Psychology and Aging

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Online First Publication, July 22, 2021. http://dx.doi.org/10.1037/pag0000615

CITATION
Davis, E. E., Chemnitz, E., Collins, T. K., Geerligs, L., & Campbell, K. L. (2021, July 22). Looking the Same, but Remembering Differently: Preserved Eye-Movement Synchrony With Age During Movie Watching. *Psychology and Aging*. Advance online publication. http://dx.doi.org/10.1037/pag0000615

AMERICAN PSYCHOLOGICAL ASSOCIATION

Psychology and Aging

ISSN: 0882-7974

https://doi.org/10.1037/pag0000615

Looking the Same, but Remembering Differently: Preserved Eye-Movement Synchrony With Age During Movie Watching

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Naturalistic stimuli (e.g., movies) provide the opportunity to study lifelike experiences in the lab. While young adults respond to these stimuli in a highly synchronized manner [as indexed by intersubject correlations (ISC) in their neural activity], older adults respond more idiosyncratically. Here, we examine whether eye-movement synchrony (eye-ISC) also declines with age during movie-watching and whether it relates to memory for the movie. Our results show no age-related decline in eye-ISC, suggesting that age differences in neural ISC are not caused by differences in viewing patterns. Both age groups recalled the same number of episodic details from the movie, but older adults recalled proportionally fewer episodic details due to their greater output of semantic and false information. In both age groups, higher eye-ISC related to a higher proportion of internal details and a lower proportion of false information being recalled. Finally, both older and younger adults showed better cued recall for cues taken from within the same event than those spanning an event boundary, further confirming that events are stored in long-term memory as discrete units with stronger associations within than across event boundaries. Taken together, these findings suggest that naturalistic stimuli drive perception in a similar way in younger and older adults, but age differences in neural synchrony further up the information processing stream may contribute to subtle differences in event memory.

Keywords: aging, episodic memory, eye-tracking, naturalistic stimuli, associative memory

Supplemental materials: https://doi.org/10.1037/pag0000615.supp

The extant literature on episodic memory and aging has typically used highly controlled stimuli and encoding conditions that bear little resemblance to events experienced in everyday life. In order to understand how age affects memory outside the lab, we must turn to more dynamic, naturalistic stimuli, such as movies (Hasson et al., 2004, 2008a, 2008b; Kurby & Zacks, 2011, 2018; Sargent et al., 2013; Wahlheim & Zacks, 2019), story narratives (see Radvansky & Dijkstra, 2007 for review), and real-life experiences (Diamond et al., 2018, 2020) to complement more traditional methods. The use of naturalistic stimuli in aging research is especially important because some of this work suggests that age differences are less pronounced than what is typically seen with standard laboratory stimuli, such as lists of words or objects (e.g., Diamond et al., 2020; Radvansky et al., 2003). Although naturalistic stimuli lack some of the empirical control that is ideal in experimental research, it provides the necessary complexity and meaning to more closely approximate true human experience.

Despite the complex nature of naturalistic stimuli, such as movies, people tend to process these stimuli in a highly similar fashion. For instance, previous functional magnetic resonance imaging (fMRI) research with young adults has shown that participants' neural responses are highly correlated when watching the same movie, both in lower perceptual regions and higher order association cortex (Hasson et al., 2004, 2010). Further, these intersubject correlations (ISC) are positively related to memory, in that more synchronous responding relates to better subsequent memory for the movie (Hasson et al., 2004, 2008a). We have shown that neural-ISC during movie-watching declines with age and relates to measures of attentional control, suggesting that older adults' idiosyncratic responding may be caused by decreased top-down attention (Campbell et al., 2015; cf., Kurby & Zacks, 2018; Oren et al., 2016). Moreover, age differences in neural synchrony are most pronounced in the frontoparietal control network, critical for

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This work was supported by the Natural Sciences and Engineering Research Council of Canada (Grant RGPIN-2017-03804 to Karen L. Campbell), the Canada Research Chairs program (to Karen L. Campbell), and the Veni grant [451-16-013] from the Netherlands Organization for Scientific Research (to Linda Geerligs). The script to calculate the eye-ISC scores was written by Tyler K. Collins and can be found at the following link: https://github.com/Andesha/eye-track-study. The Fieldtrip analysis (MATLAB) was written by Emily E. Davis can be found on the Open Science Framework: https://osf.io/atfxh/. For OSF access to the stimuli used in this experiment, please contact the corresponding author. Preliminary results from this research were orally presented at the Toronto Area Group Spring Meeting, Ontario, Canada (2019) and Virtual Psychonomics (2020). These preliminary results were also shared in a poster presentation at Psychonomics, Quebec, Canada (2019), which included a published abstract (*Abstracts of the Psychonomic Society, Vol. 24, November 2019*).

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top-down attentional control, as well as the medial prefrontal cortex and hippocampus, regions critical for memory and the integration of incoming information with existing knowledge (Geerligs et al., 2018; see also Benoit et al., 2014; van Kesteren et al., 2012).

While these findings suggest that older adults process naturalistic stimuli in a different way to younger adults, as well as to their age-matched peers (Campbell et al., 2015), it remains unclear at what point in the information processing hierarchy this idiosyncratic responding arises. For instance, do older adults also *look* at different things during naturalistic viewing? Eye movement intersubject correlation (eye-ISC) has been used in previous work with younger adults as a measure of whether participants are viewing the same locations at the same time (e.g., Bacha-Trams et al., 2017; Hasson et al., 2008b; Hutson et al., 2017). During free viewing tasks, eye-ISC is thought to primarily depend on bottom-up attentional capture because it is unaffected by comprehension of the plot (Hutson et al., 2017), is highest at the onset of motion (Mital et al., 2011; Smith & Mital, 2013), and tends to be higher for more captivating stimuli (e.g., Hollywood films relative to home movies; Dorr et al., 2010). Since bottom-up attentional capture remains largely preserved with age (Christ et al., 2008; Colcombe et al., 2003; Tales et al., 2002), we might expect age to have little effect on eye-ISC during naturalistic viewing. On the other hand, age differences in eye-movement control are well documented (for a recent review, see Wynn et al., 2020a), with older adults less able to inhibit eye movements toward targets on the antisaccade task (e.g., Mack et al., 2020; Olincy et al., 1997; Płomecka et al., 2020), prevent capture by sudden onsets in the visual field (e.g., Campbell & Ryan, 2009; Cassavaugh et al., 2003; Ryan et al., 2006), and more influenced by expectations during visual search of natural scenes (Wynn et al., 2020b). Thus, it is possible that viewing patterns may differ with age during naturalistic viewing, which could contribute to older adults' idiosyncratic neural responding higher up the information processing stream.

To determine whether eye-ISC differs with age during naturalistic viewing, we used eye-tracking to measure younger and older adults' eye movements while watching the same film used in our previous work (i.e., Alfred Hitchcock's *Bang! You're Dead*; Campbell et al., 2015), followed by surprise memory tests (cued and free recall). Using the same film allows for comparison across these studies and better inference as to whether age differences in eye movement synchrony are contributing to differences in neural synchrony. Individual differences in eye-ISC were compared across time and related to age and memory for the movie. Past research measuring eye-ISC during movie viewing has not tested whether synchrony relates to memory. That said, *neural*-ISC has been previously shown to relate to memory (Hasson et al., 2004, 2008a) and there is a substantial literature demonstrating that the oculomotor and hippocampal memory systems are linked both structurally and functionally (see Ryan & Shen, 2020 for review). Therefore, irrespective of age differences in eye-ISC, we predicted that eye-ISC should relate to subsequent memory for the movie.

A second question we sought to address regards age differences in memory for events. According to event segmentation theory (for recent reviews, see Radvansky & Zacks, 2011; Zacks, 2020), we divide continuous experience into a series of discrete events (e.g., eating breakfast, followed by driving to work). In an effort to make sense of the world around us, we create situation (or event) models that integrate existing knowledge with incoming information. When we are no longer able to predict what is going to happen next (e.g., when there is a shift in space, time, or goals), an event boundary is perceived and the current event model must be updated (Zacks et al., 2007).

Previous work examining age differences in event perception has reported mixed results. Some work suggests that event updating is largely preserved with age, such that older and younger adults' reading times are similarly slowed at event boundaries (presumably reflecting the time it takes to update one's event model; Radvansky & Dijkstra, 2007; Radvansky et al., 2001). Further, both older and younger adults show reduced access to objects encountered in one room when their memory for those objects is tested in another room, suggesting that both groups update their situation models at event boundaries (rendering details from the previous model harder to access; Radvansky et al., 2003, 2015). However, other work suggests that there may be some age differences in event model updating, in that it takes longer and more effort for older adults to update event models compared to young adults (e.g., Morrow et al., 1994, 1997). Additionally, the *type* of updating that is engaged at event boundaries appears to differ between groups, with young adults updating individual details incrementally and older adults engaging in a more global process (Bailey & Zacks, 2015). Finally, older adults may differ in how they perceive event boundaries, as they sometimes show less agreement in where they draw event boundaries relative to younger adults (Kurby & Zacks, 2011; Zacks et al., 2006; but see Kurby & Zacks, 2018; Sargent et al., 2013), echoing our findings of reduced neural synchrony with age during naturalistic viewing (Campbell et al., 2015; Geerligs et al., 2018). Thus, age differences in event perception are not consistently observed, but event model updating appears to remain largely intact, at least when tested immediately.

However, event segmentation also has consequences for long-term memory, in that segmented events are later retrieved as discrete units (Clewett et al., 2019; Zacks, 2020). Event boundaries appear to trigger brain mechanisms that bind together the details of the preceding event, as suggested by fMRI work with young adults who show increased hippocampal activity at event boundaries during movie-watching (Ben-Yakov et al., 2012, 2013; Reagh et al., 2020). Other work with young adults has shown that associations within events may be stronger than those between events, in that cued recall tends to be better when cues are taken from *within* an event, rather than just before an event boundary (i.e., testing memory for associations *between* events in a story narrative; DuBrow & Davachi, 2016; Ezzyat & Davachi, 2011). No study to date has examined whether older adults also show an advantage in cued recall for cues taken from within versus between event boundaries, or indeed whether this effect extends to memory for more complex stimuli (such as movies) in younger adults.

To test this, we used a cued-recall task in which participants viewed short clips taken from just before a scene change versus the middle of a scene. Participants were asked to recall what happened immediately following the clip. First, we expected to conceptually replicate Ezzyat and Davachi's (2011) findings in both groups, such that, younger and older adults would show higher recall when cued within the same event than across an event boundary (i.e., a main effect of event type). Second, we expected this difference to be less pronounced in the older group. This second prediction was based on a long line of work showing that older adults are less able to inhibit recently attended information than younger adults (e.g., Hamm & Hasher, 1992;

Lustig et al., 2001; Scullin et al., 2011; Weeks et al., 2020). We have shown that this inhibitory deficit sometimes leads to the inadvertent formation of associations (or "hyperbinding"; Campbell et al., 2010, 2012), for instance between successive pairs of words within a paired-associate learning paradigm (Campbell et al., 2014). If older adults are less able to inhibit recently attended information, and if this becomes bound to the current contents of attention, then we might expect their event boundaries to be less distinct than those of younger adults and for older adults to show less of a difference in long-term memory for within- versus between-event cues.

In summary, the present study had three primary aims: (1) to assess whether eye movement synchrony during naturalistic viewing differs with age; (2) to determine whether eye movement synchrony relates to subsequent memory for the movie; and (3) to replicate previous work showing that events are stored as discrete units in long-term memory (as indexed by better cued recall within than between events) and to test whether this effect is moderated by age.

Method

Participants

Participants included a convenience sample of 24 older adults (aged 61–82 years; 13 females) and 25 younger adults (aged 18–28 years; 18 females). Older adults were recruited from the community and paid $10/hr for their participation, and younger adults were recruited from Brock University and received course credit. Ten participants were replaced for the following reasons: the eye tracker did not calibrate (Old $N = 5$), cellphones were answered during the film (Young $N = 1$; Old $N = 1$), and a score less than 23 on the Montreal Cognitive Assessment (MoCA; Carson et al., 2018; Nasreddine et al., 2005; Old $N = 3$). As is common in the aging literature, older adults had more years of education, $t(47) = 2.94$, $p = .005$, $d = 0.84$, and higher vocabulary scores (Shipley, 1946), $t(46) = 4.61$, $p < .001$[1], $d = 1.33$, than young adults (see Table 1 for demographics).

Materials

The movie used was *Bang! You're Dead* from the television series Alfred Hitchcock Presents (Swanton et al., 1961). The original 25-min episode was shortened to 8-min while preserving critical parts of the storyline. This 8-min version of the film has been used in past research on aging and neural synchrony (Campbell et al., 2015; Geerligs, et al., 2018). None of the participants reported having seen the film. For the cued-recall task, short clips (duration: $M = 5.00$s, $SD = 1.47$) were taken from the 8-min version of the film using scene changes as event boundaries (i.e., points in the film where the scene faded to black before another scene started in a new place/time). These clips were selected to create two conditions: within-event clips (i.e., those taken from within an event) and between-event clips (i.e., those taken from just before a scene change). There was a total of 24 clips (12 within; 12 between); however, two between-event clips were removed from subsequent analyses—one that preceded the end of the movie and one that elicited the same response as the previous clip. In this latter clip, 78% of participants said something similar to their previous response (e.g., previous clip response: "Enters the house and pretends to shoot the maid"; response for the excluded clip: "Goes on to shoot the maid") and of those participants, 45% responded with the exact same wording as the previous response or said, "Same"/"Same thing." We interpreted the consistent response repetition for this clip as evidence that the clip was not distinct enough from the previous clip and therefore, excluded it from our analysis.

Table 1
Demographic Information

Age Group	Age	Edu (years)	Shipley Vocabulary	MoCA
Younger	20.83 (2.71)	14.74 (2.09)	29.64 (4.82)	—
Older	70.33 (5.28)	17.67 (4.51)	35.12 (3.20)	26.54 (2.09)

Note. MoCA = montreal cognitive assessment.

Procedure

The experiment was approved and carried out in line with the requirements instituted by the Research Ethics Board at Brock University. Prior to arrival at the lab, participants were told that the experiment was investigating individual differences in eye movements during movie viewing. They were not told that memory for the movie would be tested (to be consistent with the methods of Campbell et al., 2015).

Participants sat 60–65 cm from the eye tracker with their head in a chin rest to minimize head movement. They were instructed to keep their eyes on the screen during the calibration and throughout the movie. Eye movements were recorded using a Tobii 60XL eye tracker (Tobii Pro AB, www.tobii.com). This eye tracker is a dark pupil tracking system with a sampling rate of 60 Hz, accuracy of 0.5°, and 0.35° spatial resolution. Researchers operated the eye tracker in a separate room from the participant but were able to see and communicate with participants using a video camera and microphone. Calibration was completed once prior to the movie using a 5-point model. The movie was displayed using Tobii Studio software (v. 3.2.0) on a 24-in monitor, however, the movie only displayed on 960 × 720 pixels of the total screen.

Following the movie, researchers returned to the same room as the participant. Participants were audio recorded while they completed two surprise memory tasks in the following order: cued recall and free recall.[2] In the cued-recall test, participants watched short clips from the movie (within- vs. between-event boundaries) displayed on a 14-in laptop (1,366 × 786 px). After each clip, participants were asked to verbally report what happened in the movie *immediately* following the clip. Clips were presented in the same temporal order as the movie (see Figure 1).

In the free recall test, participants were given the following instructions: "*I would like you to tell me as much as you can remember about the movie you watched. Please go through the movie scene by scene. For each scene, first provide a single sentence or label that summarizes the gist of what happened. Next, describe the scene in as much detail as possible, emphasizing the progression of the story and the characters' thoughts, actions, and dialog throughout*." Participants were given unlimited time to recall the movie.

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[1] Shipley score was missing for one older adult.

[2] The cued recall task always came first because we were interested in replicating Ezzyat and Davachi's (2011) within versus between effect and they did not include a free recall test before their cued recall.

Figure 1

Visual Representation of the Event Clips Shown During the Cued-Recall Task

Note. Participants rewatched clips from the movie and were asked to recall what happened immediately following the clip. Black boxes represent the cues and green boxes represent the correct answers to the cues. For example, the within-event clip is a scene during which the father is making the uncle a beverage. The correct answer: Hands Rick a drink. The between-event cue is the end of that scene. The correct answer: Cuts to bedroom with uncle. See the online article for the color version of this figure.

Following the memory tasks, participants were asked whether they thought their memory for the movie would be tested prior to watching it. If they said no, no further questions were asked. If they said yes, they were asked when they became aware that their memory would be tested, and whether they consciously attended to certain details while watching the movie. Participants were classified as aware if they indicated that they knew their memory would be tested prior to starting the movie. Finally, participants completed the MoCA, Shipley Vocabulary test, and a demographics questionnaire.

Measure

Cued Recall

Since there were 10 usable clips from between-events and 12 usable clips from within-events, cued recall was scored as percentage correct. For each trial, verbal responses were transcribed and scored as either correct or incorrect. Accuracy was defined by a set of predetermined answers that were based on what actions or conversations happened immediately following the clip. Accurate responses did not need to be verbatim to be scored as correct but needed to contain the general correct information to be classified as accurate. For example, in Figure 1, our predetermined within-event response was “Hands Rick a drink,” but some accepted answers were, “Guy gives him a drink,” “Uncle says yes to yet more alcohol,” and “Dad hands the uncle a drink.” Examples of incorrect responses were, “Uncle tells kid he’s got a surprise,” “Goes to the bedroom,” and “Talk about whoever the missing guest is.” Two coders blind to participants’ age scored the accuracy of responses for all participants. Interrater reliability was calculated with intraclass correlation (one-way random effects model; McGraw & Wong, 1996) using the *irr* package (v.0.84.1; Gamer et al., 2019) in R 4.0.3 (R Core Team, 2020). Agreement was high for both the within-event condition (.96) and the between-event condition (.91). The scores from both raters were averaged and used for all analyses.

Free Recall

Recordings from the free recall were transcribed and scored using the Autobiographical Interview scoring method; a commonly used method in the autobiographical memory literature (for details see Levine et al., 2002; https://levinelab.weebly.com/ai-testing.html). In line with this method, details were coded as either *Internal* or *External*. Internal details are central to events in the film, such as time, place, or action (e.g., “The two boys were playing with guns.”) External details are semantic information, including general knowledge and/or facts [e.g., “(drinking was) … a theme in the 60’s. There was quite a bit of drinking and smoking and guns that we don’t do nowadays.”] and repetitions of previously stated details that do not provide additional episodic content (e.g., “Each boy had a gun, like a pistol”—the second part of the phrase is considered repetition). Unlike standard autobiographical memory studies (which assess memories for events at which the experimenter was not present; cf. Diamond et al., 2020), episodic information could be verified for accuracy in the present study. Details that were incorrect were classified into a third category, *Incorrect details* (i.e., things that did not occur in the film; e.g., “[the uncle] says, ‘How about unpacking my suitcase?’” This is incorrect because it was the father who asked the boy to unpack).

Two researchers blind to participants’ age scored the details for all participants. Interrater reliability was calculated using the same method as for cued recall. Agreement between the two raters was high for internal details (.98), external details (.96), and incorrect details (.89). The scores from both raters were averaged and used for all analyses (in line with Spreng et al., 2018). For each participant, each of these categories’ details was summed to establish the absolute number of details recalled in each category. Additionally, we computed a proportion for each category (e.g., internal details/total details recalled) to obtain estimates unbiased by individual differences in verbal fluency (sometimes referred to as “episodic specificity”; e.g., Cole et al., 2013; Ford et al., 2014; Levine et al., 2002; Peters & Sheldon, 2020). To be consistent with previous work (e.g., Lapp & Spaniol, 2017; Levine et al., 2002; Wank et al., 2020), we used both the number and proportion of details to assess age differences in the free recall task. However, the proportion scores were used as the outcome variables in the analyses with eye-ISC.

Eye Tracking

Noise reduction was completed with a moving-median filter. Saccade detection was done using a built-in I-VT Filter in Tobii

Studio set to a velocity threshold of 30°/s (min. fixation duration: 60 ms; Olsen & Matos, 2012). Saccades and detected fixations from only one eye and/or outside of the film dimensions were not used in the analysis.

The method used to calculate eye-ISC scores for each individual was adapted from the method used by Bacha-Trams et al. (2017; for original script see https://version.aalto.fi/gitlab/BML/eyeisc). For each participant, the XY fixation coordinates were segmented into 500 ms time windows, containing a maximum of 30 fixations per window. At each time window for each participant, a Gaussian kernel was applied to smooth the data and generate heat maps representing the fixation locations within that window. To compute the eye-ISC score for a participant, the heat map of that participant was correlated with the average heat map for all participants except the one in question ($n - 1$). This process was repeated for each time window, such that each participant had an eye-ISC score for every time window in the movie (954 windows in total). The eye-ISC values for all windows were averaged to create an overall mean eye-ISC score for each participant. This mean eye-ISC score represented how synchronous an individual was with their age group, with values closer to one representing greater synchrony[3] (scripts available here: https://github.com/Andesha/eye-track-study).

We also examined whether the two age groups differed in eye-ISC at different points throughout the film. To test this, each participants' eye-ISC scores across the time windows were smoothed using a Gaussian filter. The data were then submitted to a nonparametric permutations test (Monte Carlo method; 500 iterations) using a cluster-based correction method to adjust for multiple comparisons. The analysis was implemented using in-house scripts (available here: https://osf.io/atfxh/) and the FieldTrip toolbox (http://www.fieldtriptoolbox.org/) in MATLAB.

Results

We used a Bayesian approach to analyze our data and thus, report Bayes Factors (BF). For ease of reading, BF_{01} is reported when the evidence was in favor of the null hypothesis of no difference (H_0) and BF_{10} is reported when the evidence was in favor of the alternative hypothesis (H_+). For reference, $BF_{01} > 3$ (equivalent to $BF_{10} < 0.33$) suggests substantial evidence for the null hypothesis and $BF_{10} > 3$ suggests substantial evidence for the alternative hypothesis.[4] Values greater than 10 are considered strong evidence in the respective directions (Wetzels et al., 2011). Additionally, BF_{incl} refers to the posterior probability that the inclusion of the model term or interaction would produce a model that explains the observed data. Models that include the interaction term always include lower order items, so if inclusion of the interaction term is justified, only the interaction BF_{incl} needs to be reported. Evidence for the exclusion of the condition term ($BF_{incl} < 0.33$) suggests no differences between conditions and in these cases, the best supported model does not include the condition term. Finally, 95% credible intervals (CI) are a measure of uncertainty and can be interpreted as the probability that the true value in the population falls within the given values. All models reported are compared to the null model unless otherwise noted. All analyses were run in JASP using default options and priors (JASP Team, 2020) unless otherwise specified. Default priors in JASP are considered uninformed or flat.

Eye Movement Synchrony

We tested whether there were age differences in overall eye movement synchrony during movie watching. The mean eye-ISC scores were not normally distributed so the data were entered into a Bayesian Mann–Whitney U-test (2-tailed; 5,000 samples). The results from the analysis indicated that there was substantial support for the null hypothesis of no difference, $BF_{01} = 3.20$. This suggests that older adults, $M = .45$, 95% CI [0.42, 0.48], show the same degree of eye movement synchrony as younger adults, $M = .43$, 95% CI [0.40, 0.47], during naturalistic viewing (see Figure 2). Indeed, if anything, older adults' mean synchrony was numerically higher than that of younger adults.

The above analysis indicates that on average, older and younger adults did not differ in synchrony. However, these scores were averaged across the entire film and it is possible that by taking an average, we may be missing important temporal differences or times in the movie when younger and older adults differ. To investigate this, we used permutation testing and a cluster-based correction to compare older and younger adults' eye-ISC scores over time. It is important to note that the interpretation of this analysis is descriptive in nature as opposed to inferential (see Maris & Oostenveld, 2007; Sassenhagen & Draschkow, 2019).

The results from this test indicated that there was a difference between younger and older adults' eye-ISC scores across time ($p < .05$). This difference was driven by a cluster between 2 mins 05 s and 2 mins 23 s, during which older adults' eye movements were more synchronous than those of younger adults (see Figure 3). Just prior to this period, the young protagonist finds a real gun in his uncle's suitcase that he thinks is a toy. Then, during the period of age differences, the boy finds ammunition, loads the gun, and puts it in his toy holster. During this suspenseful scene, older adults' eye-ISC scores ranged from .44 to .52 and younger adults' eye-ISC scores ranged from .32 to .39. Therefore, apart from these 20 s (4% of the film), eye movement synchrony was similar for both age groups throughout the film. This result is in line with our initial analysis showing no age difference in mean eye movement synchrony.

Cued Recall

Next, we investigated whether participants remembered more when the cue and recall periods were in the middle of an event (within-events), compared to when the cue was just before an event boundary and the recall period was just after an event boundary (between-events). To this end, cued recall data were submitted to a 2 (event: within, between) × 2 (age: young, old) Bayesian mixed analysis of variance (ANOVA; numerical accuracy & posterior samples set to 5,000), in which, Event was a within-subjects variable and Age was a between-subjects variable (See Table 2 for descriptives). The analysis supported the inclusion of Event in the model ($BF_{incl} = 1.86 \times 10^9$) and no support either way for the inclusion of Age ($BF_{incl} = 0.41$) or the Event × Age interaction ($BF_{incl} = 0.57$). Thus, there was decisive

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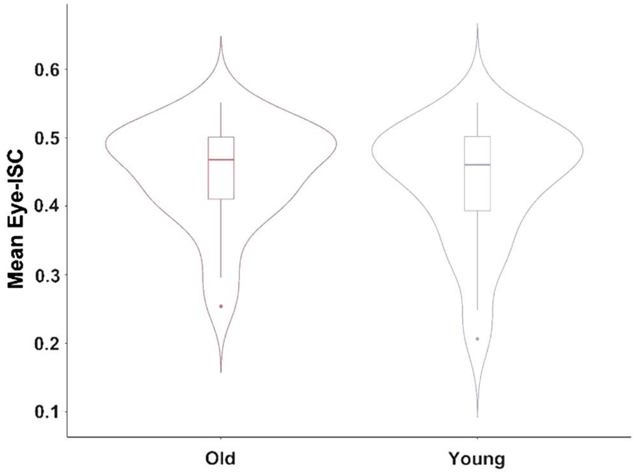
[3] We also calculated individual eye-ISC scores comparing each individual to the group as a whole (i.e., both younger and older adults combined). This analysis yielded the same pattern of results (the correlation between scores calculated within versus across groups was $r = .94$, $BF_{10} = 6.090 \times 10^{20}$), so only the within-group eye-ISCs are reported here.

[4] A $BF_{10} = 3$ can be interpreted as the data being approximately three times more likely to occur under the alternative hypothesis than under the null.

Figure 2
Violin Plot of Mean Eye Intersubject Correlation Scores Calculated Within Age Groups



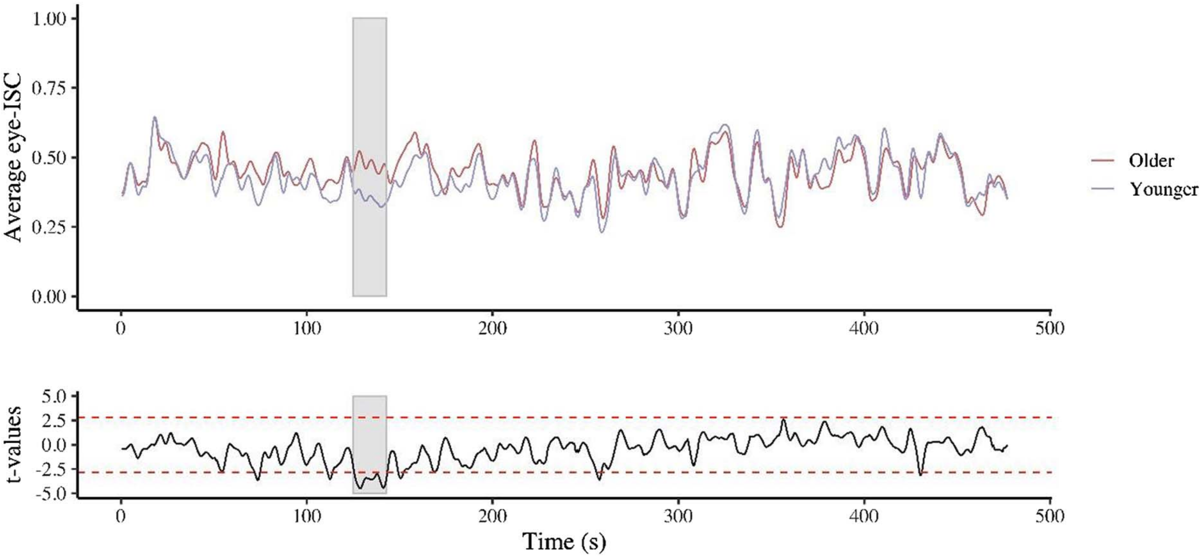
Note. Dots indicate outliers. See the online article for the color version of this figure.

evidence that the best model was the model with a main effect of Event ($BF_{10} = 1.81 \times 10^9$). The error percentage for this model was 7.85%, which is within the standard accepted rate of less than 20% (van Doorn et al., 2019). The posterior mean (the difference from the global mean) for within-events was 10.08, 95% CI [7.48, 12.69], while for between-events was −10.08, 95% CI [−12.73, −7.52], indicating that memory accuracy across both age groups was higher in the within-event condition compared to the between-event condition. This analysis suggests that both age groups formed stronger associations within events than across event boundaries. There was no compelling evidence for or against older adults showing this effect to a lesser extent than younger adults. These results replicate past work (Ezzyat & Davachi, 2011) and support our prediction that both age groups would show a memory benefit for cues from within-events compared to between. However, it does not support the prediction that older adults would show this effect to a lesser extent.

To determine if eye-ISC at encoding predicts memory for events that occurred within- or between-event boundaries, two separate Bayesian regression analyses were conducted with mean eye-ISC and age as predictors and within- and between-event memory accuracy as the dependent variables. Markov Chain Monte Carlo (MCMC) sampling and numerical accuracy sampling were set to 5,000 samples. The findings from the regression model for memory within-events suggests that eye-ISC does not predict within-event cued recall in either age group as there was moderate support for the null over both a main effect of Eye-ISC ($BF_{01} = 3.33$, $R^2 = .003$) and a main effect of Age ($BF_{01} = 3.51$, $R^2 < .001$). The regression model for between-events yielded similar results. There was anecdotal evidence for null over a model with a main effect of Eye-ISC ($BF_{01} = 2.89$, $R^2 = .01$) and no evidence either way for a main effect of Age ($BF_{01} = 1.08$, $R^2 = .06$) over the null. These results suggest that in each regression analysis, the null model was the best model; thus, there was no evidence that eye-ISC predicted cued recall within- or between-event boundaries.

Further, to test whether synchrony around the period of cued recall was a better predictor of memory, we limited our calculations of synchrony to time periods surrounding the clips used in the task. However, this did not change the pattern of results (see Supplemental Material for analyses). Interestingly, synchrony itself did increase following event boundaries (see Supplemental Material), which is in line with previous work showing that pupil dilation and saccadic movements are related to event perception (Clewett et al., 2020; Smith et al., 2006).

Figure 3
Eye-ISC Scores Over Time by Age Group



Note. The gray bar highlights a period of age differences identified by the cluster-based permutation test. The red dashed line indicates the critical value cut off. See the online article for the color version of this figure.

Free Recall

Participants' free recall was coded into three categories based on the Autobiographical Interview: internal details, external details, and incorrect details (see Table 2). To determine whether there were age differences in the number and type of details recalled, we entered the data into a 2 (age: young, old) × 3 (recall category: internal, external, incorrect) Bayesian mixed ANOVA, in which Age was a between-subjects variable and Recall Category was a within-subjects variable. The results from this analysis suggest that there was decisive evidence that the Recall Category should be included in the model ($\mathrm{BF}_{\mathrm{incl}} = 1.06 \times 10^{49}$). There was no evidence either way that age should be included in the model ($\mathrm{BF}_{\mathrm{incl}} = 0.42$). Thus, there was decisive evidence that a main effect of Recall Category was more likely than the null model ($\mathrm{BF}_{10} = 9.22 \times 10^{48}$; error = 1.60%). The main effect is driven by both groups recalling a higher number of internal details compared to external and misinformation (See Table 2).[5] Running the same analysis on the proportional measures, there is decisive evidence for the inclusion of the interaction term ($\mathrm{BF}_{\mathrm{incl}} = 2.95 \times 10^{6}$) in the model, which includes both main effects and the interaction ($\mathrm{BF}_{10} = 3.01 \times 10^{125}$, error: 1.71%). To determine what categories were driving the interaction, follow-up Bayesian *t*-tests were performed on each category. The interaction was driven by younger adults recalling a higher proportion of internal details than older adults ($\mathrm{BF}_{10} = 282.71$) and younger adults recalling a smaller proportion of external details than older adults ($\mathrm{BF}_{10} = 77.77$). There was no evidence either way for the age difference in misinformation ($\mathrm{BF}_{10} = 0.88$).

Next, to assess the effect of eye-ISC on the proportion of details recalled for each free recall category, we used separate Bayesian linear regression models to investigate whether participants' recall scores were associated with age and eye-ISC. Age was entered as a binary variable with 0 = *older adults* and 1 = *younger adults*. For each regression, MCMC and numerical accuracy samples were set to 5,000. For internal details, there was decisive evidence for the inclusion of Age ($\mathrm{BF}_{\mathrm{incl}} = 1230.33$) and Eye-ISC in the model ($\mathrm{BF}_{\mathrm{incl}} = 17.66$). There was no evidence either way for the inclusion of the interaction ($\mathrm{BF}_{\mathrm{incl}} = 0.74$). Indeed, there was decisive evidence for the model that contained both a main effect of Age and a main effect of Eye-ISC ($\mathrm{BF}_{10} = 2{,}522.11$, $R^2 = .40$) compared to the null model. The main effect of Age was driven by younger adults recalling a higher proportion of internal details than older adults, posterior $M = 0.14$, 95% CI [0.03, 0.32]. The relationship between eye-ISC and the proportion of internal details recalled was positive, such that as eye-ISC increases so does the proportion of internal details recalled, posterior $M = 0.34$, 95% CI [0.00, 0.60]; see Figure 4A.

Table 2
Means and Standard Deviations for Memory Tasks

Memory Tasks	Younger *M*	Younger *SD*	Older *M*	Older *SD*
Cued recall				
Within	74.79	14.52	74.81	13.26
Between	50.60	12.86	57.71	16.15
Free recall				
Total details				
Internal	98.58	35.36	104.08	42.64
External	4.20	5.66	12.85	16.16
Incorrect	7.74	4.26	9.90	4.39
Proportion				
Internal	0.90	0.05	0.83	0.07
External	0.03	0.03	0.09	0.06
Incorrect	0.07	0.03	0.09	0.04

For external details, there was decisive evidence for the inclusion of Age in the model ($\mathrm{BF}_{\mathrm{incl}} = 68.53$), but no evidence either way for the inclusion of Eye-ISC ($\mathrm{BF}_{\mathrm{incl}} = 0.92$) or the interaction ($\mathrm{BF}_{\mathrm{incl}} = 0.41$). There was decisive evidence against the null for this model ($\mathrm{BF}_{10} = 77.80$, $R^2 = .24$). The main effect of Age was driven by younger adults recalling a lower proportion of external details than older adults, posterior $M = -0.06$, 95% CI [-0.19, 8.55×10^{-3}]. Therefore, age predicted the proportion of external details recalled, but eye-ISC did not.

Lastly for incorrect details, there was decisive evidence for the inclusion of Eye-ISC in the model ($\mathrm{BF}_{\mathrm{incl}} = 26.46$), moderate evidence for the inclusion of Age in the model ($\mathrm{BF}_{\mathrm{incl}} = 3.63$), but no evidence either way for the inclusion of the interaction term ($\mathrm{BF}_{\mathrm{incl}} = 1.01$). There was decisive evidence for this model with two main effects ($\mathrm{BF}_{10} = 34.68$, $R^2 = .26$) over the null. The main effect of Age indicates that younger adults recalled a lower proportion of incorrect details than older adults, posterior $M = -0.05$ 95% CI [-0.14, 4.28×10^{-3}]. The relationship between Eye-ISC and incorrect details was negative, such that across both age groups, the proportion of incorrect details recalled decreased as mean eye-ISC increased, posterior $M = -0.20$, 95% CI [-0.37, -0.05]; see Figure 4B. In summary, eye-ISC did not relate to the proportion of external details recalled but was positively related to internal details and negatively related to incorrect details. This finding indicates that participants who had higher eye-ISC scores recalled the movie with higher episodic specificity. Together, these findings support our prediction that eye movement synchrony would relate to memory for film.

Awareness

Participants were not told that their memory would be tested prior to the movie; however, some suspected that this would be the case. More older ($N = 18$) than younger adults ($N = 7$), $\mathrm{BF}_{10} = 75.15$, 95% CI [-3.18, -0.72], suspected that their memory would be tested after the movie. To determine whether awareness affected mean eye-ISC scores for either age group, we entered the data into a 2 (awareness: aware, unaware) × 2 (age: younger, older) Bayesian ANOVA. Both factors were between-subjects. There was substantial evidence for the null model over a main effect of Awareness ($\mathrm{BF}_{01} = 3.49$) and a main effect of Age ($\mathrm{BF}_{01} = 3.02$). There was also definitive evidence for the null model over the interaction ($\mathrm{BF}_{01} = 22.19$), indicating that awareness did not influence eye movement synchrony in this experiment.

Further, when awareness was added as a covariate in the cued-recall analysis and all models are compared to the best model (i.e., the boundary only model), there is sufficient evidence against

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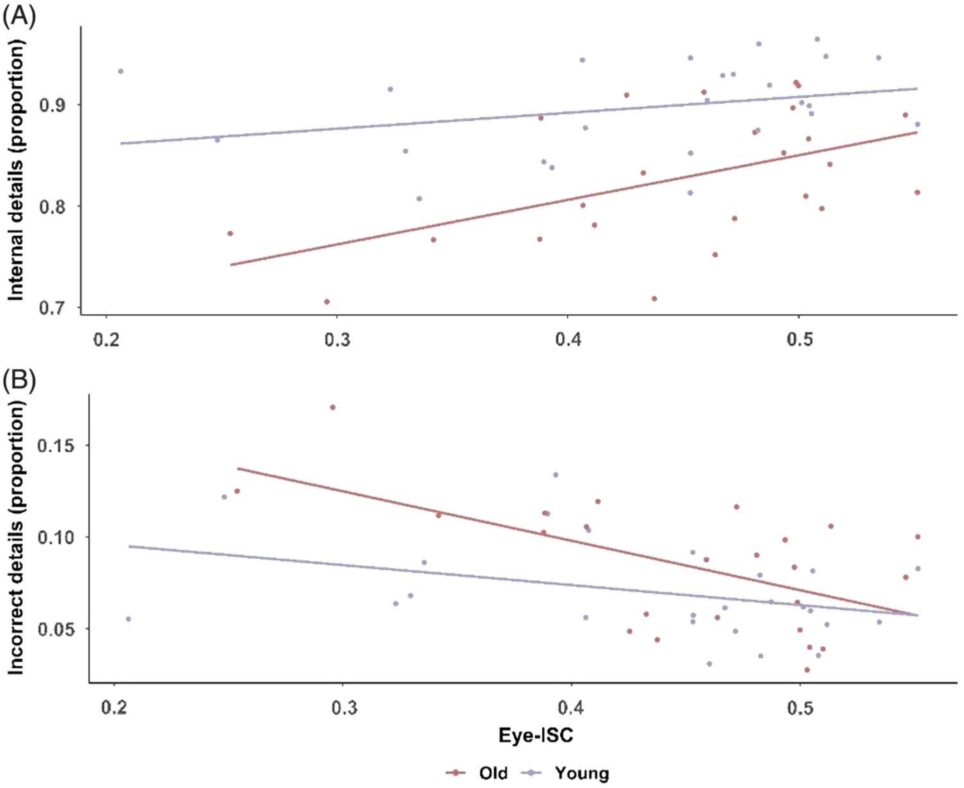
[5] It is important to note that there were two participants (one older and one younger adult) who were outliers ($z > 3$) in each free recall category, recalling substantially more details than other participants (apart from the older adult participant who was within the normal range of incorrect details). Importantly, if this analysis is run excluding these participants, the pattern of results remains the same.

Figure 4

Scatter Plots of the Relationship Between Mean Eye Inter-Subject Correlation (eye-ISC) and (A) Internal Details and (B) Incorrect Details



Note. A) Scatter plot of the relationship between mean eye inter-subject correlation (eye-ISC) and internal details by age group. B) Scatter plot of the relationship between mean eye inter-subject correlation (eye-ISC) incorrect details by age group. See the online article for the color version of this figure.

models including awareness (all $BF_{01} > 2.71$). Similarly, when awareness was added to the regression models, there was no evidence for awareness by age and/or eye-ISC interaction in any of the models (all $BF_{incl} < 0.53$). Thus, these exclusionary analyses suggest that age differences in awareness are not driving the observed effects.

To further confirm that the observed effects were not driven by awareness, we also reran the main analyses including only participants who suspected that their memory would be tested. To even out the sample sizes between groups, we tested an additional group of 10 younger adults who were explicitly told that their memory for the movie would be tested (final sample of 18 older and 17 younger adults). These analyses are reported in the Supplemental Material and show the same pattern of results as the main study, suggesting that the observed effects were unlikely caused by age differences in awareness.

Discussion

We examined age differences in eye movement synchrony during a movie previously shown to yield less synchronous neural activity with age (Campbell et al., 2015). Mean eye-ISC across the whole movie did not differ with age and, if anything, older adults showed greater synchrony than younger adults for a brief period when we examined eye-ISC over time. Follow-up analyses showed that this lack of age difference was not because more older adults suspected that their memory would be tested. Further, greater eye movement synchrony related to better memory for the movie, in that higher eye-ISC was associated with a higher proportion of episodic details recalled and a lower proportion of incorrect details recalled in both age groups. Finally, we also tested memory for the movie using a cued recall task with clips taken from either *within* events or just before event boundaries (i.e., testing associative memory *between* events). Replicating previous work (Ezzyat & Davachi, 2011), both younger and older adults showed better recall for within- than between-event cues, suggesting that associations are stronger within an event than across event boundaries. However, we did not observe the expected relative advantage for older adults in cued recall spanning event boundaries.

Previous research has shown that neural-ISC during movie watching declines with age and relates to age differences in attentional control (Campbell et al., 2015; Geerligs, et al., 2018). Moreover, age differences in neural synchrony are most pronounced in the frontoparietal control network (responsible for attentional control), and the medial prefrontal cortex and medial temporal lobes (critical for memory). Here, we tested for the first time whether eye-movement synchrony during naturalistic viewing also declines with age. We found that older and younger adults showed equivalent eye-ISC and only differed for a short period of time, which was driven by greater synchrony in the older group. Our results align with past research that identifies attentional capture as the primary driver of eye-ISC during movie watching (Hutson et al., 2017; Smith & Mital, 2013), which remains relatively intact with age (Christ et al., 2008; Colcombe et al., 2003; Tales et al., 2002). For example, Hutson et al. manipulated top-down attention in young adults by providing some participants, but not others, with vital information prior to watching a movie scene. The groups showed differences in comprehension, but eye-ISC was not affected. Similarly, Hasson et al. (2008b) had participants watch a movie in forward or backward order. Despite differences in neural synchrony, eye-ISC was highly similar between forward and backward viewing. Thus, age differences in neural synchrony in higher order areas likely reflect differences in interpretation or integration with existing knowledge, rather than differences in visual processing (a point further supported by the minimal age effects observed in primary sensory areas; Geerligs et al., 2018).

We found that eye-ISC related to the proportions of episodic and incorrect details recalled about the film, but not the proportion of external details or cued recall. These results support our prediction that eye-ISC would relate to memory performance. Eye-ISC is thought to represent instances in which there is a high degree of spatial–temporal gaze agreement, which typically surrounds regions of shared interest, especially people and motion (Smith & Mital, 2013). In professionally directed movies, directors have filmed scenes in such a way that viewers are drawn to look at the most important information within a scene (Dorr et al., 2010; Hutson et al., 2017). Thus, the observed relationship between eye-ISC and the proportion of internal and incorrect details recalled suggests that visual attention toward relevant, or at least attention-grabbing, details are critical for encoding episodically rich and accurate memories for events. It is possible that low eye-ISC scores reflect inattention, perhaps due to mind-wandering (Frank et al., 2015), and these individuals may not encode as many essential details as those who are synchronized with the group.

Although the relationship between memory and eye movements is well documented (Castelhano & Henderson, 2005; Hannula et al., 2010; for a review, see Wynn et al., 2019), most research on eye movements and memory focuses on eye movements to static scenes and gaze reinstatement at retrieval (e.g., Molitor et al., 2014; Ryan et al., 2007; Wynn et al., 2020c). Only one study (to our knowledge) has used the autobiographical interview to quantify free recall and related it to eye fixations (albeit, at retrieval; Armson et al., 2021). In that study, the number of fixations made during episodic reexperiencing of personal autobiographical events related to the number of internal, but not external, details recalled (Armson et al., 2021). This is in line with the current results showing a relationship between eye-ISC and the proportion of internal, but not external, details recalled. This differentiation between internal and external details may be because internal details are a better reflection of episodic reexperiencing, particularly when corrected for total verbal output (Cole et al., 2013; Ford et al., 2014; Levine et al., 2002; Peters & Sheldon, 2020).

Past research in the autobiographical memory literature (Addis et al., 2008; Jacques & Levine, 2007; Levine et al., 2002) typically finds that older adults recall fewer internal (i.e., episodic) details and more external (i.e., semantic) details than younger adults. We observed no age difference in the absolute number of internal details recalled, but older adults did recall proportionally fewer internal details and more external details than younger adults, in line with previous work (e.g., Levine et al., 2002). Older adults' relatively preserved episodic recall, in this case, may be due to the short delay between encoding and test. In our experiment, participants watched the movie and completed all tasks within 1.5 hr, while past research on autobiographical memory has typically tested memory for remote events occurring weeks, months, or years in the past. The short duration between encoding and recall in our experiment likely allowed for retention of more episodic details (Acevedo-Molina et al., 2020; Diamond et al., 2020; Sekeres et al., 2016). That said, when verbal fluency was controlled (i.e., details per category were divided by the total number of details produced), older adults recalled a smaller proportion of internal details than young adults. Thus, we see the typical pattern of increased semanticization of episodic memory with age after controlling for older adults' greater total output, which was likely due to the unlimited time participants were given for free recall in our study.

Our final aim related to age differences in memory for events. Previous research with young adults has shown that events are organized in long-term memory by strengthening associations for things that occur within an event and/or weakening the links between events (DuBrow & Davachi, 2016; Ezzyat & Davachi, 2011). We showed that *both* younger and older adults had better memory for cues taken from within an event than those taken from just before an event boundary. Our results are important because they show, for the first time, that the way events are organized in long-term memory does not differ between younger and older adults. Further, we demonstrate that this effect extends beyond written narratives to movie stimuli.

Older adults' reduced inhibitory control (Hasher et al., 2007; Lustig et al., 2007) has been shown to result in the formation of broader associations over time, including between successive pairs of words and triplet sequences of objects (Campbell et al., 2012, 2014). We hypothesized that this tendency to hyperbind would extend to naturalistic events, expecting older adults to show less of a difference in memory for within- versus between-event cues compared to younger adults. Although older adults ($M = 57.71$) were numerically higher in their cued recall for between-event cues than young adults ($M = 50.60$), there was no evidence for or against the age by event-type interaction. Thus, we found no evidence for hyperbinding of naturalistic events, though this question warrants further exploration, possibly using more sensitive implicit test conditions (Campbell & Hasher, 2018). However, these findings are in line with other work showing little age difference in event segmentation (Kurby & Zacks, 2018; Sargent et al., 2013; cf., Kurby & Zacks, 2011; Zacks et al., 2006) and event model updating (see Hoeben Mannaert & Dijkstra, 2019 for a review). Our work suggests that this preservation in event updating extends to how those events are ultimately stored in long-term memory.

Older adults' intact ability to update and store event models may seem surprising given robust age-related declines across a range of cognitive functions required for event processing (see Radvansky & Dijkstra, 2007 for review), including speed of processing (Salthouse, 1996), working memory (Craik & Byrd, 1982), and inhibitory control (Hasher & Zacks, 1988). However, reading stories and watching movies are activities that older adults have ample real-life experience with, unlike tasks that are typically used in the lab to test cognition. As a result, older adults may be better able to rely on these past experiences to effectively use event boundaries as cues to store and organize episodic events. An important question for future research is *how*, particularly at a neural level, do older adult make use of their superior knowledge stores to compensate for fluid loses (Spreng & Turner, 2019). For instance, do they accomplish this through superior prediction within familiar domains?

In summary, our experiment provides critical insight into the effects of age on memory for naturalistic stimuli. Few studies have used eye-tracking as a measure of attentional synchrony in aging and to our knowledge, none have evaluated its relationship to memory. In doing so, we further our understanding of the mechanisms that contribute, or rather do not contribute, to changes in neural-ISC and memory with age. Further, we show that the organization of events in long-term memory is relatively preserved with age, which has important implications for older adults' understanding of their own memory capabilities. It is possible that age differences in memory may sometimes be overestimated by typical neurocognitive tasks.

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Received October 5, 2020
Revision received April 12, 2021
Accepted April 24, 2021 ■