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Reduced Distinctiveness of Event Boundaries in Older Adults With Poor Memory Performance

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We experience the world as a continuous flow of information but segment it into discrete events in long-term memory. As a result, younger adults are more likely to recall details of an event when cued with information from the same event (within-event cues) than from the prior event (between-event cues), suggesting that stronger associations are formed within events than across event boundaries. The present study aimed to investigate the effects of age and working memory updating on this within > between cued-recall effect and the consequences for subsequent memory. Across two studies, participants viewed two different films (Hitchcock's *Bang You're Dead* and BBC's *Sherlock*). They were later shown clips taken from either the beginning/middle (within-event cues) or end (between-event cues) of a scene and asked to recall what happened next in the film. While the main effect of age was not significant in either experiment, overall memory performance related to the within > between effect in older, but not younger, adults. Low-performing older adults showed less of a difference in cued recall for within- and between-event cues than high performers. In Study 2, better two-back task performance also related to a greater within > between effect in older, but not younger, adults, suggesting that working memory updating relates to the distinctiveness of events stored in long-term memory, at least in older adults. Taken together, these findings suggest that age differences in event memory are not inevitable and may critically depend on one's ability update working memory at event boundaries.

Public Significance Statement

Everyday events, which we experience continuously, are stored in long-term memory as a series of units (e.g., eating breakfast, driving to work). Dividing experiences into distinct events is thought to involve refreshing what we have in mind when the situation changes. In this study, we find that older adults with poor refreshing ability seem to blur events together in long-term memory and this affects their ability to recall what happened.

Keywords: event segmentation, aging, episodic memory, inhibition, event boundaries

Supplemental materials: https://doi.org/10.1037/pag0000765.supp

Though we interact with the world continuously, a long line of work suggests that our experiences are divided into a series of distinct events (e.g., Newtson, 1973; Radvansky, 2012; Zacks et al., 2007). Event boundaries are perceived whenever we experience a shift in time (Ezzyat & Davachi, 2011), location (Horner et al., 2016; Radvansky & Copeland, 2006), or goals (Speer et al., 2007; Wang & Egner, 2022), and these event boundaries trigger attentional mechanisms that can affect how events are stored in long-term memory (DuBrow & Davachi, 2016; Ezzyat & Davachi, 2011; Horner et al., 2016). Given well-established age differences in attentional control (e.g., Hasher et al., 2007; Sylvain-Roy & Belleville, 2015), the goal of the present study was to examine age differences in the relationship between event boundaries and long-term memory for events.

Models of Event Segmentation

Models of event segmentation (including event segmentation theory; Zacks, 2020; Zacks et al., 2007) posit that we build representations of events in working memory by combining our prior knowledge, and previously developed event schemas, with incoming sensory information. According to this view, these *event models* allow us to predict upcoming input, and when our predictions are violated or become too difficult (i.e., prediction error increases), we perceive an event boundary and update our event representations (Zacks et al.,

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Data, analysis scripts, and materials are available at https://osf.io/857qj/.

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2007). This segmentation is thought to alter the contents of working memory (Speer & Zacks, 2005; Swallow et al., 2009) and reduce access to information from previous events (Radvansky & Copeland, 2006). While event boundary perception seems to occur in an unintentional or obligatory fashion, the boundary-triggered mechanisms that update the contents of working memory are thought to be attentionally demanding (Zacks et al., 2007), as engaging these processes impairs performance on a secondary task (Huff et al., 2012).

Event segmentation also affects the encoding of events in long-term memory. For instance, working memory capacity has been shown to indirectly predict individual differences in long-term event memory through event segmentation ability (Sargent et al., 2013), suggesting that working memory may support long-term event memory by maintaining event models and refreshing them at boundaries. Furthermore, event boundaries seem to affect the organization of events in long-term memory by modifying the relationship between the individual details that make up events, creating tighter associations within events, and greater separation between them (Clewett et al., 2019). As a result, people tend to think that details from the same event (e.g., items in a list, actions in a movie) occurred closer together in time than details from different events (Bangert et al., 2020; Ezzyat & Davachi, 2014; Lositsky et al., 2016). Importantly, event boundaries may also affect the degree of binding between details in an event, such that details are more strongly associated when they come from within the same event than when they cross an event boundary. Using written narratives, Ezzyat and Davachi (2011) showed that participants are better able to recall what happened next in the story when given cues from either the beginning or middle of events ("within-event cues") compared to when cues came from just before an event boundary ("between-event cues"), thus showing a benefit for within-event versus between-event cued recall. This benefit for within-event cues has also been shown using spatial boundaries in virtual reality (Horner et al., 2016) and in films (Davis et al., 2021).

Age Differences in Event Segmentation and Memory

Event segmentation may also contribute to age differences in episodic memory (Duarte & Dulas, 2020; Shing et al., 2010). Some work suggests that older adults segment events more idiosyncratically than young adults and this lower interindividual agreement predicts poorer event memory (Bailey et al., 2013; Kurby & Zacks, 2011; Zacks et al., 2006). Neural evidence also suggests that older adults process naturalistic stimuli (such as movies) more idiosyncratically (Geerligs & Campbell, 2018), and this idiosyncratic responding relates to individual differences in attentional control in older adults (Campbell et al., 2015). This latter finding suggests that disrupted event processing may only be apparent among older adults with impaired attentional control. Older adults in general show reduced attentional control relative to younger adults (Sylvain-Roy et al., 2015), including a reduced ability to inhibit (or "delete") no-longer-relevant information (Campbell et al., 2020; Hasher et al., 2007). For instance, older adults have been shown to maintain items in working memory after they have become irrelevant, indicating a failure to delete no-longer-relevant information—a critical component of updating working memory (Higgins et al., 2020; Lustig et al., 2001; Scullin et al., 2011; Weeks et al., 2020). This inhibitory deficit has also been shown to influence relational binding in long-term memory, with older adults forming broader associations over time (Campbell et al., 2014). Taken together, these findings lead to the prediction that aging should result in the carryover of information from one event to the next or the formation of less distinct events in long-term memory.

However, several studies suggest that event segmentation is preserved with age (Kurby et al., 2014; Magliano et al., 2012). For instance, Kurby and Zacks (2018) showed reduced agreement in the explicit identification of event boundaries in older adults but preserved neural activation in regions associated with event segmentation with age. Other studies using more naturalistic encoding (i.e., without the additional demands of explicitly identifying event boundaries) have found that older and younger adults show similar implicit markers of event boundary perception, including slowed reading times during narrative shifts in text (Morrow et al., 1997; Radvansky & Curiel, 1998; Radvansky et al., 2003; Stine-Morrow et al., 2001), and less access to narrative information following event boundaries (Radvansky & Curiel, 1998). Boundary perception, especially under implicit conditions, may be relatively preserved with age because it largely depends on crystallized knowledge (e.g., Bläsing, 2015; Newberry et al., 2021; Smith et al., 2020), which tends to be maintained or even increased with age (Horn & Cattell, 1967; Umanath & Marsh, 2014). In contrast, boundary-triggered processes (such as working memory updating and integration with the rest of the narrative) are thought to be more attentionally demanding (Stine-Morrow & McCall, 2022; Zacks et al., 2007) and may therefore be more prone to age-related differences.

Most studies of event segmentation in aging have assessed age differences in the perception of event boundaries and/or the consequences for working memory updating. Fewer studies have examined how older and younger adults differ in their organization of events in long-term memory, particularly from the perspective that older adults may identify the same boundaries but differ in the efficiency of attentional processes triggered by those boundaries.

The Present Studies

Recent work from our lab has addressed this issue using cued-recall tasks similar to those introduced by Ezzyat and Davachi (2011), using both narratives (Davis & Campbell, 2023) and films (Davis et al., 2021). Davis et al. (2021) tracked eye movements while older and younger adults viewed a shortened version of Alfred Hitchcock's *Bang You're Dead.* While the central question in that study aimed to investigate the relationship between eye movement synchrony and memory performance, participants also completed a cued-recall task to investigate whether older and younger adults differed in their relational binding within and between scenes. Participants were given short video cues taken from either the middle of events (within-event cues) or just before an event boundary (between-event cues) and asked to report what happened next in the movie. Both younger and older adults showed a similar increase in eye movement synchrony immediately following event boundaries, suggesting increased attention at event boundaries and, critically, that both groups perceived the same boundaries in the film. Furthermore, they both showed better cued recall for within-event than between-event cues, suggesting that both groups form tighter associations within than between events in long-term memory. However, in our analysis of those data, we did not examine whether individual differences in overall memory performance (or working memory updating) relate to individual differences in the within > between cued-recall effect. We might expect older adults with a lessened ability to update the contents of working memory to encode less distinct events into long-term memory and to show poorer memory for the movie overall.

Thus, the present study aimed to test this prediction. In Study 1, we reanalyzed the data from Davis et al.(2021), with participants divided into high- and low-performing groups based on their final free-recall performance. We then compared within-event and between-event cued recall between age and performance groups, with the expectation that low-performing older adults would show less of a memory advantage for within-event cues. In Study 2, we aimed to replicate this effect with a different and longer movie, which allowed us to treat overall memory performance as a continuous measure (using a multilevel modeling approach, which was not ideal for Experiment 1 given the smaller number of event boundaries [i.e., trials] and sample size). Participants also completed a two-back task, which is thought to measure working memory updating (Gajewski et al., 2018; Gray et al., 2003; Rac-Lubashevsky & Kessler, 2016; Scharinger et al., 2015). This allowed us to test our more specific prediction that it should be those individuals with poorer working memory updating who show less of a difference in cued recall for within- and between-event cues.

Study 1

Method

Transparency and Openness

De-identified data, analytic code, and stimulus information for Studies 1 and 2 are available at the Open Science Framework (OSF) link provided in the author note. As the open-ended nature of the typed responses resulted in some containing possibly identifying information, we provide only the coded data. Analyses were carried out in R (Version 4.0.4) and required packages are listed in the available script. As the stimulus used is under copyright and cannot be shared, we have included a document with time stamps, indicating the location of scene boundaries and cues. The study design and analytic plan were not preregistered.

Participants

Participants included 24 older (61–82 years, $M_{age} = 70.3$, $SD = 5.28$; 13 female; self-identified ethnicity: 24 White) and 25 younger adults (18–28 years, $M_{age} = 20.8$, $SD = 2.71$, two missing; 18 female; self-identified ethnicity: 20 White, two Latinx, one Black, one Asian Canadian, one multiracial). Younger adults were recruited from Brock University (located in a midsized city in Ontario, Canada) and received course credit. Older adults were recruited from the community and received $10/hr for their participation. As reported in Davis et al.(2021), 10 participants were excluded from analyses because the eye tracker failed to calibrate (old: $N = 5$), cell phones were answered during the film (young: $N = 1$, old: $N = 1$), or a score less than 23 was obtained on the Montreal Cognitive Assessment (MoCA; Carson et al., 2018; Nasreddine et al., 2005; old: $N = 3$). Older adults had more years of education ($p = .005$; old: $M = 17.7$, $SD = 4.51$; young: $M = 14.7$, $SD = 2.09$) and higher vocabulary scores ($p < .001$; old: $M = 35.1$, $SD = 3.20$; young: $M = 29.6$, $SD = 4.82$; one older adult missing).

Stimuli

The stimulus was an 8-min version of Alfred Hitchcock's *Bang You're Dead.* This version has been widely used in previous research; notably, it was included in the population-based Cambridge Centre for Ageing and Neuroscience study (Cam-CAN; Shafto et al., 2014). No participants reported having seen the film previously. Scene changes (i.e., points in the film when the scene faded to black before another scene started in a new location or time) were used as event boundaries. For instance, the movie opens with two boys playing with toy guns in the backyard and then cuts to three grown-ups having drinks in the living room—this cut from one scene to another was considered an event boundary. For the cued-recall task, short clips ($M_{duration} = 5.00$ s, $SD = 1.47$ s) were selected that came either from the middle of the scene (within-event cues) or just before a scene cut (between-event cues). A total of 22 clips were used (12 within, 10 between).

Procedure

The procedure (including eye-tracking details) is explained in detail in Davis et al. (2021). Here, we focus on the behavioral tasks relevant to the present study. The study was approved by the Research Ethics Board at Brock University (Individual differences in movie viewing patterns, No. 17-024). Data were collected November 2017–August 2018. Participants were not aware that their memory for the film would be tested. Participants sat alone in the room while viewing the film. Following the film, the researcher returned to the room and audio recorded participants while they completed two surprise memory tasks. First, they completed a cued-recall task, followed by a free-recall task. In the cued-recall task, participants watched the short clips (within- and between-event cues) and were asked to report what they thought happened immediately after the clip in the film. Clips were presented in the same order as they appeared in the film. In the free-recall task, participants were given unlimited time to describe what they could recall from the film. Participants were then given a follow-up questionnaire to determine whether they had thought their memory would be tested (this was entered as a covariate in subsequent analyses). Last, they completed the MoCA (Nasreddine et al., 2005), Shipley vocabulary test, and a demographics questionnaire.

Scoring

Cued Recall. Verbal responses were transcribed and coded for accuracy (binary correct or incorrect). Coders determined accuracy using a set of predefined answers based on the actions that occurred immediately following the clip. Responses did not need to be verbatim to be considered correct (see Davis et al., 2021, for example coding). Two independent coders who were blind to participant age coded all cued-recall data. Interrater reliability was calculated with intraclass correlation (ICC) using the *irr* package (V.0.84.1; Gamer et al., 2019) in R 4.0.3 and was high across both within-event (.96) and between-event (.91) cues. Scores from each rater were averaged to obtain a single within- and between-event cued-recall accuracy score for each individual.

Free Recall. Free-recall data were scored using the Autobiographical Interview scoring method (Levine et al., 2002). According to this method, descriptions are segmented into distinct pieces of information or details, and details are then coded as either internal or external, with internal details being central to the event being described and external details representing semantic information (such as general knowledge or facts) and repetitions of previous internal details. In addition to these categories, the use of a film (as opposed to description of autobiographical events) allowed for the verification of so-called internal details that resulted in a third category, *incorrect details* (i.e., details that were described as though they occurred in the film but did not). Two independent coders who were blind to participant age coded all responses and interrater reliability (ICC) was found to be high across all categories (internal details = .98, external details = .96, incorrect details = .89). The scores were averaged across coders. The proportion of internal details produced (rather than the absolute number) was used in subsequent analyses to control for individual differences in verbal fluency.

Analysis

To test the prediction that older adults with poor memory should show less distinct events in memory, we separated participants into high- and low-performance groups according to the median proportion of internal details they accurately recalled in the free-recall task (separately for each age group). We then submitted their scores on the cued-recall task to a 2 Age (between-subjects; old, young) × 2 Performance Group (between-subjects; high performers, low performers) × 2 Cue Type (within-subjects; within-event, between-event) mixed analysis of variance (ANOVA) to determine whether high- and low-performing older adults differ in the distinctiveness of their event boundaries compared to younger adults. While this analysis would ideally be run using memory performance as a continuous predictor, the relatively small number of participants and scenes in the film (stimuli) meant that the validity of the multilevel model predicting cued-recall performance would be questionable (e.g., Jenkins & Quintana-Ascencio, 2020; Maas & Hox, 2005; Moineddin et al., 2007).[1] In contrast, a sensitivity analysis for the ANOVA grouped by median split of memory performance indicates that given the sample size ($n = 49$) and the mean observed back-transformed Fisher's z (Silver & Dunlap, 1987) for the correlation among repeated measures ($r = .142$), the three-way interaction between age, cue type, and performance group (four groups, two measurements) had 80% power to detect a medium-sized effect ($f = .322$). Thus, we proceeded with the median-split analysis but encourage careful interpretation of these results, which are obtained from the artificial binarization of the performance variable.

Results

The mixed ANOVA revealed a main effect of cue type, such that memory was better following within-event ($M = 0.75$, $SE = 0.19$) than between-event ($M = 0.54$, $SD = 0.20$) cues, $F(1, 45) = 73.0$, $p < .001$, $\eta_p^2 = .619$. There was no main effect of age, $F(1, 45) = 1.28$, $p = .264$, or performance group, $F(1, 45) = 0.04$, $p = .849$, $\eta_p^2 < .001$, but there was a significant three-way interaction between age group, cue type, and performance group, $F(1, 45) = 10.5$, $p = .002$, $\eta_p^2 = .189$. None of the other interactions were significant (ps $> .140$).

The three-way interaction was followed up within each age group to reveal a significant interaction between cue type and performance group in older adults, $F(1, 22) = 10.4$, $p = .004$, $\eta_p^2 = .321$, such that high-performing older adults showed a larger cue-type effect than low-performing older adults. Pairwise comparisons revealed that the cue type effect was significant in high-performing, $t(11) = 6.58$, $p < .001$, but not low-performing, older adults, $t(11) = 1.40$, $p = .188$ (see Figure 1). In contrast, young adults did not show this interaction, $F(1, 23) = 2.22$, $p = .150$, $\eta_p^2 = .088$. The three-way interaction between age group, cue type, and performance group remained significant when controlling for demographic variables including perceived health and education (three-way interaction, ps $< .003$). It also remained significant when controlling for whether participants suspected that their memory for the movie would be tested ($p < .003$; $N = 7$ young and 18 older aware participants). Thus, both younger adults and high-performing older adults showed a memory advantage for within-event versus between-event cues, while older adults who performed poorly in the free-recall task showed no difference between these two cue types.

Discussion

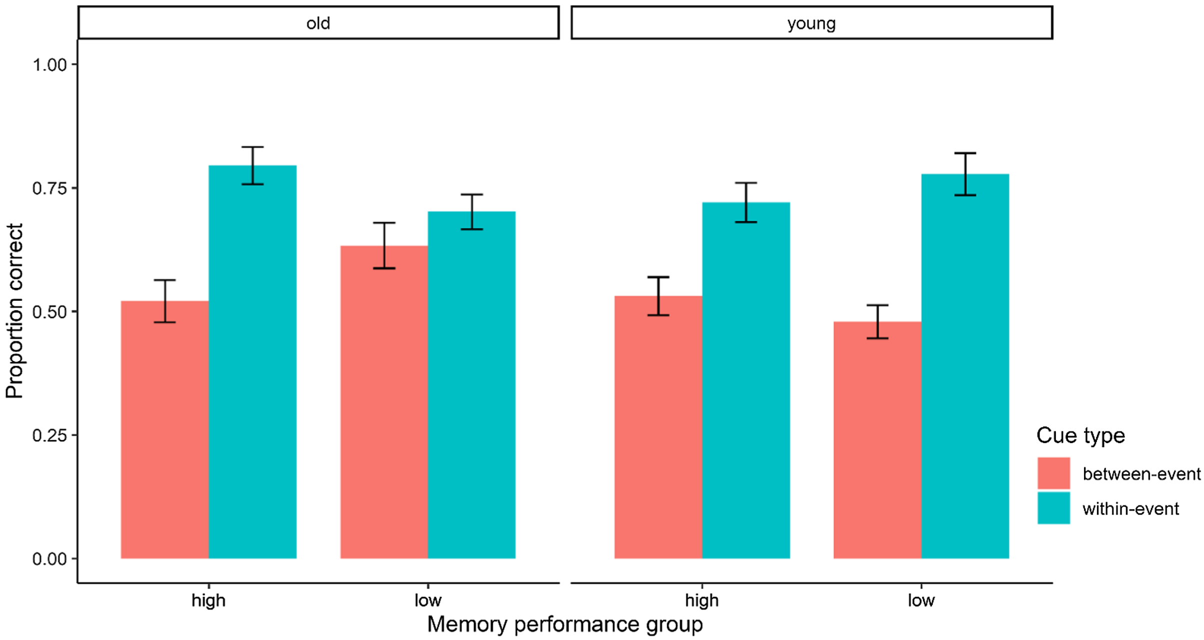
We reanalyzed the data from Davis et al. (2021) to determine whether older adults with poorer memory performance show less of a difference in cued recall for within-event and between-event cues. We found that low-performing, but not high-performing, older adults recalled a similar number of events in response to within-event and between-event cues. This exploratory analysis suggests that the formation of stronger associations within events is relatively preserved in high-performing older adults, and this may be due to high performers having intact attentional control and a preserved ability to refresh working memory at event boundaries. Meanwhile, low-performing older adults may fail to update working memory and/or integrate information from the preceding event, leading to less distinct events stored in long-term memory. Young adults, on the other hand, showed better cued recall for within-event than between-event cues regardless of their overall memory performance. While we hesitate to make any strong conclusions based on a single null result in the younger group, this finding suggests that all young adults (regardless of overall memory ability) form stronger associations within than between events (Ezzyat & Davachi, 2011).

However, there were several limitations to this study, which necessitate replication. First, due to the limited sample size and number of trials, we had to artificially binarize the continuous performance variable, splitting each age group into high and low performers. A follow-up continuous model showed a similar pattern, though the small sample size may have led to biased model estimates and should be interpreted with caution (see supplemental materials). These analyses suggest an intriguing relationship between overall memory performance and the distinctiveness of events in long-term

[1] Nevertheless, we fit a logistic mixed-effects model to predict cued-recall accuracy (using data from one coder; elsewhere, scores are based on the average across two coders, as in Davis et al., 2021) from cue type, age group, and free-recall performance. Stimulus and participant were entered as random effects. The addition of the three-way interaction term significantly improved model fit, $\chi^2(1) = 3.92$, $p = .048$, over a model including all main effects and two-way interactions (see supplemental materials for details). This is consistent with the predicted pattern of results suggesting that for older adults only, a larger within > between effect is associated with better memory performance. Though promising, we urge caution in interpreting these findings due to the small number of scenes and individuals tested.

Figure 1

Cued Recall for Within- and Between-Event Cues by High- and Low-Performing Older and Younger Adults



Note. Study 1 data originally from Davis et al. (2021). See the online article for the color version of this figure.

memory but should be interpreted with caution. Additionally, while we hypothesized that the reduced distinctiveness of events in low-performing older adults may be due to deficits in inhibitory control (and indeed, impaired inhibition may be the critical factor underlying these individuals' poor memory performance; Hasher & Zacks, 1988), this hypothesis remains to be tested directly. Last, the use of a single film limits the generalizability of the current results. We cannot say that these effects would extend to other films or more critically, real-life experiences. In Study 2, we attempt to address these issues by using a new film, larger sample size, and additional cognitive measures.

Study 2

There were three main goals in Study 2. First, we aimed to replicate our findings from Study 1, with the expectation that only high-performing older adults will show stronger associations within than between events on a test of cued recall. Second, we aimed to test our hypothesis that individual differences in working memory updating should relate to the distinctiveness of events in long-term memory. Last, we aimed to generalize these effects to a different and longer film, which would additionally allow us to take into account the variability in memorability among scenes.

To this end, participants viewed a portion of the first episode of BBC's *Sherlock*, a television show that has previously been coded for event boundaries (Chen et al., 2017). Following a filled delay, participants completed a cued-recall task, with cues taken from the beginning and end of scenes to prompt recall either within or between events. Given the results from Study 1, we predicted that low-performing older adults would show less of a difference in cued recall for within- and between-event cues than high-performing older adults. To help address the possible mechanistic link to older adults' impaired working memory updating, participants also completed a numeric two-back task (i.e., indicating whether the current number is the same as the one viewed two numbers previously) during the delay, which we then related to their within- versus between-event memory difference. While the *n*-back is somewhat controversial in the literature as a measure of working memory due to its relatively poor association with complex span tasks (e.g., Jaeggi et al., 2010; Kane et al., 2007; Redick & Lindsey, 2013), it is thought to reflect one's ability to update working memory or delete previously attended but no-longer-relevant information (Chatham et al., 2011; Gajewski et al., 2018; Gray et al., 2003; Rac-Lubashevsky & Kessler, 2016; Scharinger et al., 2015), a process that is thought to occur at event boundaries and may contribute to the distinctiveness of events stored in long-term memory. We expected better working memory updating to be related to a greater within > between difference.

Method

Participants

We determined the sample size required to detect a small–medium effect ($\eta_p^2 = .03$) for a between (age: young, old and performance groups: high, low) by within (cue type: within-event, between-event) three-way interaction with an a priori power analysis run using G*Power (Faul et al., 2007). This analysis showed that a total sample of 96 participants would achieve a power of .80 with an α of .05. Therefore, we aimed to collect a sample of 50 participants from each age group.

Participants were recruited from Prolific (https://www.prolific.co, an online participant pool) and were compensated £6/hr. A total of

105 participants were recruited, of which four were excluded for poor data quality (having repeated the same response or given no response for more than half of the trials). The final sample included 50 younger adults aged 18–30 years (27 women; $M_{age} = 23.7$, $SD = 3.36$; self-identified ethnicity: 37 White, five Black, one Asian American, two Hispanic, one Latinx, and four multiracial) and 51 older adults aged 60–80 years (31 women; $M_{age} = 65.2$, $SD = 4.85$; self-identified ethnicity: 45 White, four Black, and two multiracial). All participants were based in the United States and had English as a first language. Prior to beginning the study, participants were screened to determine if they had seen Sherlock within the past 5 years. Only those who had never seen the film or had seen it more than 5 years earlier were invited to complete the task with the rationale that the task required specific recall of individual scenes and a more general, schematic representation of the film should therefore not substantially influence performance. A majority of participants reported never having watched the series (old: $n = 32$; young: $n = 35$). Whether a participant had reported previously viewing the film was later entered as a covariate in the main analyses and did not affect the results. Older adults scored higher than young adults on the Shipley vocabulary test ($p < .001$; old: $M = 35.8$, $SD = 3.33$; young: $M = 33.2$, $SD = 3.69$). For years of formal education, we had to exclude some responses that suggested a lack of understanding or error (responses ≤9 years were excluded as the American sample should typically have at least 10 years of education; excluded $n = 8$ younger adults). In the remaining participants, there was no age difference in years of education ($p = .101$; old: $M = 16.1$, $SD = 2.70$; young: $M = 15.1$, $SD = 2.70$). Furthermore, older and younger adults did not differ in their reported sleep quality ($p = .965$; old: $M = 2.51$, $SD = 1.19$; young: $M = 2.52$, $SD = 1.11$) or perceived health ($p = .143$; old: $M = 6.80$, $SD = 2.20$; young: $M = 7.38$, $SD = 1.70$) but did differ in their reported stress such that younger adults reported being more stressed on average ($p = .002$; old: $M = 0.88$, $SD = 1.30$; young: $M = 1.74$, $SD = 1.40$).

Stimuli

The stimulus was a 23-min portion of the first episode of BBC's *Sherlock* television series preceded by a 30-s introductory clip (*Let's All Go to the Lobby*) included to reduce the influence of a general increase in attention at the onset of the video and to allow participants to adjust their volume. The video was viewed continuously but consisted of 26 distinct scenes (as coded by Chen et al., 2017) that were used to assess the influence of scene boundaries on memory performance. These scene boundaries were coded by the experimenters themselves (i.e., not participants) and occurred at major narrative shifts in location, topic, or time (Chen et al., 2017). Scenes ranged from 12 to 185 s ($SD = 47.2$ s) long. Similar to Study 1, clips were selected from these scenes to serve as cues during recall. These were selected with the parameters that they should be approximately 5 s in length and should avoid cutting off words or phrases spoken in the film. Additionally, their length was chosen to avoid giving away key details of the scene's content where possible (timing of cues available at OSF). For example, one scene in the film centers around a meeting between a main character (John Watson) and an old acquaintance. The cue shows Watson walking through the park but does not include a shot where the acquaintance is in the frame. This was intended to maximize the likelihood that participants' responses to the cues would consist of key details from the target scene that were not present in the cue. Cues were taken from the beginning (within-event cues; $M = 5.21$ s, $SD = 0.53$ s) and the end (between-event cues; $M = 4.95$ s, $SD = 0.61$ s) of scenes.

In the two-back task, participants viewed centrally presented numbers (0–9) and were asked to respond by pressing the space key every time the current number matched the one presented two trials back. If it did not match, no response was required. Each trial began with a 1,000 ms fixation cross, followed by 500 ms presentation of the stimulus. Participants could continue to respond during the 1,500 ms interstimulus interval until the fixation cross signaled the next trial. Ninety-six trials were included, of which 32 trials were targets and 64 were nontargets. Participants were given feedback on a practice block of 11 trials but did not receive feedback during the main task. Hits, false alarms, misses, and correct rejections were used to compute performance metrics, with the sensitivity index d' ($d' = Z_{Hit} - Z_{FA}$) used as a measure of performance in subsequent analyses.

Procedure

The study was approved by the Research Ethics Board at Brock University (Individual differences in film comprehension, No. 20-249). Data were collected May–July 2021. As the data were collected online through Prolific, sound volume and screen size could not be controlled; however, the videos were shown at a constant resolution (800 × 450 pixels) and volume was instructed to be adjusted to a comfortable level. The task was programed using JavaScript with the jsPsych library (Version 6.3.0; de Leeuw, 2015; https://www.jspsych.org/6.3/) and hosted on an Amazon Web Server.

The procedure closely followed the behavioral testing procedure used in Study 1, from Davis et al. (2021). Participants began the session by watching the introduction video and entire 23-min portion of Sherlock. As awareness of the memory testing did not influence results in Study 1, in Study 2, participants were informed that their memory would be tested for the contents of the film but did not know how it would be tested. Following the video, participants completed the two-back task, which lasted approximately 5 min, acting both as a filler task and as a measure of working memory updating. They then completed the cued-recall task wherein they viewed the ∼5 s clips and were asked to type a description of what they thought followed immediately after the clip in the original video. They had unlimited time to type their response and pressed "continue" to proceed to the next clip. Clips were presented in the temporal order in which they appeared in the video. Either a between-event or within-event cue was given for each scene (counterbalanced across participants), giving a total of 26 cues for each participant (13 within-event, 13 between-event). Finally, participants completed questionnaires including the Shipley vocabulary test, a general demographic questionnaire (sex, age, race, and education), and the Ability subscale of the Multifactor Memory Questionnaire (Troyer & Rich, 2002). As data were collected from online participants during the COVID-19 pandemic, we reasoned that several health factors that may influence memory, and attention may differ between groups (e.g., if participants began participating in online studies due to financial hardship). Thus, they also reported their perceived health on a 10-point scale, as well as their perceived sleep quality and stress levels on 5-point scale. These health metrics were entered as covariates in subsequent analyses but did not change the results. To ensure data quality, we also asked participants to report whether they had challenges paying attention to the task, or if they had any feedback on how it ran, but these did not result in any additional exclusions.

Scoring

Responses to the cued-recall task were coded for accuracy as well as the type of errors made. Responses were marked as correct when the participant described something that occurred in the target scene (the scene containing the cue for within-event cues or the next scene for between-event cues) that was not evident from the cue itself. Errors were coded into several categories: incorrect information (describing something that did not occur in the film), earlier scenes (describing something that occurred earlier in the film), next scenes (describing the scene following the target scene), and far errors (describing something that occurred more than one scene after the target scene). Two raters scored the data. To calculate interrater reliability, 20% of the files were scored by both raters. Interrater reliability was assessed using the *irr* package (V.0.84.1; Gamer et al., 2019), agreement was excellent ($\kappa = .919$, $p < .001$).

Analysis

While one of our primary goals in Study 2 was to replicate our main effect of interest from Study 1 using memory performance as a continuous measure, we first sought to directly replicate the median-split analysis for the sake of consistency. Thus, our a priori planned analysis was to use a median split to separate participants into high- and low-performance groups and determine whether a three-way age group (old vs. young) by performance group (high vs. low) by cue type (between-event vs. within-event) interaction was present for accurate responses. Group membership was determined by computing the overall accuracy score on the cued-recall task (collapsing across cue type) and dividing participants at the median for each age group. To assess the type of errors made in response to each cue type, separate analyses assessing the interaction between error type, age group, and performance group were run for each cue type (see supplemental materials).

In addition to this direct replication, we also analyzed the accuracy data continuously with a logistic mixed-effects model using the glmer function in R's lme4 package (Bates et al., 2015), the numDeriv package (Gilbert & Varadhan, 2019) to more accurately assess convergence using the Richardson extrapolation, and the sjPlot package (Lüdecke, 2021). Model fit was determined with comparisons using a likelihood-ratio test. Participant could not be included as a random effect in the same model as one containing overall memory performance (due to shared variance); thus, to determine the random effects structure of the model, we first left overall performance out of the model. A model containing random effects of both cue (52 unique cues; 26 within-event and 26 between-event) and participant was compared to a model containing only the random effect of participant. The inclusion of cue as a random effect significantly improved model fit, $\chi^2(1) = 616.2$, $p < .001$; ICC = .434, and was used as a random intercept in subsequent models. The model was then built to test for the three-way interaction between cue type, age group, and overall memory performance (as a continuous predictor), excluding the random effect of participant.

Performance on the two-back task was assessed by computing d' for each individual using the d' function from the psycho package in R (Makowski, 2018). Given that the task was completed online, to ensure data quality, files with particularly low d' (scores less than 0.5), were visually inspected to determine whether there were any clear patterns in responses that might indicate a lack of understanding or failure to complete the task. Three participants (two younger, one older) were subsequently removed from this analysis, one for pressing the response key every time a particular number was shown and two for abandoning the task before completion. One older adult participant had a cue benefit score beyond 3 *SD*s from the mean and was excluded from this analysis, leaving a total sample of 49 older and 48 younger adults.[2] To determine whether two-back scores uniquely predicted cue benefit, we compared the fit of a linear regression model predicting cue benefit (within-event − between-event accuracy) from the main effects of age and d' to one additionally containing the interaction term.

Results

Cued-Recall Performance

Accuracy on the cued-recall task was analyzed using a 2 Age (between-subjects; old, young) by 2 Cue Type (within-subjects; within-event, between-event) by 2 Performance Group (between-subjects; high performers, low performers) mixed ANOVA. This revealed the expected main effect of cue type, such that memory was better following within-event ($M = 0.59$, $SD = 0.19$) than between-event ($M = 0.45$, $SD = 0.17$) cues, $F(1, 97) = 60.1$, $p < .001$, $\eta_p^2 = .382$. There was also a main effect of performance group ($p < .001$), though this was expected given that the grouping variable was based on participants' overall performance. The main effect of age was not significant, $F(1, 97) = 3.51$, $p = .064$, but there was a significant three-way interaction between age group, cue type, and performance group, $F(1, 97) = 5.34$, $p = .023$, $\eta_p^2 = .052$.[3] None of the other interactions were significant ($ps > .071$).

The three-way interaction was followed up within each age group to reveal a significant interaction between cue type and performance group in older adults, $F(1, 49) = 8.70$, $p = .005$, $\eta_p^2 = .151$, such that high-performing older adults showed a larger cue type effect than low-performing older adults. Pairwise comparisons revealed that the cue type effect was significant in high-performing ($p < .001$), but not low-performing older adults ($p = .135$; see supplemental Figure S1 and supplemental Table S1 for means and SDs). In contrast, young adults did not show this interaction, $F(1, 48) = 0.12$, $p = .735$, $\eta_p^2 = .002$. The three-way interaction remained significant when controlling for demographic variables including perceived health, stress, sleep, and education (three-way interaction, $ps < .030$), and when controlling for whether participants had previously seen Sherlock (three-way interaction, $p = .025$). Thus, both younger adults and high-performing older adults showed a memory advantage for

[2] We also calculated split-half reliability for the d' measure from the n-back task (random sampling with 5,000 permutations using the splithalfr package in R, Pronk et al., 2022), resulting in a Spearman–Brown corrected coefficient of $r = .921$. This is well above the value of $r = .70$, which is often considered the lower limit for acceptable split-half reliability (Cronbach, 1951; Hedge et al., 2018).

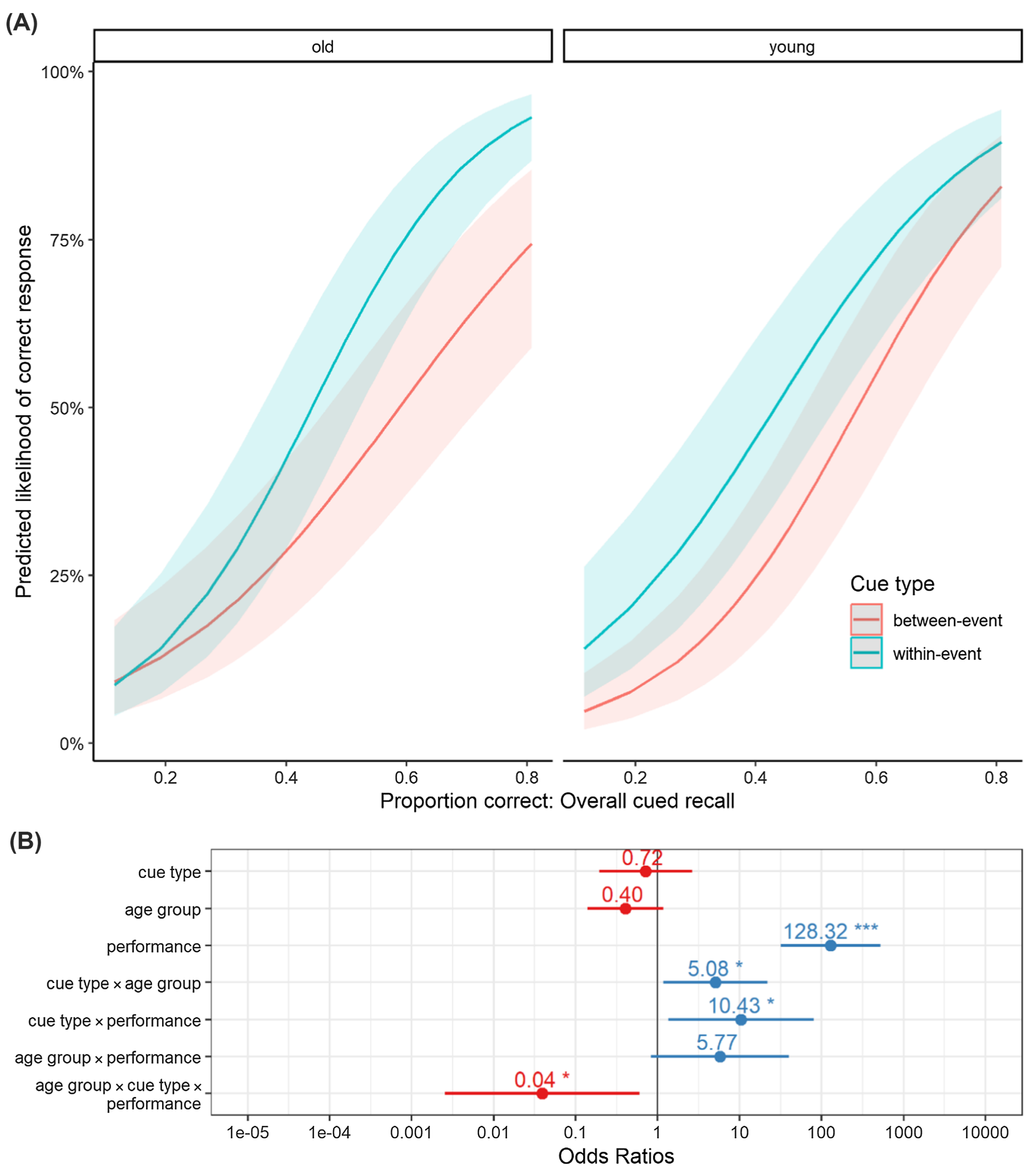
[3] While the boundaries used (from Chen et al., 2017) occurred at major shifts in location, topic, or time, we reran this analysis having removed the six scenes that did not contain shifts in location at scene boundaries to reduce the potential influence of ambiguity of scene boundaries, this did not change the results ($p = .03$ for the three-way interaction).

within- versus between-event cues, while low-performing older adults performed similarly across these two cue types.

Finally, we replicated this effect while treating overall cued-recall performance as a continuous variable. A logistic mixed-effects model was run to predict performance (the proportion of correct responses to the cued-recall task) from cue type, age group, and overall cued-recall performance, with cue (stimulus) entered as a random effect. We tested whether model fit including all main effects and two-way interactions would be improved by the inclusion of the three-way interaction between cue type, age group, and performance. The addition of the three-way interaction term significantly improved model fit, $\chi^2(1) = 5.40$, $p = .020$. As shown in Figure 2A, memory for within-event and between-event cues do not differ in low-performing older adults and start to differentiate at higher levels of overall memory performance. Odds ratios and corresponding 95% confidence intervals are presented in Figure 2B for all model predictors. Thus, the interpretation of the median-split analysis does not change when treating memory performance as a continuous variable.

Figure 2

Logistic Mixed-Effects Model Predicting Cued-Recall Performance



Note. (A) Cued-recall accuracy as predicted by the logistic mixed-effects model including overall performance as a continuous predictor. Shaded area represents 95% CI. (B) Logistic regression model coefficients for model predicting cued-recall accuracy including performance as a continuous predictor, error bars represent 95% CI. CI = confidence interval. See the online article for the color version of this figure.
* $p < .05$. *** $p < .001$.

Two-Back Performance

To investigate a possible mechanistic link between the degree of binding within and between events to working memory updating, we compared a linear model predicting cue benefit (within-event − between-event cued recall), which included the main effects of age group and d' to a model additionally including the interaction term. The model containing only main effects did not significantly predict cue benefit, $F(2, 94) = 1.85$, $p = .164$. However, the addition of the interaction term significantly improved the model ($p = .025$), resulting in a model that accounted for a significant 8.9% of variance in cue benefit, $F(1, 93) = 3.02$, $p = .034$. While age group did not contribute significantly to the model ($\beta = 0.193$, $p = .070$), both d' ($\beta = .069$, $p = .004$), and the interaction between d' and age ($\beta = -.071$, $p = .025$) were significant contributors. As shown in Figure 3, the relationship between cue benefit and d' differed in older and younger adults, such that higher d' scores were associated with a larger within-cue benefit in older adults ($r = 0.41$, $p = .004$) but not in younger adults ($r = -0.02$, $p = .910$).

Discussion

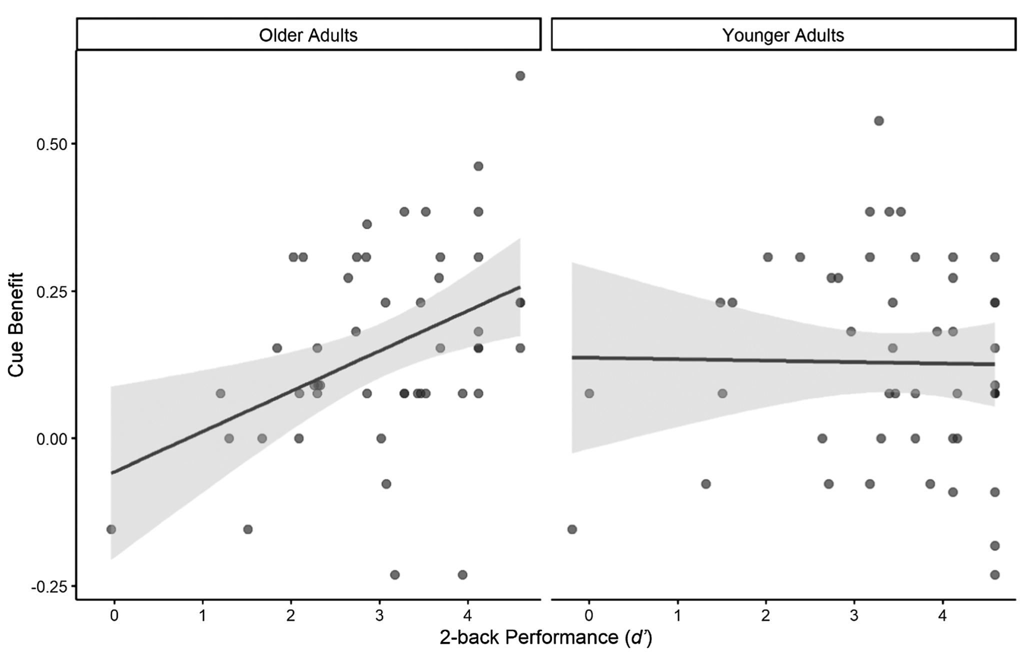
We replicated the results from Study 1, finding that both younger adults and high-performing older adults show better cued recall when tested within an event than across an event boundary, while low-performing older adults perform similarly in these two cases. This effect was observed both when treating performance as a continuous variable and when splitting participants into high- and low-performance groups. Therefore, in older adults, evidence of less distinct events being stored in long-term memory was associated with lower memory performance. Scores on the two-back task were also found to differentially predict the within > between effect in older and younger adults, such that higher two-back performance was associated with a larger within-event benefit in older, but not younger, adults. This finding suggests that for older adults, the storage of more distinct events in long-term memory relates to the ability to update working memory.

General Discussion

We examined age differences in the relationship between episodic memory performance and within-event and between-event binding in long-term memory. Using two distinct films, we replicate previous work, which has shown, across multiple stimulus modalities, that event details are more strongly bound within than between events (Davis et al., 2021; Ezzyat & Davachi, 2011). Though this effect has been observed previously in older adults (Davis et al., 2021), we extend these findings both in our exploratory analyses (Study 1) and our follow-up replication (Study 2) by showing that the within > between effect relates to overall episodic memory performance in older, but not younger, adults. In Study 2, this within > between effect also related to two-back performance in the older group, with poorer working memory updating relating to less distinct events stored in long-term memory. Taken together, these findings make the novel suggestion that poorer working memory updating in older adults contributes to the formation of relatively stronger associations between events and ultimately poorer memory for the movie. While this hypothesis requires further testing, these findings are consistent with work showing that older adults form excess associations, or *hyper-bind*, over time (Campbell et al., 2014) and maintain access to

Figure 3

Cue-Type Benefit (Within-Event Cue − Between-Event Cue Performance) as Predicted by the Linear Model Including Age Group, d′ (From the Two-Back Task), and Their Interaction Separated by Age Group



Note. Shaded area represents 95% CI, individual observed data points included. CI = confidence interval.

previously relevant representations even as tasks and goals change (Scullin et al., 2011; Weeks et al., 2020).

Working Memory Updating and Event Distinctiveness

Previous work suggests that event boundaries trigger a working memory updating process that facilitates the formation of a new event model or representation of the current event (Radvansky & Copeland, 2006; Swallow et al., 2009; Zacks et al., 2007). This has been shown by testing participants' access to information from the preceding event immediately following an event boundary, including words from a preceding sentence (Speer & Zacks, 2005) or objects "picked up" in a previous virtual room (Radvansky & Copeland, 2006). The present study builds on this literature by showing the long-term consequences of this updating process, suggesting that updating may contribute to the formation of tighter associations within events and weaker associations across event boundaries. Individual differences in working memory updating (i.e., two-back performance) related to a larger within > between cued-recall effect in older, but not younger adults. We hesitate to conclude that working memory updating is less important for event distinctiveness in younger adults based on this single null result, especially given the theoretical role of working memory updating in event segmentation (Radvansky, 2012; Zacks et al., 2007) and the considerable evidence that access to information in working memory is reduced following event boundaries in younger adults (Radvansky & Copeland, 2006; Speer & Zacks, 2005; Swallow et al., 2009). It could be that our use of a single working memory updating task, at a load that may not have been particularly challenging for young adults (i.e., two-back instead of three-back), was not ideal for measuring individual differences in working memory updating in this group. Indeed, previous work suggests that working memory tasks (Johnson et al., 2010), and the two-back task in particular, load with different measures in younger and older adults (executive functions in the young, vs. attentional, verbal memory, and updating abilities in the old; Gajewski et al., 2018), suggesting that it may be tapping into slightly different processes in each group.

One such component process that may be critical to successful performance on the two-back task is active suppression (or deletion) of previously attended, but no-longer-relevant, information (Campbell et al., 2020; Hasher et al., 2007). This process may also be important for encoding distinct or punctate events in memory. If individuals fail to inhibit information from the preceding event, they are likely to form stronger associations between events and show less of a difference in cued recall for within- and between-event cues at retrieval. Some older adults have trouble controlling their attention, and those that do, may be the same individuals who are failing to update working memory and hyper-binding across events. However, this conclusion is only speculative and entirely based on correlational results using a single updating task here. Future work should further explore this relationship using an individual differences approach and a battery of inhibitory tasks to more specifically probe the deletion function of working memory and sufficiently challenge both younger and older adults.

Event Distinctiveness and Overall Memory

Across two studies, we show that event distinctiveness (i.e., the within > between cued-recall effect) relates to better overall memory for the movie in older adults. While inferring connections between events is naturally important in forming coherent narrative representations in memory (e.g., Stine-Morrow & McCall, 2022), and this may be one of the hidden benefits of reduced inhibitory control with age (Amer et al., 2016), cross-event associations may also contribute to disordered recall and memory failures (Diamond & Levine, 2020). Encoding distinct events into memory may be particularly important for older adults, as attentional control is also required to resolve interference and guide search processes at retrieval (Healey et al., 2013; Jacoby et al., 2005). It is puzzling that event distinctiveness did not relate to overall memory in younger adults, given that other studies have shown a positive relationship between event segmentation and long-term memory in that group (e.g., Flores et al., 2017; Sargent et al., 2013). While the precise cause of this discrepancy remains unclear, it could be because low performance in the young adults tested here was caused by some other factor, such as low motivation (Ennis et al., 2013; Ryan & Campbell, 2021), mind-wandering during encoding (Jackson & Balota, 2012; Seli et al., 2021), and/or multitasking during the experiment (Madore et al., 2020). All of these effects would lower performance in young adults overall, rather than for the within-event cues in particular, and possibly disrupt the relationship between event distinctiveness and overall memory. Nevertheless, the relationship between event distinctiveness and overall memory for the movie in older adults suggests that storing events as tight units in long-term memory benefits retrieval (Diamond & Levine, 2020; Sederberg et al., 2010).

Alternative Explanations

One alternative interpretation of the current results is that low-performing older adults were impaired or more variable in their perception of event boundaries. If low-performing older adults identified different boundaries than their high-performing counterparts or younger adults, then we would also expect a reduction in the within > between effect simply because the cues used do not line up with these individuals' perceived event boundaries. This prediction is consistent with work showing that older adults are sometimes more idiosyncratic in their boundary identification (Bailey et al., 2013; Kurby & Zacks, 2011; Zacks et al., 2006), possibly reflecting the diversity of their semantic knowledge that has been shown to affect event segmentation (Pitts et al., 2022). However, previous work has shown that older and younger adults are sensitive to the same situational features in event boundary identification (Kurby et al., 2014). And indeed, some work has shown similar boundary identification in younger and older adults (Kurby et al., 2014; Magliano et al., 2012). Furthermore, eye-tracking data from Study 1 (published in Davis et al., 2021) indicate that both age groups show a similar increase in eye movement synchrony following scene boundaries. Previous work suggests that increased eye movement synchrony is indicative of increased attention (e.g., Dorr et al., 2010; Madsen et al., 2021) and thus, a similar increase in synchrony at event boundaries (coupled with virtually no age differences in synchrony at other points in the movie) suggests that both groups perceived the same boundaries (at least in Study 1). The boundaries in Study 2 were major scene changes coded by Chen et al. (2017) and were likely unmissable by either group (results also did not change after removing the six scenes whose boundaries were not followed by a location change), though future work should confirm this empirically. Thus, it seems unlikely that the reduced within-event benefit in low-performing older adults is simply due to them not perceiving the same event boundaries as others.

Another alternative explanation is that low-performing older adults are failing to bind within-event details together. This finding is consistent with recent work showing reduced hippocampal activity at event boundaries in older adults (Reagh et al., 2020) and the large body of research suggesting that aging is associated with a memory binding deficit (Chalfonte & Johnson, 1996; Naveh-Benjamin, 2000). While this well-documented binding deficit may have contributed to memory performance overall, it cannot explain a selective impairment in within-event cued recall nor a relative enhancement of between-event recall in the low-performing older adults. Though older adults likely show some general impairments in the binding of details in episodic memory and this may contribute to their poor performance (e.g., Naveh-Benjamin et al., 2004), the reduced within > between effect in low-performing older adults appears to capture other aspects of event perception and encoding—in our view, impaired working memory updating and as a result, cross-event binding.

Limitations

We acknowledge several limitations of the present study that warrant discussion. While previous work suggests that both older and younger adults identify boundaries using the same criteria (Kurby et al., 2014), and our results did not change when excluding scenes that did not end with unambiguous scene changes, we cannot rule out the possibility that age differences may be due to differences in where individuals identify boundaries. Future work might benefit from identifying boundary locations using implicit measures, such as eye tracking (pupil size linked to boundaries; Clewett et al., 2020) or neuroimaging (data-driven models can be used to identify boundaries in both electroencephalography; Silva et al., 2019, and functional magnetic resonance imaging; Baldassano et al., 2017; Geerligs et al., 2021). A second limitation is that we could not counterbalance cues across conditions (i.e., within-event and between-event cues were not interchangeable), which differs from previous work with narratives (Davis & Campbell, 2023; Ezzyat & Davachi, 2011). We attempted to control for this by counterbalancing the cues used for each scene (i.e., each scene was probed with either a within-event or between-event cue and this was counterbalanced across participations) and by using mixed models that take cue-wise variability in memorability into account. However, these steps may not entirely correct for this issue. Additionally, online samples limit what we know about environmental distractors and older adults who participate online may be higher functioning and more accustomed to technology than those typically tested in lab (Greene & Naveh-Benjamin, 2022), thus affecting potential age differences. While we replicate the effect observed in a laboratory setting from Study 1, the limited sample size of Study 1 and the fact that only the online version included a measure of working memory updating (the two-back task) suggests that caution should be used in interpreting these findings.

General Conclusions and Future Directions

We find that in older but not younger adults, event segmentation (as measured by the relational binding between vs. within events) relates to memory performance and that performance on the two-back task predicts relational binding in older, but not younger, adults. These findings suggest that averaging performance across older adults in event cognition studies may not be the best approach to understanding memory in aging. It is possible that in doing so, we are missing important variability in the sample that could lead to further insights as to why some individuals experience memory declines with age, while others do not. In addition to using alternative methods to identify individuals' event boundary locations, intervention studies should aim to investigate what factors might increase the within > between effect in low-performing older adults. For instance, previous work has shown that slowing films at event boundaries increases memory performance in both younger and older adults (Gold et al., 2017), but it is unclear how this shapes the relational binding of episodic memories. Furthermore, making event boundaries more distinct may encourage encoding of within-event associations.

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