk out of the fridge, and putting cereal into the bowl, etc. will all be considered as fine-grained events. Baldassano et al. (2017) showed both behavioral and neural evidence of this hierarchical structure using multi-voxel functional magnetic resonance imaging (fMRI) pattern analysis. They found that early sensory regions, such as early visual and auditory areas, showed faster changes in brain activity between stable patterns that are related to processing fine-grained events, and high-level brain regions, such as angular gyrus and posterior medial cortex, indicate more constant activity patterns around minutes which are related to processing coarse-grained events.

How do we know a person recognizes that one event ends and another begins? Newtson and Engquist (1976) developed a segmentation task in which viewers watch a movie and press a button whenever they think one meaningful event ends and another begins. More recent studies had used versions of this procedure in which participants watched animations of flashing objects (Tauzin, 2015), or read or listened to stories (e.g., Zacks et al., 2009). More implicit measures were recently introduced such as the dwell-time paradigm, in which participants go through a slide show by clicking a computer mouse at their own pace and longer durations for clicks are used as indices of event boundaries (Hard et al., 2011; Kosie and Baldwin, 2019). Good inter-subjective agreement and reliability were reported across participants' decisions regarding the timing of event boundaries (Speer et al., 2003), indicating that event boundaries are mostly consistent across individuals.

Neuroimaging data is also used to assess when event segmentation takes place. For example, Ezzyat and Davachi (2011) found that fMRI BOLD activity in the ventromedial prefrontal cortex (vmPFC) ramps up within events and suddenly drops at event boundaries as determined by an independent group of participants. This pattern was suggested to reflect first the accumulation and then the flushing of event-related contents from WM (Clewett and Davachi, 2017; Ongchoco and Scholl, 2019). Also, hippocampal BOLD activity increases at event boundaries and this increase predicts later serial recall (DuBrow and Davachi, 2016; Reagh et al., 2020), which suggests it could reflect learning the relationship and order between these events (also see Ben-Yakov and Dudai, 2011). Regardless of the exact mechanism, these results show that the univariate fMRI signal is sensitive to event structure.

Using multivariate measures in the fMRI or electroencephalography (EEG), sudden changes in the inter-item similarity have been suggested to reflect changes in event models - mental models claimed to reflect the aspects, rules, and items of an ongoing event (Sols et al., 2017). These studies found neuroimaging indices of event segmentation even when participants were not explicitly instructed to detect event boundaries (Zacks et al., 2001), whether participants watched a video (Swallow et al., 2011; Zacks et al., 2006), read a text (Ezzyat and Davachi, 2011), listened to an audio narrative (Whitney et al., 2009) or music (Sridharan et al., 2007). Both behavioral and neural indices indicate that we create discrete events from a continuous percept with or without explicit awareness. Segmenting the vast amount of continuous perceptual input into discrete events may be one way to achieve simplification and generalization of information for behavioral guidance and memory structure.

Segmented episodes reveal themselves in stronger integration of instances within- compared to across-events. For instance, when remembering the sequence of events, within-event instances are perceived temporally closer to each other with increased accuracy, whereas across-event instances are perceived farther apart with less accuracy (DuBrow and Davachi, 2014; Horner et al., 2016; Wang and Egner, 2022) (Fig. 1). Moreover, when deciding which of multiple items were seen more recently, the judgment is more accurate and participants are more confident if items are from the same event compared to items that span a boundary (DuBrow and Davachi, 2013, 2014, 2016; Wang and Egner, 2022) as long as the encoding context is not available at retrieval (Wen and Egner, 2022). These findings show that segmentation structures episodic memory such that within-event instances form stronger associations than across-event instances.

Although a great deal of evidence suggests that individuals perceive event boundaries with high inter-individual agreement and that these memoranda within an event are strongly associated with each other, there are different explanations for why continuous percepts are segmented into discrete memories.

3. Why does event segmentation take place?

3.1. Event segmentation theory and the role of prediction errors

Event segmentation theory (EST) is one of the most influential theories on why event segmentation occurs. According to EST, people form working event models in WM (Zacks and Swallow, 2007). Event models are the representations of the current event. They contain both the current perceptual details and relevant episodic and semantic memories, such as characters' goals, spatiotemporal information, perceptual details, and causes of actions (Bailey et al., 2013; Zacks et al., 2007). Via these representations, event models contribute to making predictions of what is likely to occur next within a particular event (Kurby and Zacks, 2008; Zacks et al., 2009). When the perceptual or contextual properties of the ongoing activity change, people experience a prediction error because their event models are no longer good at predicting what will come next. These prediction errors lead people to perceive event boundaries and update their working event models based on the currently available information (Kurby and Zacks, 2008; Sargent et al., 2013). Once the new event model proves to be more effective than the old one, the prediction error decreases, which automatically settles the error-monitoring system into a new stable state (Kurby and Zacks, 2008; Zacks et al., 2007; Zacks and Swallow, 2007).

Zacks et al. (2011) tested the prediction error account by showing participants movie clips of everyday activities, pausing the video at certain times, and asking participants to predict the following 5 s. In line with EST, they found that if there is an intervening event boundary - determined by independent raters - the prediction accuracy was lower and response times were higher for across-event items. Thus, one functional benefit of event segmentation could be to constitute a model of the world for making reliable predictions. But is it always the case?

Although mounting evidence favors explanations based on prediction error for event segmentation, the account leaves many questions open, which leads to doubt about whether the prediction error is really necessary after all. First, changes in prediction error may not be meaningful enough to reflect the event structure, for example, when the environment is too noisy or uncertain (O'Reilly et al., 2013). In that

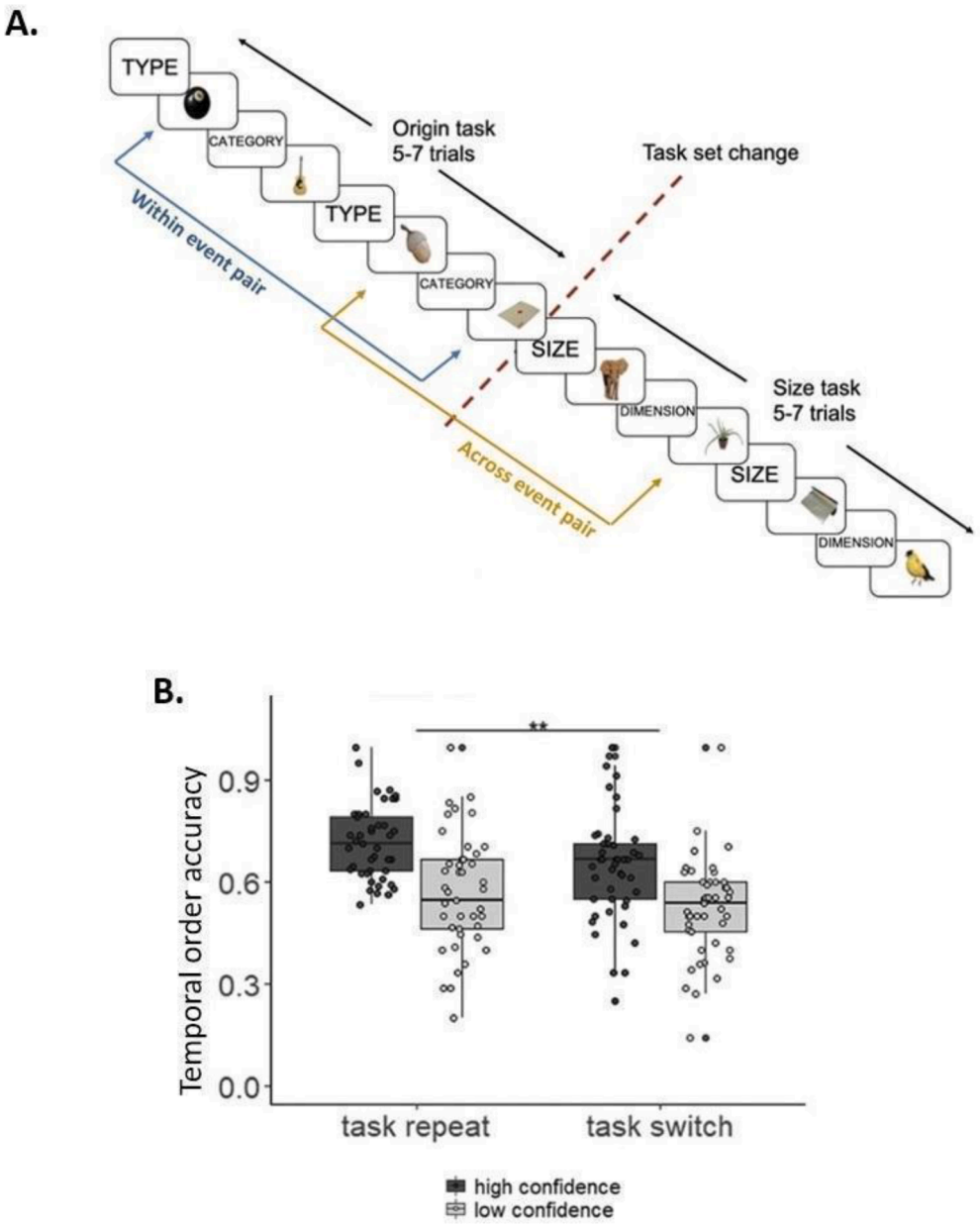


Fig. 1. An example event segmentation study design and the common consistent findings in the literature are taken from the study by Wang and Egner (2022). **(A)** During encoding, participants evaluated different objects with one of two possible rules that were defined as origin (natural or man-made) or size task (larger or smaller than a shoebox). Dashed line represents the event boundary where there is a change from one task to the other. During the temporal order task, within and across event pairs were shown. Each pair had two intervening items between. Participants were asked which item was seen first. **(B)** Temporal order accuracy and confidence judgments were higher for task repeat (within-event) pairs compared to task switch (across-event) pairs. Such higher temporal order accuracy for within vs. across event pairs is one of the hallmark indices of event segmentation.

case, we cannot rely on the prediction error system to decide events.

Second, the predictability of boundary-evoking instances, such as changes in timing context and switching between task rules, which arguably should reduce prediction error strength, does not prevent segmentation (Pettijohn and Radvansky, 2016; van de Ven et al., 2022; Wang and Egner, 2022). For example, Pettijohn and Radvansky (2016) tested how expectedness or predictability affected the segmentation using stories with foreshadowed event shifts that increased the predictability of the event shift. Regardless of the foreshadowing, behavioral indices of event segmentation were observed at event boundaries: responses were slower and less accurate. In another study, Lee et al. (2021) showed that event boundaries, as determined by temporal shifts in fMRI activity patterns, occurred earlier with each time repeated viewing of the same movie, which suggests that early experiences that increase predictability do not reduce event boundaries but rather shift them to an earlier time point due to its anticipation. If predicting event boundaries does not stop events from being segmented, then prediction errors are unlikely to be the main driving factor for event segmentation. However, there have been attempts to account for the lack of predictability effects on event segmentation via revising the standard EST. For example, Baldwin and colleagues suggested that event boundaries could be defined as predictable structures, namely statistical regularities, within a continuous stream of activity. In their view, instances with high transitional regularities would cluster together, and parts in between these clusters would constitute event boundaries (Baldwin, 2002; Baldwin et al., 2001; Baldwin and Kosie, 2021).

Third, the extent of a prediction error that is large enough to abandon the current event model and build a new one is not addressed by

EST. In other words, it is unclear how our perceptual system decides whether the upcoming information is reliable enough to stick to the current model or unpredictable enough to build a new one (Kuperberg, 2021). Thus, although prediction error can be one of the factors behind event segmentation, there is growing evidence to suggest that event segmentation can take place without prediction errors.

3.2. The role of switching across stable contexts

An influential alternative to the EST is the contextual stability account proposed by Davachi and her colleagues. Clewett and Davachi (2017) contributed to the view that prediction error might not be the only mechanism underlying segmentation by emphasizing the contextual stability surrounding the events. They proposed that internal and external contextual fluctuations such as changes in stimulus categories, time, space, goal states, or image backgrounds are the basis for event segmentation. Relatedly, several empirical studies showed that moment-to-moment fluctuations in context can induce event boundaries, which is evident in the memory organization based on these fluctuations (DuBrow and Davachi, 2013, 2014; Heusser et al., 2018).

For example, a common experimental design used to explore the contextual fluctuation account is to present images from two distinct categories such as faces and objects in a repeating series. In these studies, temporal order memory accuracy is lower for across compared to within-event pairs crossing a boundary (DuBrow and Davachi, 2013, 2014, 2016; Wen and Egner, 2022), suggesting that context changes can trigger event boundaries. Moreover, within-event associations are found to be stronger than across-event associations, as found by faster and more accurate cued-recall for within-event pairs. Stronger within vs. across-event associations could reflect binding each memorandum to the stable context representation, facilitating later remembering (Cox et al., 2021).

A major challenge in dissociating the claims of prediction error and contextual stability accounts is that transitions across stable contexts generate prediction errors. For example, in the aforementioned studies, a change from the stable context of faces to the stable context is also expected to generate a prediction error. If so, how can we contrast the predictions of each model? To overcome this challenge, we recently

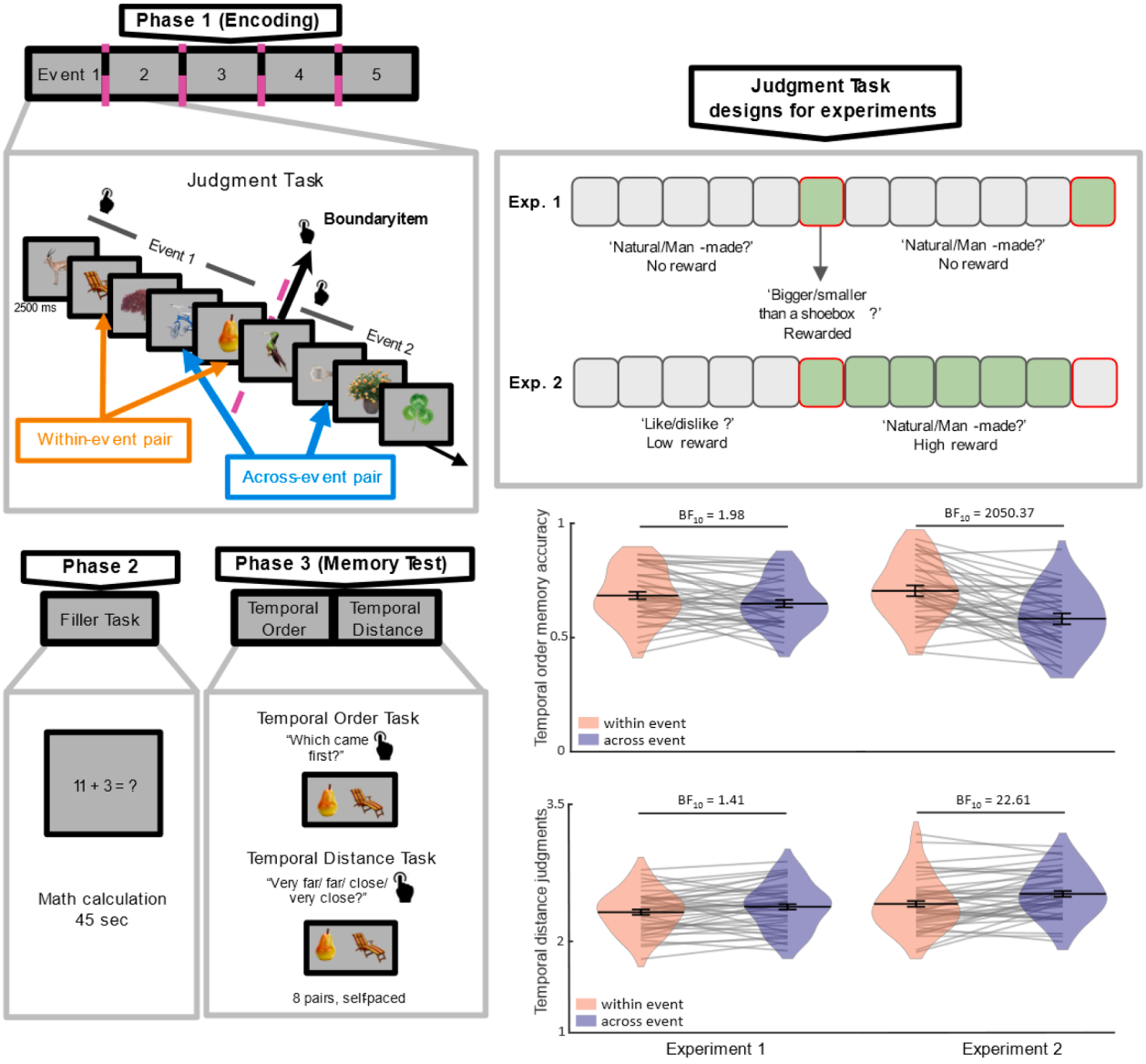


Fig. 2. The methodology, main manipulations between each experiment, and main findings for the temporal order and temporal distance judgments are shown in the figure. Experiment 1 was suggested to create prediction error without contextual stability. On the other hand, Experiment 2 was suggested to have contextual stability with stable reward value and task-rule during an event, while keeping the prediction error constant.

developed a paradigm that allows disentangling prediction errors from contextual stability (Güler et al., 2023; Fig. 2). Experiment 1 created prediction errors by having a different task rule and reward value every 6 items on a list of images evaluated under a particular judgment rule (e.g., like/dislike). In Experiment 2, the task rule and reward value persisted for another 5 items before switching back to the original values. This alternating pattern created a stable context during 6 consecutive items. Thus, while prediction error was present in each experiment, only Experiment 2 contained stable contexts. Reaction time costs at boundaries for the judgment task were larger in Experiment 1 vs Experiment 2, confirming that prediction errors were stronger in Experiment 1. In a temporal order task performed at the end of each image series, we found event segmentation only in Experiment 2 but not in Experiment 1. These results, derived from the first controlled comparison of the effects of each factor on event segmentation, suggest that contextual stability is the primary predictor of event segmentation. Consequently, previous studies interpreting their findings in terms of prediction errors may instead have found segmentation triggered by switches across stable contexts.

Although the debate over EST and contextual stability account is mostly based on externally driven factors such as changes in perceptual input, changes in the individual's internal states can also trigger event segmentation. In an opinion paper, Shin and DuBrow (2020) proposed that viewers' expectations about the subsequent future, i.e., their interferences, motivations, and beliefs, are the basis of event segmentation. Wang and Egner (2022) obtained support for this claim by showing that individuals' subjective intentions to switch between task rules are sufficient to create boundaries. The influence of such internal dynamics of observers on event segmentation is consistent with the contextual stability account of Clewett and Davachi (2017), as internal goals and states of an observer are parts of a broad definition of context.

To summarize, there is an ongoing debate regarding the fundamental cause of event segmentation. Traditionally, event segmentation was attributed to prediction errors, but an emerging body of evidence suggests that transitions across stable contexts may be the primary predictor. While when or why segmentation takes place remains a subject of debate, there is consensus regarding the strong influence of event segmentation in the organization of memories. Thus, an interesting question is how this influence is achieved. In other words, what are the cognitive mechanisms that turn continuous events in perception into discrete segments in memory?

4. How are continuous percepts segmented into discrete memories?

4.1. The need to clarify the role of WM in event segmentation

Numerous studies consider WM to play a crucial role in event segmentation. For example, WM is suggested to store event models that keep track of rules and features of the ongoing event (Zacks, 2020; Zacks et al., 2007). Evidence supporting this notion includes an increase in BOLD signal within the vmPFC within an event has been taken as evidence for the accumulation of instances within an episode in WM (Ezzyat and Davachi, 2011). If the accumulation of within-event information in WM is critical for the temporal structure of memories, then individual differences in WM capacity should predict segmentation differences. In line with this, individuals with higher WM capacity tend to segment events at boundaries that are commonly agreed on by other individuals, which in turn predicts better event recall (Bailey et al., 2013; Sargent et al., 2013).

Nevertheless, our understanding of how WM functions in event segmentation remains incomplete. Studies that directly track the accumulation of information within events are missing, leaving the specifics of WM involvement in event segmentation to be unexplored. Furthermore, the argument that WM underlies event segmentation due to its limited capacity (Jafarpour et al., 2022; Radvansky, 2017) is predominantly theoretical. For example, it is unclear how the WM system achieves a sense of continuity (Jafarpour et al., 2022) while operating within its constrained capacity (Baddeley et al., 1984; Cowan, 2001; Luck and Vogel, 1997; Oberauer, 2006; Oberauer et al., 2016), thus presenting a puzzle for event model theory. Likewise, the particular role of WM in creating a segmented episodic memory structure, both within and across events, has traditionally been overlooked (Radvansky, 2017). As such, numerous aspects of WM's involvement in event segmentation remain unexplored. Given the proposed critical role of WM in event segmentation, addressing these gaps is of great importance. Given that WM and LTM are continuously interacting for the encoding and retrieval of memories, and memory-driven behaviors (Ataseven et al., 2022; Ericsson and Kintsch, 1995; Fukuda and Woodman, 2017; Oberauer, 2002), we believe that how these processes are implemented is an important question that needs to be addressed.

One attempt to address these limitations is to question how WM stores and processes the event information. Even though previous studies did not have a direct measure of how WM deals with information within an event, they provide valuable insights into the underlying WM mechanisms. Here, we formulate two hypotheses that aim to elucidate the cognitive mechanisms responsible for establishing stronger associations within events. Both hypotheses suggest that stronger associations within events are due to the simultaneous storage of memoranda, given the suggested role of WM in forming associations (Van Dijck and Fias, 2011; Vogel et al., 2001). However, they differ in their claims on how WM and LTM jointly handle these memoranda *until* an event boundary is reached.

4.2. Accumulation and reactivation models

Given the proposed role of WM in event segmentation and the previously established role of WM in forming associations between memoranda, we posit that WM storing each memorandum within an event is critical for the observed behavioral effects of event segmentation on higher temporal order judgments and lower perceived distance for within-event instances. We propose that within-event associations are built during the simultaneous storage of instances, either as they are accumulated during an event or reactivated at the end of an event (Fig. 3).

4.2.1. Accumulation model

The first possible role of WM is to maintain and integrate the instances of an event by accumulating them until an event boundary. Then, all instances within this event are collectively transferred to LTM. WM repeats this process by starting to accumulate instances of the next event until the following event boundary. We will refer to this hypothesis as the "accumulation" model.

4.2.2. Reactivation model

The second model, which we will call the "reactivation" model, differs from the accumulation model such that each within-event memoranda are handed off to LTM right after its encoding instead of being accumulated in WM until an event boundary. Upon detection of an event boundary, previously encoded items in the present event are reactivated in WM to be associated with each other.

4.3. Supporting evidence

4.3.1. Supporting evidence for the accumulation model

Indirect evidence for the accumulation model comes from fMRI studies that show an activity increase in vmPFC, which is involved in storing task-relevant information (Banich et al., 2000; Walton et al., 2015), within events, and a sharp decrease at event boundaries (DuBrow and Davachi, 2016; Ezzyat and Davachi, 2011). Another circumstantial evidence was suggested via an EEG study (Wu et al., 2023), which found a gradually increasing within-event pattern similarity

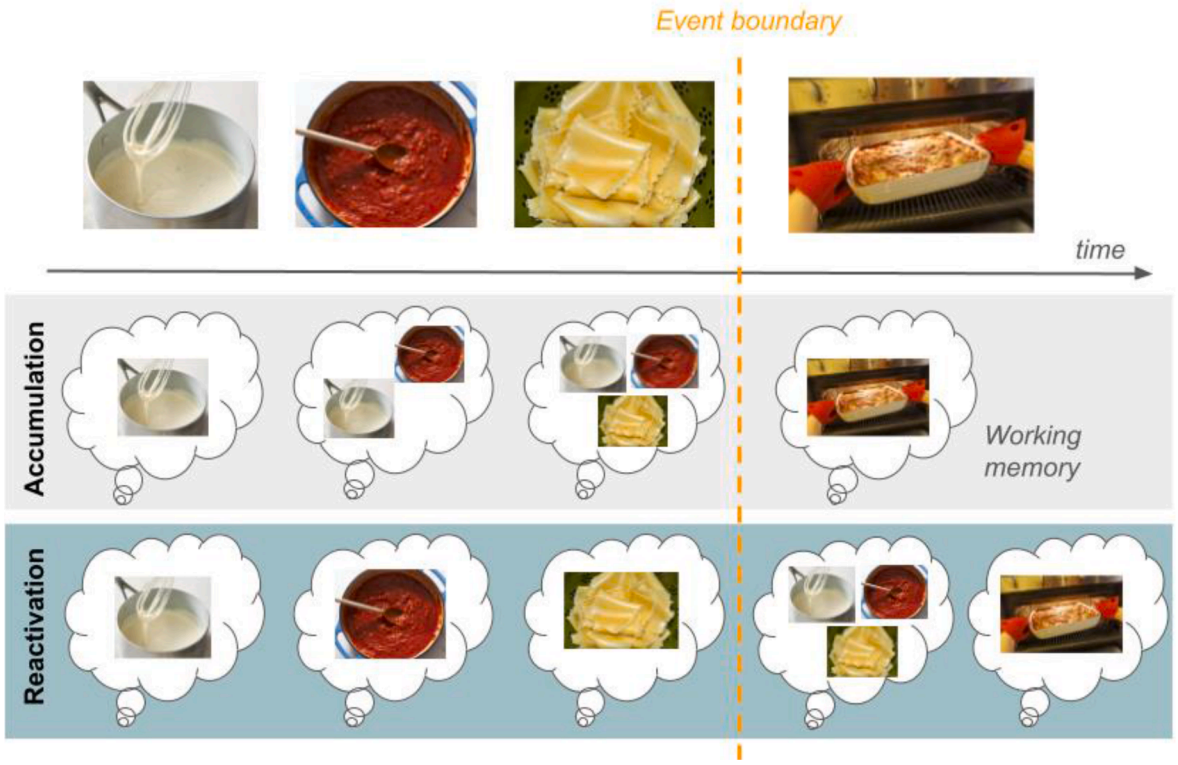


Fig. 3. Two theoretical views regarding how WM handles information within and across events. Imagine preparing lasagna for dinner with your friends. The process ends when the lasagna is ready and comes out of the oven. According to the accumulation model, WM stores all instances within an event in mind until an event boundary. Information is dropped at an event boundary, emptying WM for the memoranda of the new event. According to the reactivation model, WM stores only the most recent instance. All other memoranda are transferred to LTM. Upon the detection of an event boundary, all memoranda from the previous event are reactivated in WM. Soon after, they are removed from WM, which starts representing the instances of the new event.

when the instances of an event are accumulating in a stable context. Also, when there was an incongruent item defined as a boundary, this stable neural pattern was distributed compared to congruent transitions. Moreover, this decrease was followed by an increased reactivation of the just-encoded episode when encountered with an incongruent item, indicated by an increased N400. However, this increase in activity was associated with worse item recognition for boundary items. This gradually increasing activity during an event can be used as evidence for the accumulation of event-related information in WM.

The hippocampus is also suggested to be involved in WM maintenance during encoding and retrieval of sequential information since it plays a comprehensive role in memory processes (Baldassano et al., 2017; Davachi and DuBrow, 2015). In line with this, Heusser et al. (2016) found that increasing theta-phase locked gamma power in the hippocampus for each additional memory item during a sequential encoding. In that sense, the hippocampus can contribute to associating the event items while accumulating them in WM during encoding (Baldassano et al., 2017; Ben-Yakov and Henson, 2018; Ben-Yakov and Dudai, 2011; Cohn-Sheehy et al., 2020; Davachi and DuBrow, 2015; Kota et al., 2020; Reagh et al., 2020; Reagh and Ranganath, 2023; Sperling et al., 2003; Staresina and Davachi, 2010; Wang et al., 2014). Forming associations via hippocampal contribution can foster the encoding of an event and later accurately retrieving these memories.

4.3.2. Supporting evidence for the reactivation model

Evidence for the reactivation hypothesis comes from EEG and fMRI studies that observed indices of memory reactivation at event boundaries. In an EEG study, participants viewed a series of categorized images (faces and objects) and made judgments regarding which memory probe was more recently presented (recency discrimination). Multivariate EEG activity patterns observed during the perception of memory items within an event were reinstated at event boundaries (Silva et al., 2019; also see Sols et al., 2017). Moreover, the strength of these reactivations, as measured in the EEG, correlated with the memory performance in the recency discrimination task (Sols et al., 2017). Importantly, counter to the accumulation model, the reinstatement was specific to event boundaries no reinstatement was observed before an event boundary. Behavioral evidence for the reactivation account comes from a recent study indicating that item recognition memory is worse for items that are presented right after an event boundary compared to pre-boundary items (Morse et al., 2023). This disadvantage following event boundaries could reflect the increased memory load due to reactivation interfering with the encoding of novel input considering that increasing WM load is associated with worse memory (Bays and Husain, 2008; Luck and Vogel, 1997; Zhang and Luck, 2008). These results suggest that when an event boundary is encountered, all memoranda within that event might be reactivated in WM. Given that reactivation is specific to boundaries, they also imply that participants may be rehearsing only the latest encountered item in WM until an event boundary while handing off previous items to LTM. In that regard, the reactivation hypothesis differs from the accumulation hypothesis, as within-event items are simultaneously stored at or after event transitions (reactivation) vs during an event (accumulation).

While we discuss reactivation regarding reactivating retrieved from LTM, an alternative is reactivating passively held WM items. This argument stems from the recent theories that posit WM storage can also be neurally silent, as for LTM, particularly for currently less relevant information (Oberauer and Awh, 2022; Stokes, 2015; Wolff et al., 2015, 2017). Given that previous items within an event are currently less relevant, they can be stored in an activity-silent manner, which can then be reactivated at an event boundary. Albeit speculative, this reactivation of passive WM representations can also take place during transition

across fine-grained elements and not just coarse-grained event transitions. However, given the debate regarding whether such silent states reflect episodic memories (Beukers et al., 2021), we are cautious in our claims regarding reactivating silent WMs at boundaries.

What could be the function of memory reactivation at boundaries? There are at least three mutually non-exclusive possibilities. First, reactivation could help forming stronger associations within vs across events. In line with this, stable patterns of activations during the encoding of an event were later related to better temporal order memory for the tested items (Clewett and Davachi, 2017; DuBrow and Davachi, 2014). Second, reactivation could contribute to forming a coherent flow across events. Evidence for this comes from DuBrow and Davachi (2016), which showed that increased hippocampal activity at event boundaries was correlated with the successful retrieval of event translations. They argued that this increased activation reflects the reactivation of the pre-encoded event to form a stronger binding between events. Third, reactivation can serve to associate the current event with temporally distant but contextually similar memories, which could help forming meaningful memory chunks of relevant experiences (Hahamy et al., 2023). Schema-based knowledge and prior information could help this process in terms of accurate encoding of the current event and the reactivation of relevant information (Newberry and Bailey, 2019; Webb and Dennis, 2020). For instance, the capacity of WM can be enlarged thanks to the meaningful stimuli with prior knowledge (Chung et al., 2023). Also, with the help of schema-based knowledge, reactivation can benefit from associations that are also linked to schemas as a context.

At event transitions, fMRI univariate activity in the hippocampus is typically found to increase (Baldassano et al., 2017; Ben-Yakov and Henson, 2018; Reagh et al., 2020; Reagh and Ranganath, 2023). Given the role of the hippocampus in episodic retrieval (Eldridge et al., 2000; Tanaka et al., 2014), this activity increase could reflect the retrieval and reactivation of within-event instances. Specifically, the hippocampus may act as a pointer for reactivating the contents of the previous event at boundaries (Goode et al., 2020; McNaughton, 2010; Samsonovich and Ascoli, 2005). This hippocampal pointer can be held actively in mind during an event while the cortical representations of instances associated with it are held passively in LTM (Todorova and Günseli, 2023). At a boundary, the hippocampal pointer could trigger the reactivation of the cortical event representations belonging to the recent event, possibly via the reconstruction of a theta-gamma coupling in the hippocampus (Griffiths and Fuentemilla, 2020), which has been associated with memory recall (Tort et al., 2009). This hippocampal reactivation could help the integration of consecutive events (Cohn-Sheehy et al., 2021; Griffiths and Fuentemilla, 2020; Horner et al., 2015). The reactivation driven by the hippocampus could trigger the cortical reinstatement that can take place in modality-specific and parietal regions during retrieval at boundaries via sensory recruitment (Kosslyn, 2005; Vilberg and Rugg, 2008), as the posterior parietal regions are suggested to be involved in memory retrieval (Vilberg and Rugg, 2008; Wagner et al., 2005) and recognition associated with remembering event details (Henson et al., 1999; Wheeler and Buckner, 2004). Together, these findings suggest that encountering event boundaries may trigger the reactivation of memoranda that were initially rapidly handed off to LTM during an event, which in turn facilitates the forming of associations among these memoranda.

4.4. Limitations

4.4.1. Limitations of the accumulation model

Although accumulation within WM is a likely candidate to underlie the gradual increase in vmPFC activity, an alternative explanation is increasing demands for forming within-event associations. Importantly, not all these items need to be stored in WM simultaneously as the accumulation model suggests. Instead, associations can be formed by reactivating subsets of items within an event, each time storing only the most novel piece of information in WM. In line with this interpretation of gradually increasing mPFC function, Ezzyat and Davachi (2011) found that the within-event increase in mPFC activity was correlated with the successful integration of items within an event, as measured with fMRI. Likewise, Wu et al. (2023) found that memory reactivation, as measured by EEG, was associated with stronger associations between reactivated and encoded memories. Reactivation at boundaries was observed not only for temporally close but also for remote memories (Hahamy et al., 2023). These findings are consistent with the role of WM in reactivating early experiences while encoding new ones (Hupbach et al., 2008). Together, these results suggest that increased measures attributed to memory accumulation might instead reflect processes related to the integration of information, some of which can reside in LTM, instead of the accumulation of all information in WM. This alternative explanation that can challenge the accumulation model requires further investigation.

4.4.2. Limitations of the reactivation model

One of the challenges for the reactivation model is the necessity of the enrollment of WM to reactivate within-event items at boundaries. If information is recalled from LTM at boundaries, what is the necessity of the WM to participate in reactivation? First, theoretical models and recent empirical work suggest that WM buffers information retrieved from LTM (Atkinson and Shiffrin, 1968; Fukuda and Woodman, 2017; Vo et al., 2022). Therefore, WM involvement is a requirement to store the recalled information. However, there is recent work to suggest that the level of WM reactivation to store LTMs could be modulated depending on task demands (Ataseven et al., 2022; Yücel et al., 2023; Şentürk et al., 2023). Thus, the level of WM reactivation for representing information retrieved from LTM could vary depending on various properties of an event such as its length and importance, which warrants future research. Second, the simultaneous rehearsal in WM is suggested as a crucial step in forming stronger associations across within-event items (Savarimuthu and Ponniah, 2023). Thus, stronger binding within events could reflect the simultaneous storage of the reactivated contents in WM. Third, following the same associative power of WM, another role of WM can also involve binding the current event with previous experience, which is an essential feature of what defines an event. Lastly, recent memories related to the current moment could be activated automatically even when not needed (Bae and Luck, 2019), suggesting that WM reactivation could be an involuntary by-product of experiencing an event boundary.

4.4.3. Limitations common to both models

Both models propose that strong within vs. across-event associations are established via the simultaneous maintenance of memoranda in WM. This raises the question of how WM, which has a severely limited capacity of three or four pieces of information (Baddeley, 1992; Cowan, 2001; Luck and Vogel, 1997; Vogel and Machizawa, 2004), deals with representing event models and memoranda that belong to an event. Particularly, what happens when the accumulation or the reactivation of instances in WM exceeds its capacity?

First, WM capacity itself may act as an event boundary, resulting in generating an event boundary each time its capacity is reached or by remembering some of the items better compared to the other items within an event. For instance, it was shown that the initial encoded items within an event are remembered better in memory tests compared to the latest items (Wen and Egner, 2022). While no other study explored the memory performance for items based on their order within an event, this finding suggests that accessing memoranda after WM capacity is filled may be harder due to the formation of an event boundary.

Second, the effective usage of WM capacity can be guided by offloading LTM-available items from WM (Ball et al., 2022). In this way, the WM capacity can be freed up for novel information within an event (Bartsch and Shepherdson, 2023). This is in line with the view that event boundary formation is not only dependent on external factors such as changes in location, time, etc. but rather on the internal dynamics of the

observer, such as their goals and representation of time, in this case, their saturated WM capacity.

Third, individuals might switch between each strategy back and forth to optimize the use of cognitive capacity depending on the circumstances instead of sticking with accumulation or reactivation alone. The role of item difficulty and familiarity in memory encoding is well-known (e.g., Poppenk et al., 2010; Ptok et al., 2019; Reder et al., 2016; Son and Metcalfe, 2000). If the encountered item is familiar or easy to encode, the person can transfer each item to LTM and then reactivate them when encountered with a boundary. If the information encountered is unfamiliar or difficult to encode, the person can accumulate each item in WM. Therefore, switching between two strategies can be possible.

A recent study indicated that task-switching ability, as an endogenous cognitive control process, is a crucial factor in the segmentation of events (Wang and Egner, 2022). At the same time, it has been suggested that the occurrence of event segmentation could be based more fundamentally on task switching rather than context changes. WM has a role in controlling attention, updating tasks, and switching between them when it is necessary (Baddeley et al., 2001; Logan, 2004; Salminen et al., 2012). When the role of WM in switching between tasks and updating event models is considered, switching between two strategies could be one of the functions controlled by executive functions, which could support the creation of segmented memory units. Such approaches would mean optimizing the use of cognitive capacity and still being able to process the incoming information that is beyond the capacity of WM.

Either of the above possibilities could be shaped by the hierarchical structure of events. In terms of the accumulation perspective, there can be several accumulation bumps within a long event that are influenced not only by the WM capacity but also by structural changes within an event, e.g., fine and coarse-grained segments. In other words, accumulation in WM may also be carried out not only on an item level but also on a structural level. For example, as finer events cluster into coarser events (Baldassano et al., 2017; Kurby and Zacks, 2008; Richmond et al., 2017), there could be a hierarchical priority for fine-grained events in accumulation while processing the items within an event. During this process, information can be selected according to the perceptual properties of the stimuli, such as saliency (Pedale and Santangelo, 2015; Pooresmaeili et al., 2014) or emotional valence (Gotoh et al., 2010), and by the task demands (Myers et al., 2017; Towse et al., 2008). By relying on such a mechanism, segmentation could occur more frequently on a fine-grained level if the items within an event exceed the WM capacity. For the memory performance, an increased number of fine-grained segments could decrease the temporal order memory performance (Jafarpour et al., 2022). However, it could be at least adaptively possible to remember the source memory of these items (Heusser et al., 2018).

The argument of hierarchical priority for the fine-grained events can also apply to the reactivation hypothesis considering that WM capacity might not allow reactivating all the items of an event to bind when faced with a boundary. In this case, each fine-grained structure can be reactivated rather than activating every single item. Therefore, one way to overcome exceeding the WM capacity might be reactivating or accumulating each fine-grained structure in chunks instead of individual items.

Further research is needed to test the validity of these explanations. Likewise, future research is needed to explain how limited WM could be used to bridge consecutive events. One possibility could be to associate the end of the previous event and the beginning of the next one, which would not require representing multiple items in WM.

4.5. Experimental predictions for the reactivation and accumulation models

Experimental investigations would be beneficial to compare the accumulation vs. reactivation of within-event instances in WM by utilizing neuroimaging methods or behavioral experiments. For instance, contralateral delay activity (CDA), an EEG component, can be used to track the accumulation of within-event instances in WM. CDA is a commonly used measure to track the number of items held in WM (Luria et al., 2016; Vogel et al., 2005). By tracking the number of encoded items within an event, accumulation vs. reactivation of the items can be evaluated. If the items in WM accumulate during encoding, a steadily increasing CDA can be seen until an event boundary. As an alternative, CDA could show a stable throughout an event suggesting that information is not accumulated in WM, which would support the reactivation hypothesis. To assess reactivation, alpha-band (8–12 Hz) power suppression in the EEG, which is sensitive to the memory load during LTM retrieval (Fukuda and Woodman, 2017) could be tracked during and at the end of events: The reactivation account predicts an increase in alpha-band power at boundaries relative to within events.

In behavioral studies, a secondary task can be used during encoding to evaluate the potential costs that may be produced while another process is held in WM. To achieve this, a dual-task (e.g., n-back) can be used since the cost of dual processing in WM is mainly known (Baddeley et al., 1984; Lozito and Mulligan, 2006; Naveh-Benjamin et al., 2000; Naveh-Benjamin and Guez, 2000). For the accumulation model, the cost (e.g., decreased item memory, increased response time, worse temporal order, etc.) should be observed during encoding since there is an accumulation of items as a parallel process. On the other hand, according to the reactivation account, the cost of a dual task should be apparent at the beginning of an event and less so during an event since the cost of reactivating the just-encoded items is presumably apparent when encountering an event boundary or right after it. Distinguishing the underlying processes behind the event segmentation through different experimental methods would contribute to the understanding of both the role of WM in event segmentation, which is suggested to play a role in event segmentation (Zacks, 2020; Zacks et al., 2007), and in long-term memory formation.

4.6. What happens after an event boundary: flushing or interference?

The role of WM in forming associations between related units is also indicated by the studies evaluating memory performance. Previous studies suggest that when one event ends and another begins, we update our working event model in WM for the novel information. This consequently results in flushing the old event model. That is why we experience difficulty retrieving the information from the previous events.

Radvansky et al. (2011) studied this updating phenomenon by asking participants to carry objects through virtual rooms by either crossing a doorway or not. Participants were asked at random times about the object that they were carrying but not seeing after they picked it up, where an accurate memory performance in these trials could indicate intact WM. Crossing a doorway, which was determined to be an event boundary by independent raters, decreased memory performance and increased response times when participants were asked about the carried object (Pettijohn and Radvansky, 2016; Radvansky et al., 2010; Radvansky and Copeland, 2006). These results could indicate that information in WM is removed when faced with a boundary. Studies found similar memory consequences of flushing when using different stimuli such as real rooms (Lawrence and Peterson, 2016), video manipulations (Baker and Levin, 2015), or movement (Ongchoco and Scholl, 2019). Memory performance decrements observed for the recent items experienced before such changes in contexts are typically interpreted as existing information in WM to be dropped as a result of experiencing an event boundary.

We propose two alternative explanations to account for flushing arguments at event boundaries. The first explanation involves perceptual interference. Contextual changes that accompany event boundaries also contain perceptual changes, such as two rooms containing different colors and shapes of furniture. Previous studies have shown that perceptual interference is detrimental to WM (Clapp et al., 2010; Dolcos

et al., 2007; Hakim et al., 2019; Rademaker et al., 2015; van Moorselaar et al., 2015). Such perceptual interference could distort memory quality and accessibility (van Moorselaar et al., 2015), which could make it harder and slower to access memoranda from previous events. Also, switches between the two processes of WM, which are maintaining the items and modifying the event representations, can cause the switching cost for memory accuracy and increased RT (Kessler and Oberauer, 2014). Thus, a decline in memory accessibility after a contextual change can reflect memories deteriorating as a result of perceptual interference as opposed to their removal from WM as proposed by EST.

The second alternative that can explain the greater difficulty in accessing memoranda from previous events is attentional blinks or lapses that take place at event boundaries. Ongchoco and Scholl (2019) presented participants with moving dots that started and stopped at variable times and instructed participants to estimate the number of dots that moved within each trial. They found that participants underestimated the number of moving dots that end at variable times as opposed to all ending at the same time. They concluded that each time some dots stop moving, an event boundary takes place, which in turn results in flushing the items belonging to that event, resulting in an underestimation of the total number of dots that moved. However, previous studies in the attentional blink literature have shown that processing a target results in not being able to detect a second target about 200–500 ms following the first one (McArthur et al., 1999). Therefore, attending to an event boundary (i.e., the end of the movement of some dots) might lead to missing other information, such as the end of another group of moving dots. This failure, combined with worse multiple object tracking with divided attention (Allen et al., 2004; Kumar et al., 2016; Tombu and Seiffert, 2008), can result in forgetting that some dots have been moving. A similar attentional blink could be present in other studies that involve videos, stories, or series of images.

Thus, although previous studies used poor memory for former events to support the removal of event models upon an event boundary, attentional distortions that take place at event boundaries can also account for these effects. Carefully designed studies are needed to assess the flushing and distortion arguments to evaluate their contributions to the difficulty of accessing information from former events. To eliminate the perceptual interference or attentional blink, task-irrelevant or implicit stimuli can be used as a boundary. These arguments could be tested by manipulating the perceptual interference between events. For instance, if some events contain high perceptual interference and some others low, then the flushing explanation would not predict differences in accessing previous events as long as the event boundaries are clear (e.g., a switch from a perceptually distracting to a perceptually non-distracting event). The perceptual interference explanation, on the other hand, would predict greater difficulty in accessing the previous event if the switch is from a low interference to a high interference event.

5. Conclusion

We segment ongoing activity into meaningful events in a hierarchical fashion, progressing from smaller units that build up to bigger units. There are different theoretical accounts to explain why memories are segmented. One of the most influential accounts is the EST, which proposes that experiencing a prediction error triggers event model updating and consequently an event boundary (Bailey et al., 2013; Zacks et al., 2007). However, the prediction error account fails to explain the segmentation in predictable situations (Clewett and Davachi, 2017). Another account is the contextual stability account which explains segmentation through internal and external contexts (DuBrow and Davachi, 2013, 2014). Our recent work demonstrates that prediction errors without transitions across stable contexts may not be sufficient to drive event segmentation (Güler et al., 2023).

This temporal memory structuring comes with many benefits and some costs for memory. As events are associated with a common context, they become more tightly bound to each other, which enables their collective retrieval as a meaningful unit (Zacks and Swallow, 2007). Converging evidence from behavioral and neuroimaging studies shows that the functional connectivity between the hippocampus and the vmPFC plays a role in binding within-events (Ezzyat and Davachi, 2011). WM is also essential for within-event binding and associating events with each other (Radvansky, 2012; Radvansky and Zacks, 2017; Zacks, 2020), though the specific roles and mechanisms remain to be explored. When it comes to binding across events, the hippocampus is shown to be involved (Hahamy et al., 2023). Across-event binding has a cost on processing time and memory accuracy (DuBrow and Davachi, 2013; Wang and Egner, 2022). This cost has been suggested to reflect the updating of the event models that contain predictions regarding the present situation (Ongchoco and Scholl, 2019), though we argue that attentional lapses that take place at event boundaries can also explain these costs.

Although WM is claimed to be essential for event segmentation (Radvansky and Zacks, 2017; Zacks, 2020), its exact contributions remain unclear. To help overcome this limitation, we discuss two possible mechanisms by which WM might be contributing to the segmented memory structure. One possibility is that WM accumulates information within each event until an event boundary (Ezzyat and Davachi, 2011). The second possibility is that WM holds only the most recent memoranda and transfers the rest to LTM to be reactivated when encountering an event boundary (DuBrow and Davachi, 2016). Thus, while both of our proposals involve the simultaneous storage of information in WM, which could explain stronger associations between memoranda (Van Dijck and Fias, 2011), they differ in how WM deals with information during an event. Exploring the underlying mechanisms of event segmentation and the role of WM can benefit our knowledge regarding memory and cognition in general, as event segmentation is at interplay with various other cognitive functions, such as attentional control and formation and recollection of episodic memories.

Funding

This paper was supported by a grant from the Scientific and Technological Research Council of Turkey (TÜBİTAK) to Eren Günseli (grant number: 122K919).

CRediT authorship contribution statement

Berna Güler: Conceptualization, Writing – original draft, Writing – review & editing. **Zeynep Adıgüzel:** Conceptualization, Writing – original draft. **Bilge Uysal:** Conceptualization, Writing – original draft. **Eren Günseli:** Conceptualization, Writing – original draft, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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