Goal Shifts Structure Memories and Prioritize Event-defining Information in Memory

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Abstract

■ Every day, we encounter far more information than we could possibly remember. Thus, our memory systems must organize and prioritize the details from an experience that can adaptively guide the storage and retrieval of specific episodic events. Prior work has shown that shifts in internal goal states can function as event boundaries, chunking experiences into distinct and memorable episodes. In addition, at short delays, memory for contextual information at boundaries has been shown to be enhanced compared with items within each event. However, it remains unclear if these memory enhancements are limited to features that signal a meaningful transition between events. To determine how changes in dynamic goal states influence the organization and content of long-term memory, we designed a 2-day experiment in which participants viewed a series of black-and-white objects surrounded by a color border on a two-by-two grid. The location of the object on the grid determined which of two tasks participants performed on a given trial. To examine if distinct types of goal shifts modulate the effects of event segmentation, we changed the border color, the task, or both after every four items in a sequence. We found that goal shifts influenced temporal memory in a manner consistent with the formation of distinct events. However, for subjective memory representations in particular, these effects differed by the type of event boundary. Furthermore, to examine if goal shifts lead to the prioritization of goal-relevant features in longer lasting memories, we tested source memory for each object's color and grid location both immediately and after a 24-hr delay. On the immediate test, boundaries enhanced the memory for all concurrent source features compared with nonboundary items, but only if those boundaries involved a goal shift. In contrast, after a delay, the source memory was selectively enhanced for the feature relevant to the goal shift. These findings suggest that goals can adaptively structure memories by prioritizing contextual features that define a unique episode in memory. ■

INTRODUCTION

As we navigate the world, we are bombarded by a continuous stream of incoming information. Yet, in memory, our experiences are discrete and selective. A growing body of work shows that ongoing experiences are segmented at perceived context shifts, or "event boundaries," leading to the formation of discrete, temporally integrated episodes in memory (Shin & DuBrow, 2021; Clewett, DuBrow, & Davachi, 2019; Clewett & Davachi, 2017; Radvansky & Zacks, 2017; Davachi & DuBrow, 2015; Kurby & Zacks, 2008). Event segmentation helps facilitate the efficient storage of new memories, including better long-term recall for parsed events, reducing interference between similar memories, and optimizing the allocation of cognitive resources to encode important information (Baldwin & Kosie, 2021; Shin & DuBrow, 2021; Radvansky & Zacks, 2017; Zacks, Speer, Swallow, Braver, & Reynolds, 2007). However, it is not useful or even plausible to retain every detail from these events in long-term memory; instead, it is adaptive to prioritize salient, goal-relevant information in memory, making it possible to remember critical information to guide decisions and better predict future events. Here, we examined if event boundaries adaptively facilitate both the selectivity and discrete organization of episodic memory. We queried how distinct types of event boundaries affect the content and structure of memories, and whether boundaries only prioritize memories for the most important, event-defining features in episodic memory.

Event boundaries are theorized to be salient shifts in context that signal the need to update active mental representations of what is happening from moment to moment (Shin & DuBrow, 2021; Clewett et al., 2019; Clewett & Davachi, 2017; Davachi & DuBrow, 2015; Kurby & Zacks, 2008). A byproduct of this mental updating process is that individuals perceive and remember an otherwise continuous experience as a series of discrete and meaningful events (Clewett et al., 2019; Zacks et al., 2007). For example, a typical day could be defined as a series of distinct activities, such as going to work, entering your workplace, and then opening your computer. Research on event segmentation processes has flourished in recent years, with studies showing that event boundaries facilitate the temporal organization of events

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in memory. For example, several studies demonstrate that, relative to information encountered within a shared context, event boundaries lead to impaired temporal order memory and inflated retrospective estimates of temporal distance between pairs of items in a sequence (Clewett et al., 2019; Clewett & Davachi, 2017; Davachi & DuBrow, 2015). These temporal memory effects are generally thought to index event segmentation processes because they capture a disruption of sequential binding processes and the mental distancing of memories representing different events.

An interesting open question is: What makes an event boundary? Do the number or the kinds of changes that comprise a shift in context have differential effects on the organization of information in long-term memory? Event segmentation effects in memory have been shown using various types of context shifts, including changes in perceptual features (Clewett, Gasser, & Davachi, 2020; Heusser, Ezzyat, Shiff, & Davachi, 2018; Ezzyat & Davachi, 2014), task demands (Wang & Egner, 2022; Wen & Egner, 2022; DuBrow & Davachi, 2013, 2014, 2016), linguistic narratives (Ezzyat & Davachi, 2011), spatial contexts (Brunec et al., 2020; Brunec, Moscovitch, & Barense, 2018; Horner, Bisby, Wang, Bogus, & Burgess, 2016), emotional images, auditory tones or music (Clewett & McClay, 2023; McClay, Sachs, & Clewett, 2023; Wang & Lapate, 2023), and shifts in reward structure (Rouhani, Norman, Niv, & Bornstein, 2020). However, it is unclear which specific factors drive these segmentation processes and whether these effects differ in magnitude. For example, perceptual boundaries are often accompanied by a change in task demands, such as switching hands to make a judgment about an object (e.g., Clewett et al., 2020) or in the type of task itself (e.g., DuBrow & Davachi, 2014). Without disambiguating the effects of distinct types of context shifts, it is unclear if any change in an ongoing experience is sufficient for altering the structure and content of memory.

It may be adaptive to structure memories by segmenting an experience at particularly salient event boundaries, such as a context shift that requires a reorientation of one's current motivational or goal state (Wang, Adcock, & Egner, 2023; Shin & DuBrow, 2021). Evidence from the "event prioritization" framework suggests that goals can exert graded effects on event perception, with higher-level goals overriding the effects of lower-level goals (Khemlani, Harrison, & Trafton, 2015; Magliano, Radvansky, Forsythe, & Copeland, 2014). In line with this interpretation, prior work has proposed that changes in task demands drive greater impairments in temporal order memory compared with simple perceptual changes because the former elicit higher-level, internal goal changes (Wang et al., 2023; Wang & Egner, 2022). In addition, the number of changes or context shifts may also determine whether experiences are remembered as distinct episodes. For example, evidence suggests that the influence of context shifts can be additive, exerting greater effects on event segmentation

with increasing numbers or combinations of changes (Wen & Egner, 2022; Pettijohn, Thompson, Tamplin, Krawietz, & Radvansky, 2016; Magliano et al., 2014). Thus, event segmentation effects may depend on both the quantity and the quality of the event boundaries. Here, we sought to adjudicate how distinct types and numbers of featural changes at event boundaries affect the segmentation of experience in memory, operationalized as impairments in temporal order memory and exaggerated retrospective estimates of temporal distance relative to same-context information.

Beyond having consequences on the temporal organization of events in memory, boundaries may also provide a mechanism for enhancing memory selectivity, signaling which information is most adaptive to retain in long-term memory to facilitate the later retrieval of specific episodes. By reducing the accessibility of previous events in working memory during an ongoing experience, event segmentation could help highlight the information that is most relevant to the current event (Shin & DuBrow, 2021) and, thus, most adaptive to retain in memory. Similarly, much research in the domains of emotional and motivated memory (e.g., reward, threat) have demonstrated that salient information is preferentially prioritized in long-term memory compared with neutral, irrelevant information (Mather & Sutherland, 2011; Shohamy & Adcock, 2010; LaBar & Cabeza, 2006). The divergent trajectory of salient and neutral information in memory tends to emerge in a delay-dependent manner (Cowan, Schapiro, Dunsmoor, & Murty, 2021; Clewett, Huang, Velasco, Lee, & Mather, 2018; Murty, Tompary, Adcock, & Davachi, 2017; Igloi, Gaggioni, Sterpenich, & Schwartz, 2015; Yonelinas & Ritchey, 2015; Murayama & Kitagami, 2014; Dunsmoor, Martin, & LaBar, 2012; Murty, LaBar, & Alison Adcock, 2012; Schwarze, Bingel, & Sommer, 2012; Murayama & Kuhbandner, 2011; Sharot & Yonelinas, 2008; Adcock, Thangavel, Whitfield-Gabrieli, Knutson, & Gabrieli, 2006; LaBar & Cabeza, 2006; Nielson & Bryant, 2005; Wittmann et al., 2005; Sharot & Phelps, 2004; Kleinsmith & Kaplan, 1963). As such, it is thought that interactions between encoding and subsequent processes of memory consolidation support the prioritization and persistence of meaningful or salient details in long-term memory (Cowan et al., 2021; McGaugh, 2013; Mather & Sutherland, 2011; Shohamy & Adcock, 2010; LaBar & Cabeza, 2006; Cahill & McGaugh, 1998). Critically, there are some indications that similar selection mechanisms are at play when individuals encounter event boundaries. According to the arousal-biased competition model, a spike in arousal serves to amplify the prioritization of information in perception and memory, increasing the encoding of goal-relevant, important information and suppressing the processing of lower priority information (Mather & Sutherland, 2011). This idea bears a striking resemblance to influential models of event segmentation, which posit that event boundaries trigger arousal-related processes that prioritize processing of new inputs to facilitate event-model

updating (Zacks & Sargent, 2010; Zacks et al., 2007). Indeed, empirical work has shown that salient event boundaries elicit increases in autonomic arousal, which relate to memory measures of segmentation across individuals (Clewett et al., 2020). Even so, little work has directly bridged these frameworks to examine if event boundaries selectively modulate the content of information retained over time.

An adaptive memory framework would predict that only the most goal-relevant features of experience should be prioritized for retention in long-term memory. From this perspective, encountering a goal shift during experience would be expected to result in the prioritization of information that is most "event defining" and relevant to the boundary itself, compared with extraneous or irrelevant features that also accompany the boundary. Alternatively, it is possible that event boundaries could instead elicit nonspecific boosts to encoding processes, resulting in a general enhancement of features encountered at the boundary compared with those shown subsequently in the same context (i.e., nonboundary [NB] items). Indeed, prior work has shown benefits for boundary over NB items in recognition memory (McClay et al., 2023; Clewett et al., 2019; Gold, Zacks, & Flores, 2017; Swallow, Zacks, & Abrams, 2009) and associative or source memory (McClay et al., 2023; Clewett et al., 2020; Siefke, Smith, & Sederberg, 2019; Heusser et al., 2018; Swallow & Jiang, 2010). However, these studies generally only test one type of boundary change and its effects on associative memory, rendering the specificity with which event boundaries influence memory unclear. Furthermore, although there are some indications that event boundaries can enhance free recall up to a month after encoding (Flores, Bailey, Eisenberg, & Zacks, 2017), most prior studies probe the effects of event boundaries on source memory at relatively short delays, on the order of seconds to minutes (Heusser et al., 2018; Swallow et al., 2009). Focusing on immediate memory outcomes might not capture the adaptive significance of boundaries in structuring memories that can guide context-appropriate behaviors. In line with delay-dependent memory selectivity in the domain of affective memory, we would also expect the modulatory effects of boundaries to become most apparent after a period of consolidation.

The present 2-day experiment was designed to test two main questions: How does the quantity and quality of features changed at event boundaries influence the temporal organization of events in memory? Do event boundaries selectively boost memory for defining features of a new event, particularly after a delay? In this task, an adaptation of the Ezzyat-DuBrow-Davachi event boundary paradigm, we had participants view sequences of black-and-white images of objects surrounded by colored borders in the quadrants of a two-by-two grid. Participants completed two different cognitive tasks: judging if the color–object combination was pleasant or if it was realistic. To avoid confounding endogenous task switches with external perceptual cues, participants were trained to associate different halves of the grid with each task before the encoding session. Thus, the location of the image on the grid implicitly cued which task participants should perform on that trial. This paradigm allowed us to examine the effects of two different types of shifts in goal states: one related to the color–object pairing, as color is a component of the judgments participants made about each object, and the other related to the actual decision participants performed (the task itself).

To manipulate the event structure within the sequences of objects during encoding, after four consecutive images appeared with the same color border and in the same grid location, the image always moved to a new quadrant on the grid. This spatial transition could also be accompanied by different types and combinations of featural changes to generate an event boundary, namely, a change in the border color (with no change in task), a change in the task (with no change in the border color), or a change in both the border color and task. The current design was thereby uniquely well suited to query how distinct types and combinations of context shifts modulate the effects of event segmentation, including whether the magnitude of segmentation effects depends on the extent to which a change involves a shift in goal state or simply the number of features that change. Building on prior work, we examined how different types of event boundaries affected memory for temporal order and temporal distance for pairs of items from encoding behavioral measures commonly used to operationalize event segmentation effects in memory. Finally, we examined how event boundaries shape the selectivity, or content, of long-term memory. We tested if only transition-relevant features are prioritized in memory. Source memory was tested for each object's color border and grid location both immediately following encoding and after a 24-hr delay. Considering the dearth of studies examining how event boundaries interact with memory consolidation processes to modulate memory, we specifically tested if memory selectivity for event-defining information emerges after a time delay.

METHODS

Participants

Thirty-eight participants were recruited for this 2-day experiment conducted at New York University. Three participants were excluded because of technical issues, and 7 participants did not complete both days of the experiment. A further 3 participants were excluded for having below chance recognition memory performance. The final sample size of 25 participants is similar to prior work demonstrating behavioral effects of event boundaries (Heusser et al., 2018; DuBrow & Davachi, 2014, 2016; Ezzyat & Davachi, 2011). All participants were between 18 and 35 years, fluent in English, had normal or normal-to-

corrected vision and hearing, and were not color blind. Informed consent was obtained from all participants, and participants were compensated in line with the protocol approved by New York University's IRB.

Stimuli

Participants viewed a series of grayscale images of objects (Heusser et al., 2018). A subset of 384 stimuli were randomly subselected from a pool of 580 stimuli for each participant. During encoding, each object was shown with a border in one of four colors: red, yellow, blue, or green.

Stimulus–color pairings were randomized in accordance with the event structure described below.

Procedure

The overall design of the experiment is outlined in Figure 1A. The first day of the study consisted of a brief practice to ensure clarity of the task instructions, eight blocks of study-test rounds assessing temporal order and distance ratings, followed by two types of source memory tests. Twenty-four hours later, participants
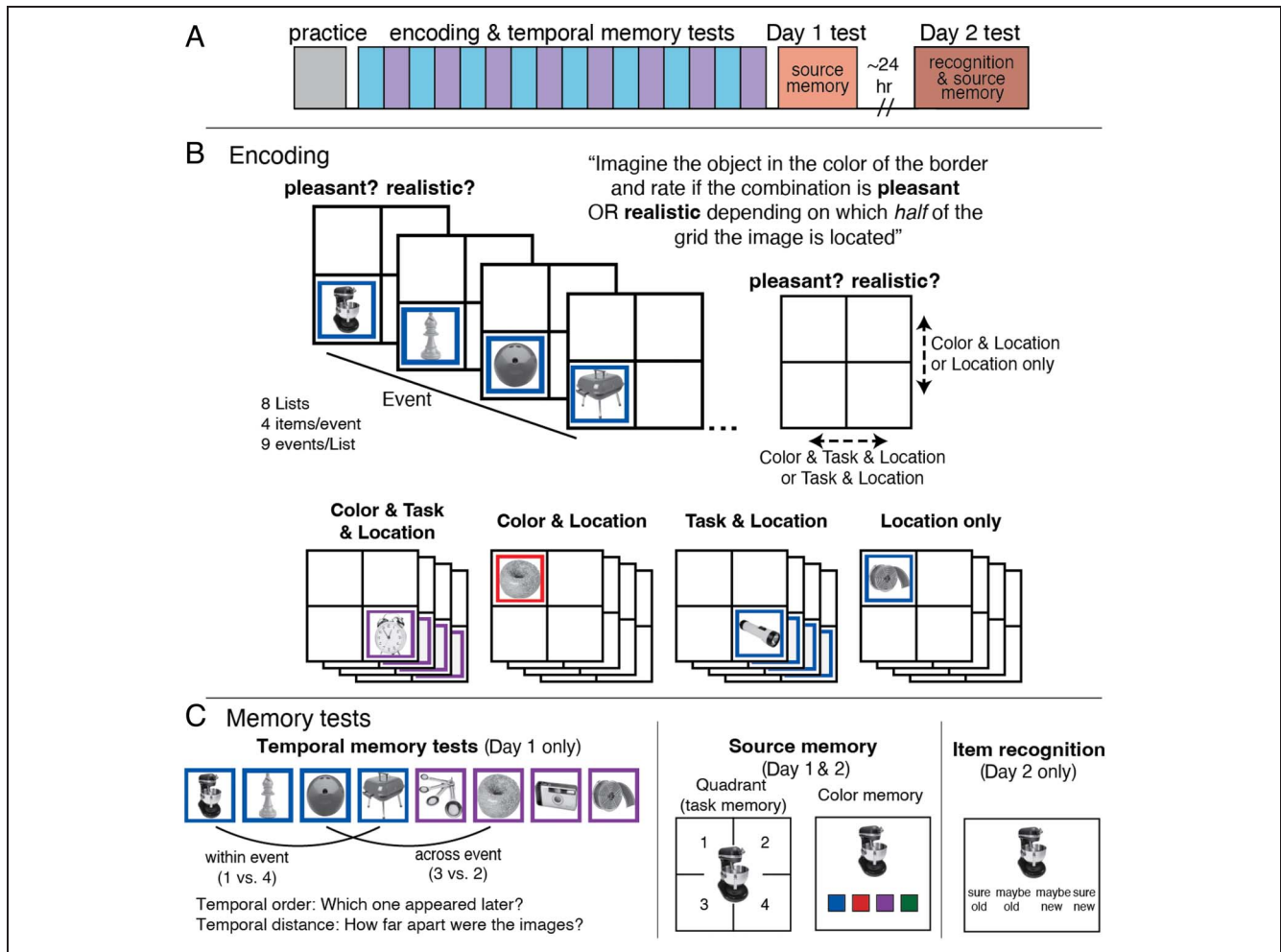

Figure 1. Task design. (A) In this 2-day study, participants first completed a brief practice to ensure clarity on task instructions. After the practice session, participants performed the sequence encoding task and temporal memory tests (i.e., temporal order and temporal distance), divided into eight study-test blocks. Source memory was tested on Day 1, following the study-test blocks, as well as after a 24-hr delay, following an old/new recognition test. (B) During encoding, participants viewed sequences of black-and-white images of objects surrounded by colored borders in the quadrants of a two-by-two grid. Participants were asked to imagine the object in the color of the border and then judge if the combination is pleasant or realistic, depending on which half of the grid the image was located (counterbalanced left/right vs. top/bottom). After four images were shown with the same color border and in the same quadrant ("event"), the images moved to a new quadrant ("Location Only"). This transition could also be accompanied by a change in the border color (without a change in task, "Color & Location"), a change in the task (without a change in color, "Task & Location"), or both a change in the color and task ("Color & Task & Location"). (C) Temporal memory (temporal order, subjective temporal distance) was tested between following the encoding of each list for pairs of images that were either from the same event (within-event) or spanned an event boundary (across-event). Source memory was tested at the end of Day 1 and 24 hr later, following the old/new item recognition task. For the source memory test, participants were asked to make two judgments indicating: (1) which quadrant an object was seen during encoding and (2) what the color of the border was for the given item during encoding. The quadrant memory was used as a measure of memory for the associated task, operationalizing accuracy as the average proportion of trials participants correctly chose the half of the grid representing the task associated with that item.

returned for a recognition test as well as a second test of source memory.

Encoding Task

For the encoding task, we adapted the Ezzyat–DuBrow–Davachi event boundary paradigm. Participants were presented with grayscale images of objects surrounded by a colored border on a two-by-two grid. Each trial was shown on screen for a fixed period of 2.5 sec with a 2-sec ISI. The color border remained on screen for an equal amount of time as the image (as in Heusser et al., 2018). For each image, participants were asked to imagine the object in the color of the border. To induce shifts in goal states without any visual or auditory cues, we designed the grid so that we could introduce two types of encoding tasks: For images shown on one side (e.g., the left half), participants were asked to judge if the object–color combination was pleasant, whereas for images shown on the other side (e.g., the right half), participants judged if the object–color combination was realistic. The grid was divided either along the vertical dimension (i.e., right/left halves) or along the horizontal dimension (i.e., top/bottom), and the task assignment was counterbalanced across the dimensions, generating four possible conditions.

During encoding, four consecutive images were shown in the same border color and quadrant location (and hence, with the same type of judgment task)—hereafter referred to as an "event." After each four-item event, the images moved to an adjacent (nondiagonal) quadrant on the grid. Critically, we generated three types of 'event boundary' transitions such that, in addition to this change in location, there could be: a change in the color border and task judgement (Color & Task & Location), a change in just the color border without a change in task (Color & Location), or a change in the task without a change in the border color (Task & Location). As an experimental control, we also included a transition that involved a change only in the quadrant position without any changes in color or task (Location Only). As an illustrative example, in Figure 1B, following the four images shown with the blue border in the lower left quadrant of the grid, the next four-item event could either move to the bottom right or top left quadrant. Because in this example the judgment tasks are divided on the right/left dimension of the grid, a move to the bottom right quadrant would necessitate a transition to the other task, whereas a move to the top left would not involve a change in task but could include a change in the color border.

Encoding was divided into eight study lists, consisting of nine events per list (36 items per list; 288 objects total). Each transition type, or "event boundary," was sampled 2 times per list, and the first event in each list did not constitute a transition itself. Events could be shown twice in each quadrant of the grid. The starting location for each list was randomized, whereas the order of the transitions was pseudorandomized (maintaining transitions only across nondiagonal, adjacent quadrants).

Before starting the encoding task, participants completed a brief practice to ensure the clarity of instructions and so that participants could learn to associate the different halves of the grid with the respective judgment task. A separate list of stimuli was generated that only consisted of five events (each transition type sampled once). Participants first went through the practice encoding task with labels shown indicating the mapping of the grid half and task type (realistic vs. pleasant). Participants had the option to repeat the practice session with the labels once, then all participants went through the same list again but without any labels. Participants were then allowed to ask questions before completing a practice session for the temporal memory tests (see below). Before beginning the actual encoding session, participants were provided a reminder of the task-grid mapping.

Analyses on the encoding data focused on the RT to make pleasant/realistic judgements, in seconds, across all items in the four-item event. Objects in Position 1 of an event, those that comprise the transition, are considered "boundary items." Objects shown in Positions 2–4 of the event are considered "nonboundary items." For these analyses, we classified transitions as a function of the preceding event. The first event from each list was not analyzed because there was no transition.

Arrows Distractor Task

After each list, participants completed a brief distractor task to reduce potential recency effects in memory. Participants viewed a rapid stream of arrow images facing right or left and were asked to identify the direction (Stark & Squire, 2001). The direction of the arrows was randomized. Responses were self-paced, and the entire task lasted 45 sec, with an ISI of 0.4 sec.

Temporal Memory Tests: Order and Distance

Following the arrows task, participants completed tests of temporal order and temporal distance. Participants were shown pairs of grayscale objects (without a border) studied on the preceding list that either spanned an event boundary or were from the same event. For the "across-event" condition, pairs consisted of objects shown in the third position of one event and the second position of the subsequent event. For the "within-event" condition, item pairs consisted of objects shown in the first and fourth positions of the same event. Thus, the objects in both pair types were separated by the same objective distance (two intervening objects) during encoding.

For each item pair, participants were first asked to judge how far apart the two images were during the encoding phase, using keyboard responses to indicate: "very close," "close," "far," or "very far." Participants were then asked to rate which of the two objects in the pair appeared later

during encoding, along with a confidence rating ("sure left object appeared later," "think left object appeared later," "think right object appeared later," "sure right object appeared later"). Distinct computer keys were used for the two memory tests. The next trial began after participants made a response or if 15 sec elapsed without a response.

Because trials from a given event were used in the within-event pairs and as one element of the across-event pairs, we pseudorandomized the trial order to ensure that pairs drawn from the same event were shown at least two trials apart. In addition, for half of the pairs drawn from the same event, the within-event pair was tested first; for the other half, the across-event pair was tested first. The within-event pair from the first event was not analyzed, because the first event in a list could be construed as an event boundary of no interest. This resulted in 64 tested pairs for each of the within- and across-event for all analyses.

For the temporal order memory test, the average proportion of correct answers was analyzed first by comparing within-event versus across-event pairs, regardless of transition type, to examine if boundaries induce overall impairments in order memory. Second, we compared differences in temporal memory for the across-event pairs as a function of the intervening transition type (Color & Task & Location, Color & Location, Task & Location, and Location Only).

For the temporal distance judgments, we converted the ratings into a discrete 1–4 scale, where a rating of 1 denotes *very close* and 4 denotes *very far*. As above, we first performed analyses focused on comparing the average distance rating for all across-event versus within-event pairings, collapsed by the type of transition. We then broke down the distance ratings by their respective transition types, so we could examine the influence of different types and numbers of boundaries on retrospective estimates of time.

Source Memory Tests

On Day 1, participants completed two types of source memory judgments after completing the eight lists of encoding and temporal memory tests. Participants were shown all of the grayscale object images studied during encoding but without the color border and in a randomized order. Each object was shown individually in the middle of the grid with numbers 1–4 in each quadrant. Participants were asked to first indicate the quadrant in which the object was seen during encoding. Then, participants were asked to recall the color of the border that accompanied that object during encoding. The next trial began once participants made a response or if 15 sec elapsed without a response. Distinct keyboard keys were used for the two types of source judgments. All 288 studied objects from each list were tested, and the stimulus order was randomized across participants.

The source memory tests were used to examine if the specific feature that changed at an event boundary was selectively prioritized in memory. As such, these analyses focus specifically on event transitions with either a change in the task judgment or a change in the color border, but not both (i.e., Task & Location or Color & Location). We operationalized accuracy on the color source memory test as the average proportion of trials that the color border was correctly recalled. We operationalized source memory for the encoding task as the average proportion of trials participants correctly chose the *half* of the grid representing the task (pleasant or realistic judgments). Although participants' memory was technically queried for the quadrant the image was shown during encoding, we were primarily interested in assessing if a transition involving a change in task leads to enhancements in memory for task-related information. In this way, our goal was to determine whether people had abstracted the correct task representation away from the precise physical location in long-term memory. To do this, we counted correct responses for task context as the endorsement of either quadrant associated with the correct task for a given trial (i.e., the quadrant the object was shown or the adjacent quadrant coded for the same task judgment). Because the location of the items changed for every type of event boundary, this more general measure better specifies memory for the object–task association (e.g., pleasant vs. realistic). We used this measure so that we could examine if color and task source memory are specifically enhanced following the relevant Color & Location or Task & Location transition, respectively. We did not conditionalize either measure of source memory on the accuracy on the item recognition test conducted on Day 2 (see below).

For this analysis, we sorted source memory trials according to whether they were "transition relevant" versus "transition irrelevant," where transition relevant was operationalized as either color source memory following a Color & Location transition or task source memory following a Task & Location transition. Transition irrelevant was operationalized as color source memory following a Task & Location transition or task source memory following a Color & Location transition. In addition, we examined the source memory measures for the trials following a Location Only transition to isolate the specific effect of goal shifts on source memory ("location change control condition").

We examined memory for objects shown at the boundary (i.e., Item Position 1 in event), which comprise the transition between events, and NB objects (i.e., item Positions 2–4) for both the immediate and delayed source memory tests.

Day 2: Recognition and Source Memory Tests

Participants completed a multi-step object recognition test upon returning to the laboratory 24-hr later. The 288 studied objects and 96 novel foils were randomly intermixed

and presented individually without their original source information (e.g., shown in the middle of the screen without the grid or a colored border). For each object, participants were asked to indicate if the object had been studied previously or was new. There were four response options indicating participants' confidence in their endorsements ("sure old," "maybe old," "maybe new," "sure new"). If participants responded that the object was "old" (regardless of confidence), they were then asked to again complete the source memory tests first for quadrant location and then for color as explained above. To analyze differences in accuracy on the recognition test based on boundary position and transition type, we collapsed across confidence into "old" and "new" (e.g., "sure" and "maybe" responses).

Statistical Analyses

Analyses were completed in RStudio (Version 1.2.5001) and MATLAB 2018, Version 9.4 (MathWorks). Repeated-measures ANOVAs were conducted to examine main effects and interactions of different boundary types and delays on temporal memory and source memory performance. To follow up on any significant effects, we used planned post hoc paired t tests where appropriate. All statistical tests were two-tailed with an $\alpha = .05$.

RESULTS

Event Boundaries Lead to Slower RTs during Encoding

We first examined if the transitions between events resulted in a cost in RTs during encoding. For this analysis, we calculated the average RTs for each item in the four-item events, broken down by the preceding transition type (Color & Task & Location, Color & Location, Task & Location, or Location Only). We specifically compared RT to objects shown in Position 1 in the event, at the boundary, compared with the average RTs to item Positions 2–4, the NB objects.

As expected, a 4 (Transition Type: color & task & location, color & location, task & location, location only) × 2 (Position: boundary, NB) repeated-measures ANOVA on RTs yielded a significant main effect of Position, $F(1, 24) = 38.95$, $p < .00001$, with slower RTs for boundary trials compared with NB trials. There was also a significant main effect of Transition Type, $F(3, 72) = 4.11$, $p = .009$, and a significant Position × Transition Type interaction effect on RTs, $F(9, 216) = 4.34$, $p < .0001$. Follow-up paired t tests demonstrated that for the three transition types of interest, RTs were slower for objects in the boundary position compared with NB positions, Color & Task & Location: $t(24) = 6.97$, $p < .00001$; Color & Location: $t(24) = 3.17$, $p = .004$; Task & Location: $t(24) = 6.21$, $p < .00001$ (Figure 2). For the Location Only control condition, which involved a change only in the location on the grid but not the border color or task,
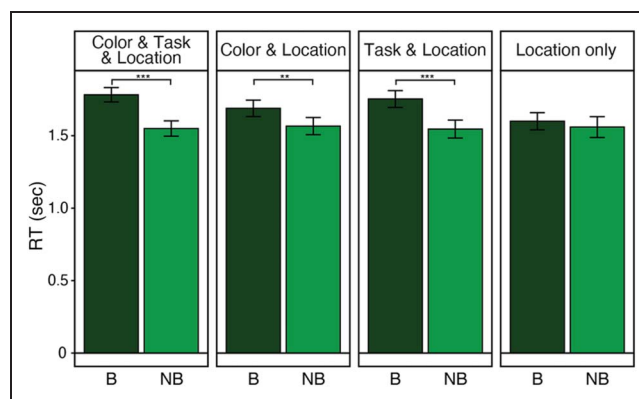

Figure 2. RTs during encoding separated by transition type and item position within an event. Dark green bars represent boundary items (B) that were encountered in Position 1 when the transition occurred (i.e., change in Color & Task & Location, Color & Location, Task & Location, or Location Only). Light green bars represent averaged RTs for all three NB items, located in Positions 2–4 in an event. **$p < .01$, ***$p < .001$; error bars = *SEM*.

there was not a significant difference between RTs for boundary and NB items, $t(24) = 1.58$, $p = .13$.

A closer examination of only the boundary items further demonstrated that the Color & Task & Location, Color & Location, and Task & Location conditions all elicited greater costs in RTs compared with the control condition, Color & Task & Location > Location Only: $t(24) = 4.65$, $p = .0001$; Color > Location Only: $t(24) = 2.39$, $p = .025$; Task > Location: $t(24) = 4.86$, $p < .0001$. These results suggest that only salient event boundaries—a change in color or task—elicited a significant effect on RT during encoding. Interestingly, additional comparisons revealed that the RTs for the Color & Task & Location transition boundary items were significantly slower than the Color & Location boundary RTs, $t(24) = 2.68$, $p = .013$. However, no other statistical comparisons between transition types were significant, Color & Location vs. Task & Location, $t(24) = -1.52$, $p = .14$; Color & Task & Location vs. Task & Location, $t(24) = 0.77$, $p = .45$.

Temporal Memory Measures Are Differentially Modulated by the Type of Event Boundary

Next, we examined if the type of event boundary influenced the magnitude of event segmentation effects in memory, as indexed by impairments in temporal order memory and exaggerated retrospective estimates of temporal distance for boundary-crossing item pairs. We compared temporal memory for objects that spanned an event boundary (across-event) to pairs of objects encountered as part of the same four-item event (within-event), as illustrated in Figure 1C. In particular, we were interested in testing if changes in temporal memory differed between object pairs that spanned an event transition involving a change in one feature, either the percept (Color & Location) or task (Task & Location), versus a combination of the two (Color & Task & Location). We also compared these

changes in memory to performance for pairs that spanned the Location Only transition, the control condition in which no task-relevant features were changed.

For temporal order memory, we first tested whether accuracy was greater for pairs encountered within the same event than those spanning an event boundary, as shown in prior work (Clewett et al., 2019; Clewett & Davachi, 2017; Davachi & DuBrow, 2015). Indeed, we found this same pattern, with higher temporal order accuracy for within-event pairs compared with across-event pairs, $t(24) = 2.65, p = .014$ (Figure 3A). Next, we examined if such boundary-induced impairments in temporal order memory differed by the number and type of transitions. A repeated-measures ANOVA with a factor of Transition Type (Color & Task & Location, Color & Location, Task & Location, Location Only) did not yield a significant main effect, indicating temporal order memory did not differ between the four transition types, $F(3, 72) = 0.26, p = .86$.
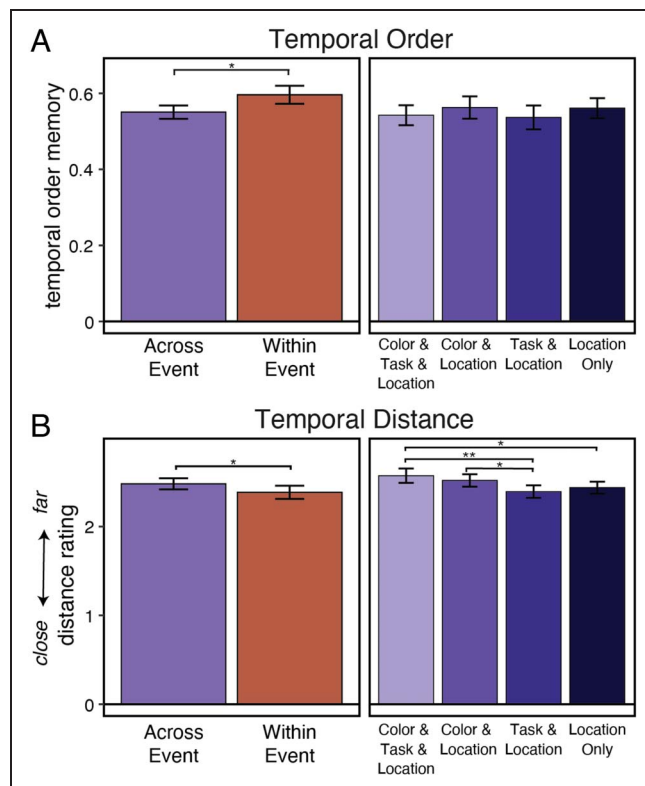

Figure 3. Effects of event boundaries on temporal order and temporal distance memory. (A) Overall, the memory for temporal order was significantly worse for object pairs that spanned an event boundary transition than object pairs encountered in the same event (left). However, there were no significant differences between temporal order memory for pairs spanning the four different types of transitions (right). (B) For subjective temporal distance ratings, pairs that spanned an event boundary transition were rated as farther apart in time than pairs from the same event, in line with a boundary-induced time dilation effect (left). Pairs of items that spanned transitions that involved a change in color (Color & Task & Location, Color & Location) resulted in higher temporal distance ratings compared with Task & Location transitions as well as compared with the average ratings for the within-event pairs. *$p < .05$, **$p < .01$; error bars = SEM.

To further understand how impairments in temporal order memory differed across each transition type, we next compared the across-event pairs for each transition to the average accuracy for all within-event pairs. Paired t tests revealed that, compared with the average of the within-event pairs, temporal order accuracy was marginally lower for pairs spanning a Task & Location transition, within-event > Task & Location across-event: $t(24) = 1.89$, $p = .07$, or Color & Task & Location transition, within-event > Color & Task & Location across-event: $t(24) = 1.76, p = .09$. Temporal order did not differ between the within-event and Color & Location, $t(24) = 1.28, p = .21$, or Location Only, $t(24) = 1.51, p = .14$, transitions. As such, although all the transitions induced a temporal order memory impairment, this effect seems to be mostly driven by a change in task.

Turning to the effects of event boundaries on subjective measures of temporal distance, we again first tested whether pairs spanning an event boundary were rated as farther apart in time than those encountered within the same event, as shown in prior work (Clewett et al., 2019; Clewett & Davachi, 2017; Davachi & DuBrow, 2015). Collapsed across all transition types, across-event pairs were rated as being farther apart in time than within-event pairs, $t(24) = -2.37, p = .026$ (Figure 3B). To examine if the magnitude of this subjective time dilation effect differed based on the type of transition, we conducted a repeated-measures ANOVA on the across-event pairs for the four transition types: Color & Task & Location, Color & Location, Task & Location, and Location Only. This analysis revealed a significant main effect of Transition Type on temporal distance ratings, $F(3, 72) = 3.70, p = .015$. As illustrated in Figure 3B, events that spanned a combined Color & Task & Location transition were rated as being significantly farther apart in time than pairs that spanned a Task & Location transition, $t(24) = 2.84, p = .009$, or Location Only transition, $t(24) = 2.15, p = .04$, but did not significantly differ from the ratings for pairs that spanned a Color & Location transition, $t(24) = 0.95, p = .35$. Likewise, across-event Color & Location transitions resulted in higher subjective temporal distance ratings than Task & Location transitions, $t(24) = 2.03, p = .05$. There were no significant differences between the subjective temporal distance ratings for the across-event Color & Location or Task & Location transitions and the Location Only transitions, Color versus Location: $t(24) = 1.34, p = .19$; Task versus Location: $t(24) = -0.93, p = .36$.

Directly comparing the across-event pairs for each transition type to the average of all the within-event pairs revealed a similar pattern, with significantly higher subjective distance ratings for the Color & Task & Location across-event pairs and Color & Location across-event pairs compared with the within-event pairs, Color & Task & Location > within-event: $t(24) = -3.38, p = .002$; Color & Location > within-event: $t(24) = -2.77, p = .01$, whereas there was no difference between the within-event pairs and the Task & Location across-event pairs,

$t(24) = -0.15$, $p = .88$, or Location Only pairs, $t(24) = -0.92$, $p = .37$.

Together, these results suggest that event boundaries defined by changes in color may play a leading role in driving event segmentation effects in memory, as evidenced by more expanded subjective estimates of distance between temporally adjacent events for color changes compared with boundaries define by the type of cognitive task.

Event-defining Information Is Selectively Enhanced in Source Memory

The results thus far indicate that event boundaries, or transitions between the four-item events, segment continuous experience into discrete mnemonic events. Next, we examined whether these event boundaries also selectively influence source memory immediately after encoding and after a 24-hr delay. We predicted that goal shifts that elicit stronger event segmentation effects would result in selective enhancements in source memory for the event-defining information—the source information that was most relevant to the change at the boundary between adjacent events—particularly after a period of memory consolidation.

To test this hypothesis, we examined if an event boundary involving a change in one of the features—color or task—led to a selective enhancement in source memory for the transition relevant feature (i.e., color memory after a Color & Location transition, task memory after a Task & Location transition) and not the transition irrelevant feature that did not change at those moments (i.e., color

memory after a Task & Location transition, task memory after a Color & Location transition), as illustrated in Figure 4A. Furthermore, to isolate the specific effect of goal shifts on source memory, we used the Location Only transition as a control condition. The Location Only transition did not include any relevant shifts at the feature level because these trials did not include a change in either the color of the object's border nor the task judgment. As such, we would not expect the location change control trials to constitute a shift in goal state, and therefore should not lead to a boost in source memory. Critically, we examined source memory for both the boundary item, the image encountered at the moment of change in the color or the task (e.g., Position 1 in an event), as well as the NB items from the same event. For example, a transition-relevant NB item would include color source memory for items in Positions 2–4 of the event, following a preceding Color & Location transition (e.g., when the color border changed but the task remained the same). Finally, to examine if a period of consolidation facilitates selective source memory enhancements at boundaries, we compared source memory tested immediately (at the end of Day 1) and after a 24-hr delay.

Source memory accuracy was subjected to a repeated-measures ANOVA, with factors of Position (boundary, NB items), Delay (immediate, delayed), Relevance (transition relevant, transition irrelevant, location change control) and Memory Type (color, task memory). The results showed significant main effects of Position, $F(1, 24) = 15.45$, $p = .0006$; Relevance, $F(2, 48) = 7.23$, $p = .002$;
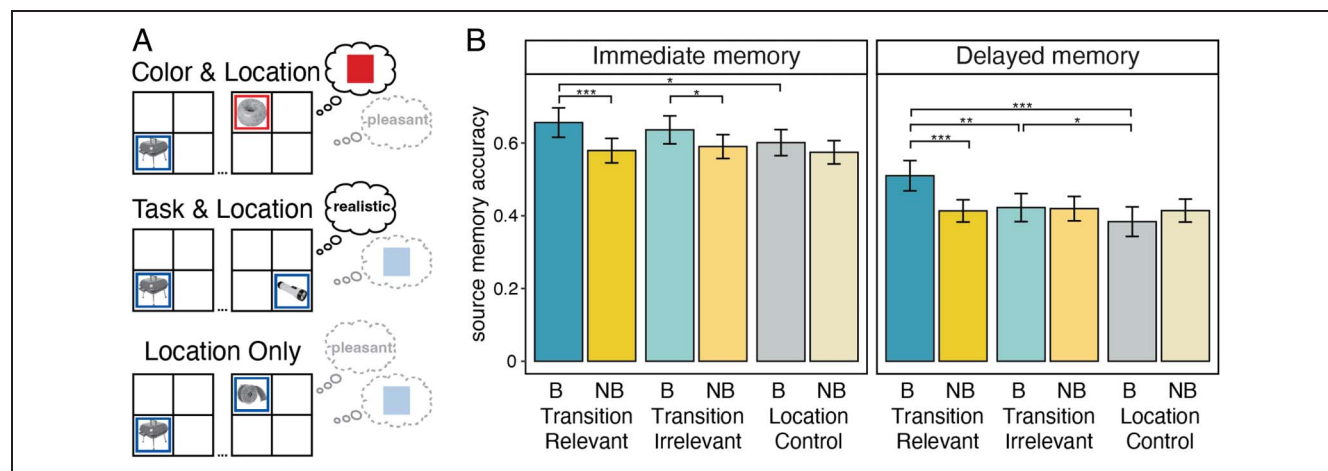

Figure 4. Effects of event boundaries on source memory for event-defining versus irrelevant features. (A) We examined if an event boundary led to a selective enhancement in source memory for the transition relevant feature that changed at the boundary, compared with a transition irrelevant feature that did not change at the boundary. As illustrated, for the Color & Location transition, we expect to find enhanced color source memory but not task source memory, whereas for the Task & Location transition, we expect enhanced task memory but not color source memory. In addition, we examined the location-only transition as a control condition, in which there were no relevant features that changed at the event boundary. In this case, neither source memory for color nor task should be enhanced. (B) When tested immediately after the encoding task on Day 1 (left column), both the transition relevant and transition irrelevant boundary items (blues) were remembered better than NB items (yellows). By contrast, for the location change control condition, when the transition did not instill a change in the current goal state, boundaries did not influence source memory; there was no difference between boundary and NB items when the location changed without an accompanying change in the task or border color. After a 24-hr delay (right column), event boundaries selectively enhanced the source memory for the feature that defined the transition between adjacent events (e.g., memory for the color of the border when the transition involved a change in color). *$p < .05$, **$p < .01$, ***$p < .001$; error bars = SEM.

delay, $F(1, 24) = 116.3, p < .0001$; and Memory Type, $F(1, 24) = 76.19, p < .0001$, on source memory. Critically, we also found a significant three-way Position × Relevance × Delay interaction effect, $F(2, 48) = 4.34, p = .019$. Additional significant two-way interaction effects on source memory included Position × Relevance, $F(2, 48) = 8.63, p = .0006$; Position × Delay, $F(1, 24) = 4.90, p = .037$; Relevance × Delay, $F(2, 48) = 4.37, p = .018$; Position × Memory Type, $F(1, 24) = 6.90, p = .015$; Relevance × Memory Type, $F(2, 48) = 3.06, p = .06$; and Delay × Memory type, $F(1, 24) = 7.13, p = .013$. No other effects were statistically significant. To unpack these significant interaction effects, we next separately examined source memory on the immediate and delayed tests.

Immediate Source Memory Effects

For the immediate source memory test, a 2 (Position) × 3 (Relevance) × 2 (Memory Type) repeated-measures ANOVA showed significant main effects of Position, $F(1, 24) = 23.18, p < .0001$, and Memory Type, $F(1, 24) = 84.34, p < .0001$. The main effect of Relevance was marginally significant, $F(2, 48) = 2.73, p = .08$. None of the interaction effects were statistically significant. As shown in Figure 4B, for immediate memory, boundary items were generally remembered better than the NB items for both the transition relevant and transition irrelevant conditions, relevant: $t(49) = 4.26, p < .0001$; irrelevant: $t(49) = 2.09, p = .042$. In contrast, source memory for boundary and NB items did not significantly differ for the location change control condition, when the transition itself did not involve a change in either the color or task features, $t(49) = 1.41, p = .16$.

We next compared differences in the boundary items across conditions. Source memory for the transition relevant and transition irrelevant boundary items did not significantly differ, $t(49) = 0.71, p = .48$. However, source memory for the transition relevant boundary items was higher than the location change control boundary items, $t(49) = 2.39, p = .02$, but there was not a significant difference between the transition irrelevant and location change control boundary items, $t(49) = 1.62, p = .11$. Thus, when tested immediately, event boundaries led to a general boost in source memory irrespective of relevance to the transition itself, but only if the transition involved a shift in goal state and not simply a spatial change of the image's location on the grid.

Delayed Source Memory Effects

In contrast to the Day 1 findings, after a 24-hr delay, we found a significant main effect of Relevance, $F(2, 48) = 10.19, p = .0002$, and Memory Type, $F(1, 24) = 46.74, p < .0001$, on source memory. The main effect of Position was marginally significant, $F(1, 24) = 3.85, p = .061$. There was a significant Position × Relevance interaction effect, $F(2, 48) = 13.29, p < .0001$. For the transition

relevant items, source memory was again greater for the boundary items compared with NB items, $t(49) = 4.50, p < .0001$. However, for the transition irrelevant items, source memory for boundary and NB items did not significantly differ, $t(49) = 0.18, p = .86$ (Figure 4B).

When examining source memory effects in the location change control condition, we found evidence for a distinct pattern. Specifically, for the location change control, source memory for boundary items was marginally lower for boundary items than for NB items, $t(49) = -1.95, p = .058$. It is possible this pattern may reflect a suppression of information that does not coincide with a shift in goal state in memory, perhaps because it is not relevant for structuring unique episodic memories.

Across conditions, source memory accuracy was higher for transition relevant boundary items compared with the transition irrelevant boundary items, $t(49) = 3.24, p = .002$. Furthermore, source memory for both the transition relevant and transition irrelevant boundary items was higher than the location change control boundary items, relevant > location control: $t(49) = 4.98, p < .0001$; irrelevant > location control: $t(49) = 2.01, p = .05$. Thus, after a delay, event boundaries selectively enhanced memory for contextual features relevant to the event boundary.

Event Boundaries Do Not Significantly Influence Recognition Memory after a Delay

Overall, recognition memory on Day 2 was higher for hits than misses, $t(24) = 9.06, p < .00001$. A repeated-measures ANOVA with factors for Position (boundary, NB) and Transition Type (Color & Task & Location, Color & Location, Task & Location, Location Only) did not yield significant main effects or an interaction effect on recognition memory, suggesting there were no differences based on boundary status or transition type, Transition Type: $F(3, 72) = 0.34, p = .80$; Position: $F(1, 24) = 0.56, p = .46$; Transition Type × Position $F(3, 72) = 1.48, p = .23$. Thus, event boundaries did not significantly modulate recognition memory after a delay.

DISCUSSION

In the present work, we examined if different types and combinations of event boundaries adaptively influence the temporal organization and content of long-term memory. We were specifically interested in adjudicating if the effects of goal shifts on event segmentation are hierarchical, with some goal shifts superseding lower-level perceptual or spatial changes. We also examined if, by contrast, the segmentation effects driven by context changes are additive. In addition, we tested the novel hypothesis that event boundaries facilitate the selectivity of source memory, such that event-defining features are prioritized in longer lasting memories over irrelevant, unchanging features that are not diagnostic of an event shift. To test these ideas, we designed a 2-day experiment in which event

boundaries involved a change in one or both of key features of the encoding experience: The color of the border surrounding an object stimulus and/or the cognitive task participants had to perform on those color-object combinations.

We found that event boundaries altered the temporal structure of memory, as evidenced by impaired temporal order memory and inflated subjective temporal distance ratings for information spanning event transitions. These results are consistent with the emergence of discrete events in memory (Clewett et al., 2019; Clewett & Davachi, 2017; Davachi & DuBrow, 2015). When tested immediately after encoding, source memory was better for objects encountered at the event boundary compared with NB items, regardless of whether the source features were relevant to the preceding transition type. However, after a 24-hr delay, source information that was relevant to the transition was selectively enhanced in memory for boundary items. Thus, although boundaries initially boosted source memory for any concurrent contextual feature, after a delay, boundaries selected specifically for the feature that defined the transition between adjacent events. Together, these results suggest that event boundaries adaptively structure memories and promote the selective retention of event-defining information—a cognitive "bookmark" that signals the onset of a new episodic memory.

By leveraging the multifeatural nature of our design, we could test how the type or number of features that changed at event boundaries influenced event segmentation, as measured by the effects on temporal memory. Although overall we replicated prior work showing that event boundaries impaired temporal order memory and inflated ratings of subjective distance across events (McClay et al., 2023; Pu, Kong, Ranganath, & Melloni, 2022; Wang & Egner, 2022; Wen & Egner, 2022; Brunec et al., 2020; Clewett et al., 2019, 2020; Heusser et al., 2018; Clewett & Davachi, 2017; DuBrow & Davachi, 2013, 2014, 2016; Horner et al., 2016; Lositsky et al., 2016; Ezzyat & Davachi, 2011), these effects did not seem to be additive. Changes in both the color of the border and the task judgment did not result in more exaggerated effects than a change in only one of these features. However, there were some indications that the type of transition differentially influenced subjective measures of event segmentation in memory. Transitions involving a change in the color of the border (i.e., Color & Task & Location and Color & Location) led to greater expansion effects in memory than transitions that involved only a change in task. In contrast, for temporal order memory, accuracy did not significantly differ between the transition types. As such, although any goal shift (i.e., a change in the relevant features during encoding) seems to equally disrupt sequential binding processes and reduce objective measures of temporal order accuracy, changes in perceptual features had a stronger impact on the subjective memory for the distance between events. A change in a visual feature (here, the color of the border) may lead to more distinctive memories compared with a change only in the task judgment, inflating memory for the distance between the events. However, such effects may depend on the salience of the change itself. Prior work has shown that abrupt, but not gradual, changes in color lead to altered duration judgments during encoding (Sherman, DuBrow, Winawer, & Davachi, 2023). Furthermore, in the current work, a change in the item's grid location alone did not modulate temporal memory measures, suggesting a perceptual change without any need to update the orientation of one's current goal state is not sufficient to elicit effects on temporal memory. The current findings also align with evidence showing that boundary-induced time dilation effects are selectively associated with pupil signatures of decision or motor processes (Clewett et al., 2020). On the basis of this work, we would indeed expect that the influence of goal shifts on temporal memory would be most evident in the subjective separation of temporally adjacent experiences in memory. However, whether color itself is a unique organizing principle for memory remains an open question for future work.

In addition, the effects of such goal-relevant perceptual event boundaries on temporal memory generally support the idea that shifts in internal goal states drive event segmentation effects in memory. Recent findings suggest that task switches are most prescriptive of a shift in internal goal states and, therefore, elicit stronger segmentation effects in temporal memory measures (Wang & Egner, 2022). In the present experiment, both the color and task-related information are relevant during encoding, because the color information was a necessary component of participants' judgments. Therefore, our results expand upon prior work by suggesting that changes in goal states cannot be so narrowly defined as being only switches in the task type. Instead, any changes that require updating the features currently relevant to the ongoing experience seem to promote event segmentation effects in memory. Future work could specifically test this idea by testing the effects on temporal memory that arise when the color border change is incidental to the task judgment.

Beyond temporal memory measures, our results also shed light on how event boundaries modulate source memory after a period of consolidation. Although event boundaries enhanced source memory indiscriminately when tested immediately, only the transition relevant information was preserved after a 24-hr delay. To our knowledge, this is the first study that tested the effects of multiple types of boundaries on both immediate and delayed source memory. Prior work has generally focused on immediate measures of singular boundary-related changes, demonstrating superior source memory for boundary over NB items (Heusser et al., 2018; Swallow et al., 2009). The current results extend this finding, demonstrating that immediate boundary-related memory enhancements on source memory are relatively broad, encompassing even features that did not change at the event boundary. However, it is important to note that there were limits on these effects that seemed to be based

on the type of event boundary itself, as we did not find any differences in source memory for boundary and NB items following a Location Only transition.

Unlike the general immediate source memory benefits, we found that only relevant features were selectively retained after a delay. This pattern draws a striking parallel with reports of delay-dependent memory benefits for salient information in the emotional memory and motivated memory (e.g., stimuli paired with reward, threat) literatures. Many studies have shown that although immediately neutral information is remembered equally well as salient information, there is a mnemonic advantage for salient information that emerges or increases after a delay (Cowan et al., 2021; Murty et al., 2012, 2017; Igloi et al., 2015; Yonelinas & Ritchey, 2015; Murayama & Kitagami, 2014; Dunsmoor et al., 2012; Schwarze et al., 2012; Murayama & Kuhbandner, 2011; Sharot & Yonelinas, 2008; Adcock et al., 2006; LaBar & Cabeza, 2006; Nielson & Bryant, 2005; Wittmann et al., 2005; Sharot & Phelps, 2004; Kleinsmith & Kaplan, 1963). Memory consolidation processes are thought to facilitate the selective stabilization and retention of salient information. Theories posit that exposure to salient information engages neuromodulatory systems, such as the noradrenergic and dopaminergic systems, which in turn drive the strengthening of synapses specific to such information (Shohamy & Adcock, 2010; Lisman & Grace, 2005; Cahill & McGaugh, 1998) and can bias systems-level consolidation to facilitate the selective retention of salient features over neutral or irrelevant features in long-term memory (Cowan et al., 2021). This putative mechanism also provides a potential explanation for the delay-dependent nature of our results. A salient shift in goal state during experience could engage these neuromodulatory systems, "tagging" the event-defining information as most relevant to the change itself. The goal-relevant information could then be prioritized by consolidation-related mechanisms, whereas the irrelevant features are forgotten. Indeed, recent work has begun to draw connections between event boundaries, neuromodulatory systems, and memory (Rouhani, Niv, Frank, & Schwabe, 2023; Antony et al., 2021; Clewett et al., 2020). According to the arousal-biased competition theory (Mather & Sutherland, 2011), a surge in arousal selectively enhances processing of high priority information. Because event boundaries have been shown to induce arousal (Clewett et al., 2020) and are also thought to reorient attention to prioritize new information (Radvansky & Zacks, 2017; Zacks et al., 2007), boundary-related information may be generally retained compared with the subsequent NB items immediately. Then, with consolidation, further selectivity could emerge such that only the most relevant, event-defining features at the boundary are represented in long-term memory.

We speculate that the hippocampus likely plays a critical role in promoting the retention of such event-defining information in memory. It is well established that hippocampal processes support representations of unfolding contexts and facilitates encoding temporal information in memory (Clewett et al., 2019; Davachi & DuBrow, 2015). Furthermore, it has been shown that hippocampal responses are sensitive to the presence of event boundaries, and these responses have been linked to enhanced memory for details from preceding events (Barnett et al., 2023; Clewett et al., 2019; DuBrow & Davachi, 2014, 2016; Davachi & DuBrow, 2015; Ezzyat & Davachi, 2014; Ben-Yakov, Eshel, & Dudai, 2013; Ben-Yakov & Dudai, 2011). Likewise, in the realm of memory consolidation, the hippocampus is thought to repeatedly reactivate or "replay" information from encoding, from which cortical networks can integrate new memory traces without interference (Cowan et al., 2021; Moscovitch, Cabeza, Winocur, & Nadel, 2016; Diekelmann & Born, 2010; Tambini, Ketz, & Davachi, 2010; McClelland, McNaughton, & O'Reilly, 1995). Thus, the hippocampus may differentially organize boundary versus NB information during encoding, and then mechanisms of consolidation can further select which memories to prioritize for long-term retention. Future neuroimaging studies can be used to specifically test this hypothesis.

The retention of goal-relevant information at event boundaries may be an adaptive mechanism by which we can recall complex events. It has been theorized that boundary-related information may act as a "gateway" or "entry point" into the recall of specific episodic memories (Michelmann, Hasson, & Norman, 2023; Shin & DuBrow, 2021; Clewett et al., 2019; Heusser et al., 2018). Prior research has provided evidence that boundary items may stand out in memory and enable further recall; during free recall, participants tend to recall boundary items out of order (Heusser et al., 2018; DuBrow & Davachi, 2016) and tend to make more forward transitions from boundary-items compared with pre-boundary items (Heusser et al., 2018; DuBrow & Davachi, 2013). Thus, retaining the event-defining features of a given event boundary may enable more specific recall of given events. As a result, like in the affective domains, our memory system's ability to tag and retain the most critical information from experience can adaptively allow us to recall information from the past to guide behaviors.

Despite this pattern of source memory results, we did not find differences in recognition memory for items encountered at an event boundary. When tested after a delay, there was no significant difference in recognition memory for boundary and NB items. As such, event boundaries seemed to specifically modulate associative rather than item memory. These results run counter to a long-held assertion that event boundaries anchor item representations in long-term memory (Clewett et al., 2019; Swallow et al., 2009). Yet, prior evidence regarding boundary-related enhancements of item recognition is also relatively mixed. Although some reports have shown superior recognition of boundary items (McClay et al., 2023; Rouhani et al., 2020; Gold et al., 2017; Swallow et al., 2009), others find no differences (Horner et al., 2016;

DuBrow & Davachi, 2013) or even enhanced recognition of items preceding a boundary (Morse, Karagoz, & Reagh, 2023; Brunec et al., 2020). Furthermore, few studies have examined boundary-related effects on item recognition after a delay. By testing recognition memory after a 24-hr delay, our results suggest that it may be the conjunction of the item and its associative information—rather than just the item alone—that is most critical for long-term memory. If boundary-related information does provide a gateway for subsequent episodic recall, perhaps having access to the event-defining associative information provides a better tag or entry point than the item alone. Future work using free recall could examine the relationship between boundary-related effects on item and associative memory, including whether the retention of event-defining source information facilitates recall.

An important open question is whether these selective memory effects for event-defining information generalize to more complex, real-world memories. Prior research using movies as stimuli to elicit more multidimensional investigations into the segmentation and recall across event boundaries (Reagh & Ranganath, 2023; Zheng et al., 2022; Reagh, Delarazan, Garber, & Ranganath, 2020; Zacks, 2020; Baldassano et al., 2017; Chen et al., 2017) may provide a means of testing this interpretation more directly. Broadly, event cognition research has yet to address whether all aspects of an ongoing event model are "cleared" from working memory at event boundaries (Radvansky & Zacks, 2017; Zwaan, 1996). Increasing work shows that boundaries provide an ideal opportunity to link new information to a broader narrative structure, thereby facilitating our comprehension of temporally unfolding events (Reagh & Ranganath, 2023; Cohn-Sheehy et al., 2021, 2022; Baldassano, Hasson, & Norman, 2018; Baldassano et al., 2017; Radvansky & Zacks, 2017; Pettijohn & Radvansky, 2016). However, it would not be sensible or even possible to retain every aspect of these event models in long-term memory. Our data suggest boundaries selectively preserve information that is relevant to defining a new episodic event. Future work could examine if observing dynamic goal shifts in more naturalistic experiences influence how boundary versus within-event information is recalled.

In summary, our results demonstrate that event boundaries adaptively structure new memories, translating and organizing the overwhelming quantity of information we encounter into memories of selective, discrete events. By prioritizing retention of event-defining information, goal shifts may support memory for distinct episodes that can be used to guide future context-appropriate behaviors.

APPENDIX

The Effect of the Number of Changes at a Boundary on Temporal Memory Measures

To look at the effect of the number of features changed at a given transition on temporal distance and order memory,

we reanalyzed our data using a linear mixed effects regression model comparison approach. For the across-event pairs, we recoded our conditions as a vector indicating the number of features changed, rather than the type: 3 = Color & Task & Location, 2 = Color & Location or Task & Location, 1 = Location Only. We compared a model including the number of changes as a fixed effect with a random effect of subject to a null model including only subject as a random effect (e.g., accuracy ~ 1 + (1|subject)), predicting distance ratings/accuracy.

For temporal distance, the model comparison was significant, indicating that the model including the number of changes predictor yielded a better fit for the differences in across-event dilation effects observed for subjective distance ratings ($X^2 = 6.20$, $p = .045$). A post hoc test conducted using the emmeans package yielded marginal differences between 1 compared with 3 changes ($\beta = -0.13$, $p = .072$), and 2 versus 3 changes ($\beta = -0.12$, $p = .074$). There was not a significant difference between the 1 and 2 changes ($\beta = -0.018$, $p = .93$). Together, these results may suggest that an event boundary involving three features could lead to more dilation in subjective distance ratings compared with event boundaries involving only one or two changes.

For temporal order accuracy, the model comparison was not significant ($X^2 = 0.27$, $p = .87$), suggesting including the number of changes as a predictor did not improve the model fit and that the number of changes does not have a differential effect on across-event temporal order accuracy.

Event-defining Information Is Prioritized in Source Memory for Color and Precise Quadrant Location

In our analyses, because our main interest was in assessing if a transition involving a change in border color or task judgment leads to corresponding enhancements in memory for color and task-related information, respectively, we used the quadrant source memory test to derive a more general measure of "task memory." However, to test the specificity of this effect, we also conducted the same set of analyses using color source memory and the precise measure of accurate quadrant memory (i.e., identifying the correct quadrant on the grid the image was located during encoding). As outlined below, we found a consistent pattern of results as is reported in the main text.

Source memory accuracy was subjected to a repeated-measures ANOVA, with factors of Position (boundary, NB items), Delay (immediate, delayed), Relevance (transition relevant, transition irrelevant, location change control) and Memory Type (color, quadrant memory). The results showed significant main effects of position, $F(1, 24) = 24.71$, $p < .0001$; relevance, $F(2, 48) = 5.58$, $p = .007$; and delay, $F(1, 24) = 121.2$, $p < .0001$, on source memory, but the main effect for Memory Type on source memory was not significant, $F(1, 24) = 0.001$, $p < .97$. With quadrant memory, we found a marginal three-way interaction

effect between Position, Relevance, and Delay, $F(2, 48) = 2.79, p = .07$. Additional significant two-way interaction effects on source memory included Relevance × Delay, $F(2, 48) = 4.13, p = .02$; Position × Relevance, $F(2, 48) = 6.79, p = .003$; Position × Delay, $F(1, 24) = 7.19, p = .013$; Position × Memory Type, $F(1, 24) = 20.66, p = .0001$; Relevance × Memory Type, $F(2, 48) = 5.19, p = .009$. No other effects were statistically significant.

Immediately, a 2 (Position) × 3 (Relevance) × 2 (Memory Type) repeated-measures ANOVA showed significant main effects of Position, $F(1, 24) = 31.04, p < .0001$. The main effect of Relevance was not significant, $F(2, 48) = 1.02, p = .37$, nor was the main effect of Memory Type, $F(1, 24) = 0.1, p = .76$. There were significant interaction effects between position and memory type, $F(1, 24) = 15.75, p = .0006$, and relevance and memory type, $F(2, 48) = 3.94, p = .026$. For immediate memory, boundary items were generally remembered better than the NB items for both the transition relevant and transition irrelevant conditions, relevant: $t(49) = 4.44, p < .0001$; irrelevant: $t(49) = 2.80, p = .007$. Unlike in the main text, when calculated using the precise measure of quadrant memory, the location change control condition also showed significantly better memory for the boundary items than the NB items, $t(49) = 2.31, p = .02$. There were no significant differences between the boundary items across conditions.

On the delayed memory test, a 2 (Position) × 3 (Relevance) × 2 (Memory Type) repeated-measures ANOVA showed significant main effects of Relevance, $F(2, 48) = 9.43, p = .0004$, and Position, $F(1, 24) = 11.06, p = .003$, on source memory, but the main effect of Memory Type on source memory was not significant, $F(1, 24) = 0.06, p = .82$. There was a significant interaction effect between Position and Relevance, $F(2, 48) = 11.39, p < .0001$. When using the precise measure of quadrant memory, the ANOVA also yielded significant Position × Memory Type, $F(1, 24) = 13.95, p = .001$, and Relevance × Memory Type interaction effects, $F(2, 48) = 3.37, p = .04$, on source memory.

For the transition relevant condition, source memory was greater for boundary items compared with NB items, $t(49) = 5.48, p < .0001$, whereas for the transition irrelevant items, source memory for boundary and NB items did not significantly differ, $t(49) = 1.25, p = .22$. Source memory also did not significantly differ for the boundary and NB items for the location change control condition, $t(49) = -0.55, p = .59$. Across conditions, source memory accuracy was higher for transition relevant boundary items compared with the transition irrelevant boundary items, $t(49) = 2.96, p = .005$. Furthermore, source memory for both the transition relevant and transition irrelevant boundary items was higher than the location change control boundary items, relevant > location control: $t(49) = 4.90, p < .0001$; irrelevant > location control: $t(49) = 2.40, p = .02$. These results are consistent with those reported for task memory in the article suggesting an event-defining information is selectively enhanced in memory after a delay.

Data Availability Statement

Data are available upon request from the authors.

Author Contributions

Emily T. Cowan: Conceptualization; Data curation; Formal analysis; Investigation; Visualization; Writing—Original draft; Writing—Review & editing. Avi J. Chanales: Conceptualization; Investigation; Writing—Review & editing. Lila Davachi: Conceptualization; Writing—Review & editing. David Clewett: Conceptualization; Writing—Original draft; Writing—Review & editing.

Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience* (*JoCN*) during this period were M(an)/M = .407, W(oman)/M = .32, M/W = .115, and W/W = .159, the comparable proportions for the articles that these authorship teams cited were M/M = .549, W/M = .257, M/W = .109, and W/W = .085 (Postle and Fulvio, *JoCN*, 34:1, pp. 1–3). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance. The authors of this paper report its proportions of citations by gender category to be: M/M = .431; W/M = .278; M/W = .167; W/W = .125.

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