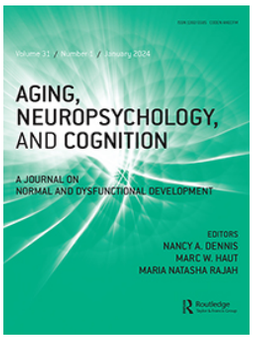

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Investigating the impact of healthy aging on memory for temporal duration and order

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ABSTRACT

Temporal information, including information about temporal order and duration, is a fundamental component of event sequence memory. While previous research has demonstrated that aging can have a detrimental effect on memory for temporal order, there has been limited insight into the effect of aging on memory for durations, particularly within the context of sequences. In the current study, neurologically healthy young and older participants were administered two temporal match-mismatch tasks: one in which they were instructed on each trial to compare the temporal order or duration information of stimulus sequences presented first in a study phase and then, after a short delay, in a test phase (event sequence task); and a second in which participants were required to compare single durations or sequences of durations across study and test phases of each trial (pinwheel task). Consistent with the literature, the older participants were significantly poorer compared to their younger counterparts at making temporal order match-mismatch judgments in the event sequence task. In addition to this, data from both tasks suggested that the older adults were also less accurate at match-mismatch judgments based on duration information, with tentative evidence from the pinwheel task to suggest that this age-related effect was most prominent when the duration information was presented within a sequence. We suggest that age-related changes to medial temporal and frontal lobe function may contribute to changes in memory for temporal information in older adults, given the importance of these regions to event sequence memory.

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Sequence memory; time; episodic memory; working memory; aging

Introduction

It is well established that healthy aging can have a significant impact on working and episodic memory processing (Cabeza et al., 2018; Grady, 2012). For instance, compared to younger adults, older individuals can be impaired on span tasks (e.g., Braver & West, 2008; Salthouse, 1994), demonstrate poorer verbal and non-verbal list learning and associative

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memory (e.g., Craik & Rose, 2012), and exhibit altered autobiographical memory recall (e.g., Levine et al., 2002; Piolino et al., 2002).

Since our memories are structured temporally, a pertinent question is how healthy aging impacts memory for temporal information. To date, much research in this area has focused on memory for the temporal order of sequentially presented stimuli as well as the processing of duration information in association with individual stimuli. Broadly speaking, this work has found differences between older adults and their younger counterparts. Specifically, a number of studies have revealed that older adults are poorer at remembering the order in which a sequence of words or visual images were previously seen (Allen et al., 2015; Blachstein et al., 2012; Cabeza et al., 2000; Newman et al., 2001; Roberts et al., 2014). Furthermore, there is evidence to suggest that older adults are less accurate in their estimation and reproduction of single durations on the order of seconds associated with single auditory tones or visual shapes (Xu & Church, 2017), such as overestimating (Coelho et al., 2004; Rakitin et al., 2005) or underestimating (Carrasco et al., 2001; Craik & Hay, 1999) intervals of time.

One area of temporal memory that has not yet, to our knowledge, been explored in relation to healthy aging is memory for sequences of duration information. This is an important gap in the literature since our memories often capture the sequential nature of our experiences and as such, studies that focus on memory for single durations in isolation do not capture the full extent of temporal duration memory processing. In addition to this, recent work has highlighted an important role for the medial temporal lobe (MTL), a brain region associated with reduced volume and connectivity in healthy aging (Grady, 2012; Fjell and Walhovd, 2010; Raz et al., 2010; Cardenas et al., 2011; Hedden and Gabrieli, 2004), in remembering durations in the context of sequences of events (Bellmund et al., 2020; Lee et al., 2020). For instance, Barnett et al. (2014) and Thavabalasingam et al. (2018) used functional magnetic resonance imaging (fMRI) to scan neurologically healthy young participants while they made match-mismatch judgments on each trial between a study sequence of events (scene images) and a subsequent test sequence. By manipulating either the order in which the images were presented or the durations of the intervals separating the images within each sequence between the study and test phases, these studies revealed that hippocampal activity (as measured by univariate signal change and multivariate pattern similarity) was sensitive to changes in both image order and the durations of the intervals within a sequence. More recently, Palombo et al. (2020) investigated whether the MTL is critical for temporal duration memory by examining the performance of amnesic patients with MTL damage on a novel pinwheel task. On each trial, participants were presented with an initial study phase of 1 or 2 spinning pinwheels and then after a short delay (250 ms), a test phase of 1 or 2 spinning pinwheels was presented. Participants were required to decide if a change (i.e., match vs. mismatch) had occurred in the spin duration between the initial study and test presentations. It was found that the patients were significantly impaired at remembering sequences of short durations but not individual durations presented in isolation and notably, even patients with selective hippocampal damage performed poorly, pointing toward a critical role for the hippocampus. Crucially, the patients' impairment could not be explained by differences in memory load for total duration or the number of elements of information between sequences and individual durations. Thus, this study converges with the aforementioned neuroimaging work by providing further evidence

that the MTL is important for temporal duration memory in the context of event sequences and highlights the importance of moving beyond the use of single durations when studying the impact of aging on duration memory.

In light of the above, we were interested in whether aging impacts memory for temporal information embedded in an event sequence. Specifically, we sought to add to the existing literature that has focused on memory for individual durations (Xu & Church, 2017) by investigating whether there are age-related changes in memory for durations within a sequence over and above age-related changes in memory for single durations. To address this question, neurologically healthy older adults were compared to younger adults using two distinct experimental paradigms. While prior data suggests that the MTL is involved in temporal duration memory in the context of short-term and long-term memory tasks (e.g., for review see, Lee et al., 2020), both of the current tasks emphasized the processing of temporal information in the working memory domain. The first task (the "event sequence" task) was adapted from the paradigm that was used previously in conjunction with fMRI in Barnett et al. (2014) and Thavabalasingam et al. (2018), which provided an opportunity to assess memory for both temporal order and temporal duration information contained within a sequence of events. The second experimental task was identical to the procedure used in Palombo et al. (2020) (the "pinwheel" task), which has been shown to be sensitive to focal MTL damage. Of note, this task allowed us to investigate potential differences in memory for single durations compared to that for durations within a sequence. Since the processing of duration and other sequence-related temporal information such as temporal order may be supported by overlapping hippocampal mechanisms (Lee et al., 2020), we hypothesized that any age-related deficits in temporal order memory could also be accompanied by a deficit in memory for short durations embedded within a sequence.

Material and methods

Participants

Twenty-eight younger-adults (YAs) and twenty-seven older-adults (OAs) participated in the study in exchange for course-credit or payment. YAs were recruited via the University of Toronto Scarborough Introduction to Psychology participant panel and OAs were recruited through the Adult Volunteer Pool at the University of Toronto St. George Campus. All participants were screened for a history of psychological illness, traumatic brain injury, and current use of neuroleptic medications, and gave informed written consent prior to participation. This research received ethical approval from the University of Toronto Research Ethics Board (protocol #33306). Participants were excluded if they failed to complete the entire study due to a lack of time (i.e., did not complete one of the experimental conditions) or did not follow the correct experimental protocol for one of the tasks by incorrectly using the response keys (i.e., gave the same response throughout). Two YAs and one OA met both of these criteria and their data, therefore, were not analyzed. The final sample of participants included in the analyses were 26 YAs (5 Male, M_{Age} = 18.65 years, SD_{Age} = 1.31, $M_{Education}$ = 14.26 years, $SD_{Education}$ = 0.73) and 26 OAs (10 Male, M_{Age} = 68.30 years, SD_{Age} = 4.64, $M_{Education}$ = 16.5 years, $SD_{Education}$ = 2.00). There was a significant difference in age between the two groups ($t(50) = 53.52$, $p < 0.001$)

and OAs had significantly more years of education in comparison to YAs ($t(50) = 5.38$, $p < 0.001$). A Fisher's Exact test revealed that there was no significant difference in the proportion of male and female participants between the YA and OA groups ($p = 0.22$).

Our sample size was informed by the sample sizes of related studies in the literature as well as our findings in Palombo et al. (2020). Specifically, aging studies that have examined duration processing or temporal order memory have typically involved participant groups with numbers ranging from 10 to 46 (i.e., Cabeza et al., 2000; Newman et al., 2001; Roberts et al., 2014; Xu & Church, 2017). In addition, in our previous study using the pinwheel task with focal lesion amnesic patients, we observed a group by condition interaction (across three conditions) with an observed effect size of $\eta^2_p = 0.29$ (Palombo et al., 2020). In expectation of a more subtle effect in the present study, we conducted a power analysis using G*Power (Faul et al., 2007) with an effect size a third of the previously observed value ($\eta^2_p = 0.1$), a type I error probability of 0.05, and 80% power, which revealed a total sample size of 48. We reasoned, therefore, that our chosen sample size was appropriate.

Neuropsychological tests

OAs completed a series of neuropsychological tests to better characterize cognitive status, including the MoCA (Nasreddine et al., 2005), the Vocabulary and Similarity subtests from the Wechsler Abbreviated Scale of Intelligence (WASI; 2nd ed.; Wechsler, 2011), the Logical Memory subtests from the Wechsler Memory Scale (WMS; 4th ed.; Wechsler, 2009), the Word-Picture matching test (word-picture matching from the semantic memory battery in (Hodges & Patterson, 1995), the Short Recognition Memory Test for Faces and Words and the Topographical Recognition Memory Test from the Camden Memory Test (CMT; Warrington, 1996), and the Copy and the Immediate Recall subtests from the Rey Complex Figure Test (RCFT; Meyers & Meyers, 1995). Importantly, all neuropsychological scores for OAs fell within normal range for their age (Table 1).

General methods

All experimental tasks were completed on a desktop computer running E-Prime 2.0 software (Psychology Software Tools, Inc.) together with a 19-inch monitor (1024 × 768 pixels). For the event sequence task, stimuli consisted of original grayscale images (350 × 350 pixels) of a variety of real-world scenes (e.g., outdoor landscapes, indoor rooms, buildings, etc., used previously in Taylor et al., 2007; Barnett et al., 2014) presented centrally on the screen with a black background. For the pinwheel task, stimuli consisted of a colored pinwheel (297 x 252 pixels) presented as a pair or individually in the center of the screen with a black background, as in Palombo et al. (2020). Responses were collected using two pre-specified buttons that were keyed in by the experimenter. All participants completed the pinwheel task first and returned within a week to complete the event sequence task. For OA participants, all neuropsychological testing was done in the first testing session prior to conducting the computerized task. A short practice was administered prior to each experimental task, using a different set of stimuli, and importantly participants were explicitly discouraged from using any verbal strategies (e.g., counting) during both of the tasks. Participants were asked whether they had used any verbal strategies after the completion of each task and all participants confirmed that they had not done so.

Table 1. For each test, mean raw score is provided, with the associated percentile (%ile) relative to the established norms in parentheses. MoCA = Montreal Cognitive Assessment; WMS-IV LM = Wechsler Memory Scale, 4th ed. Logical Memory subtest; WASI-II = Wechsler Abbreviated Scale of Intelligence, 2nd ed.; CMT = Camden Memory Test; RCFT = Rey Complex Figure Test.

Test	OA mean score
MoCA	27.27
Word-Picture matching	63.38
WMS-IV LM I	32.04 (84%ile)
WMS-IV LM II	23.62 (63%ile)
WMS-IV LM Recognition	25.27 (51–75%ile)
CMT Topography	25.62 (75%ile)
CMT Word	24.81 (90%)
CMT Faces	23.54 (75%ile)
WASI-II Vocabulary	41.38 (70%ile)
WASI-II Similarities	33.19 (70%ile)
RCFT Copy	32.15 (>16%ile)
RCFT Immediate Recall	15.12 (54%ile)

Event sequence task

This task was an adapted version of a paradigm used in previous fMRI work examining the role of the MTL structures in temporal order and duration memory (Barnett et al., 2014; Thavabalasingam et al., 2018). Each trial in the event sequence task consisted of a study phase, delay period, test phase, and subsequent response screen (Figure 1). The study phase was comprised of four scene images presented sequentially for 700 ms each. These scenes were separated by 3 blank ISIs, jittered around mean durations of 500 ms, 1000 ms, and 2000 ms (all SD 80 ms), with the order of these ISIs pseudo-randomized across trials. A fixation cross was then presented during a jittered delay period (mean 3500 ms, SD 500 ms), after which the same four scenes were presented during the test phase. Participants completed 60 trials of the event order block where they were instructed to monitor sequence order and 60 trials of the interval duration block where they monitored sequence interval durations. Administration of the event order and interval duration blocks was counterbalanced across subjects. The event order and interval duration blocks were further divided into "difficult" and "easy" blocks (30 trials each). Within the easy event order block, the scene order was either preserved (Order Match) or changed completely (Order Mismatch). In the difficult blocks, Order Mismatch test sequences were created by holding the first two scene images in a sequence constant, and swapping the latter two scenes. In contrast, only the ISIs were manipulated during interval duration blocks, either being held constant (Duration Match) or rearranged completely (Duration Mismatch) in the easy blocks. In the difficult interval duration blocks, Duration Mismatch trial sequences were created by holding the first interval duration in a sequence constant and swapping the second and third intervals. Participants were not informed that the scene order or interval durations were altered completely or partially in the mismatch trials and were asked to monitor the entire sequence. To encourage this, responses were made after the test phase during a 2500 ms response screen displaying the question

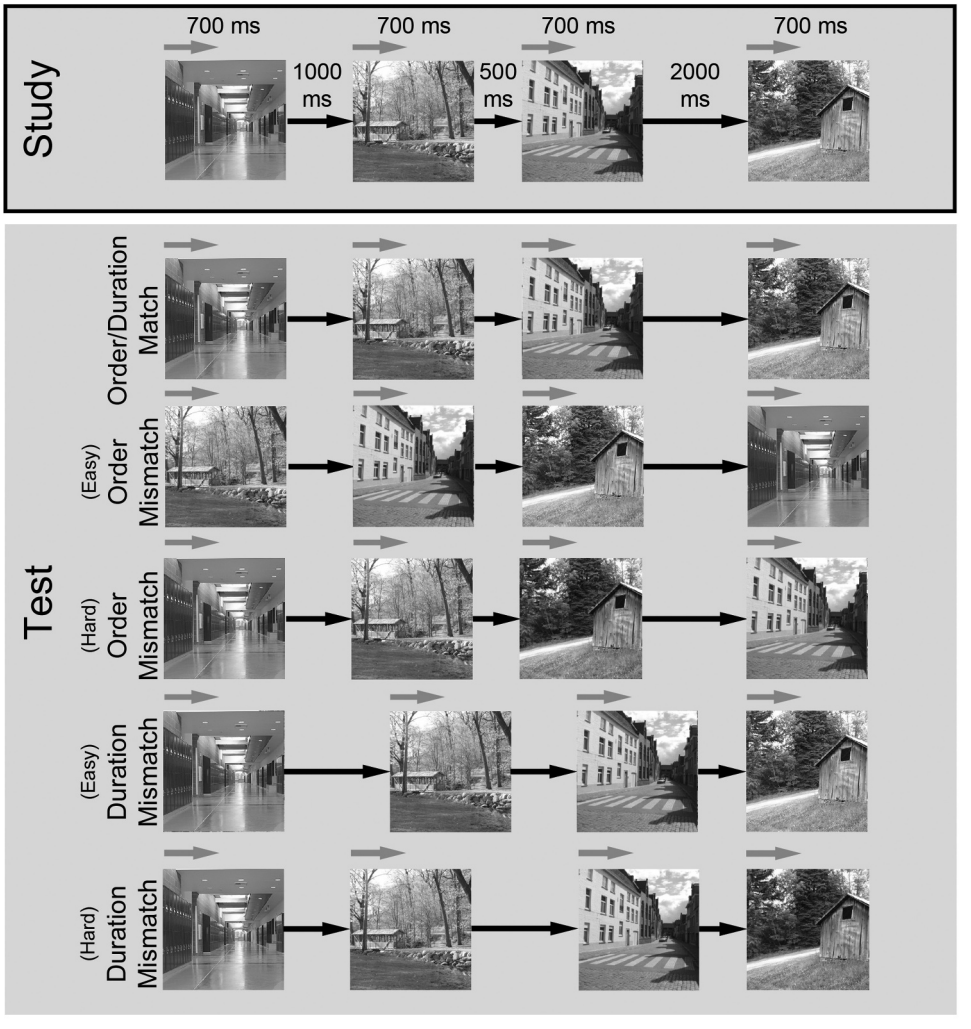

Figure 1. Graphic depicting the Event sequence task. Participants were presented with blocks of trials in which they were instructed to monitor event order or interval durations and make a match vs. mismatch decision. In the study phase of each trial participants saw four scenes separated by three intervals (mean 500, 1000, 2000 ms). This was followed by a test phase, where the four scenes were repeated in the same order with their original interval durations (i.e., Order/Duration Match) or with the scene order or interval durations rearranged. Difficult versions of event order and interval duration blocks were included where only the latter two scenes/intervals were swapped. The encoding and test phases were separated by a 3500 ms fixation cross, and participants were asked to indicate their response during a 2500 ms response screen showing the words "Change (1) or No Change (2)?" at the end of each test phase.

"Change (1) or No change (2)?." Our conception of block difficulty pertained to the magnitude of mismatch signal that was present at the test phase of each Mismatch trial, with a larger mismatch signal assumed to be easier to detect for participants. Specifically, since the temporal positions of all scenes/durations were changed in the "easy" blocks, there would be a larger mismatch signal for these trials compared to

mismatch trials in the "difficult" blocks, in which only the final two scenes/duration were swapped with each other.

Pinwheel task

The pinwheel task was identical to that reported previously in Palombo et al. (2020) and was composed of four separate test conditions: Sequence, Single Short, Single Long (Palombo et al., 2020 Experiment 1), and Single High-Load (Palombo et al., 2020 Experiment 2). All pinwheel test conditions were completed in the same session. On each trial for each test, participants were presented with an initial study phase of one or two spinning pinwheels and then after a short 250 ms blank delay, a test phase of one or two spinning pinwheels. In an immediately ensuing untimed response screen, participants were then required to decide if a change (mismatch vs. match) had occurred in the spin duration between the study and test presentations.

In the Sequence condition, participants were required to remember the *sequence* of two pinwheels spinning (Figure 2). At study on each trial, both pinwheels spun in sequence, one after another. The same sequence was then presented again at test with the spin duration of both pinwheels being the same as study or with one of the pinwheels spinning for a longer or shorter amount of time.

Group differences in accuracy in the sequence condition could be due to a number of reasons that are independent of an impairment in processing sequential durations. For example, older adults may simply not be able to estimate the durations of the individual pinwheels comprising a sequence. To test for this, the Single Short control condition was administered. This condition was similar to the Sequence condition with the exception that only *one* of the two pinwheels would spin and the other remained static (Figure 2). During the test phase, the two pinwheels were presented again, with the same pinwheel spinning. Critically, in the Single Short condition, the pinwheel spin time was equal to the spin time of a single pinwheel in the Sequence test to ensure that participants were able to accurately detect the timing of individual pinwheels in the Sequence test. If this was indeed the case, then we expected normal performance on this condition.

Another possible reason for impairment on the Sequence test is that the combined duration of *both* pinwheels within a studied sequence exceeds the short-term memory capacity for the OA participants. To test for this, the Single Long condition involved an identical procedure to the Single Short condition, with the exception that the pinwheel spin time was equal to the total spin time of *both* pinwheels in the Sequence condition (Figure 1). If an impairment on the Sequence condition was due primarily to the processing of short durations within a sequence and not due to limitations in short-term memory capacity, then accuracy for Single Long should not differ from that of YA participants.

Lastly, the Single High Load condition was designed to ensure that any impairment in the Sequence condition was not due to the requirement to maintain a greater number of durations in memory in the Sequence condition compared to the Single Short and Single Long conditions. Therefore, in the Single High Load condition, participants first saw one pinwheel spinning during study (Figure 1) and then during the test phase, saw two pinwheels spin one after another. Participants were required to determine if *either of the two* pinwheels in the test presentation matched the duration of the spinning pinwheel

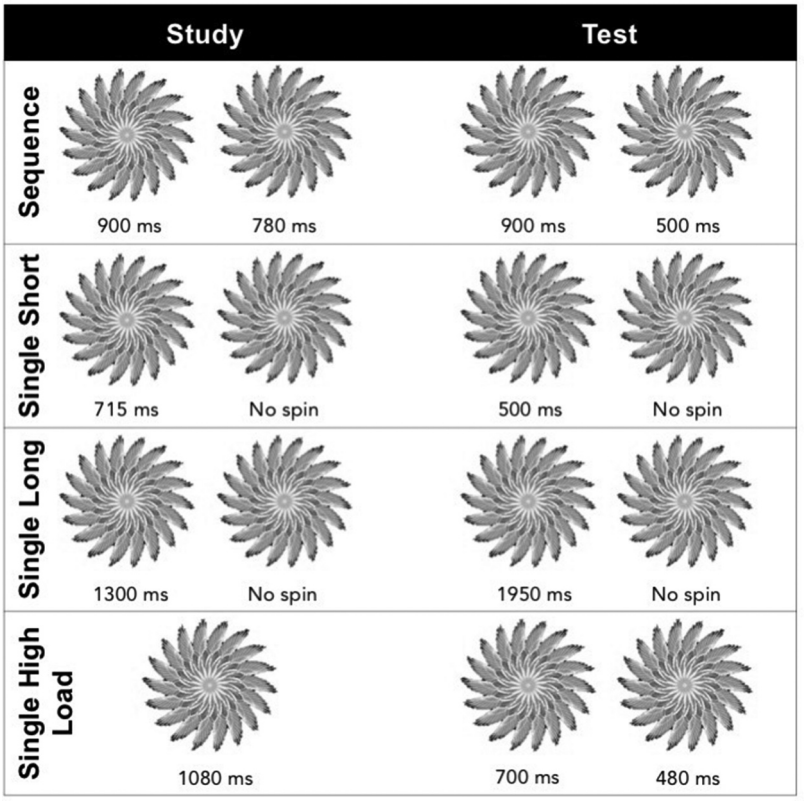

Figure 2. Schematic of the four different tests that were used in the Pinwheel task. In each (Sequence, Single Short, Single Long, and Single High Load), participants saw a study screen with either one or two pinwheels spinning, followed by a 250 ms blank screen, and a subsequent test screen with either one or two pinwheels spinning. During a response screen, participants were required to indicate if the timing between study and test screens was a "Match" or a "Mismatch" on the basis of the duration of the spinning pinwheels. In this figure, all examples are Mismatch trials.

in the study phase. We were particularly interested in Single High Load trials in which the second test pinwheel duration matched the study pinwheel duration (Palombo et al., 2020). Successful performance on these trials required participants to maintain three durations in memory, which is equal to the memory load of trials in the Sequence condition in which the 1st pinwheel was mismatched. Thus, any difference in performance between these two types of trials would reflect the requirement to process sequences. Note that accurate responses to Single High Load trials in which the second test pinwheel was mismatched with the study pinwheel duration, may also have reflected successful memory for three durations. It was not possible, however, to rule out the possibility that participants were, in fact, making a mismatch response based purely on the duration of the first test pinwheel (which would also be a mismatching duration) – hence, our focus on Single High Load trials in which the second test pinwheel duration matched the study pinwheel duration.

Across all conditions, a series of predetermined "original" and "adjusted" pinwheel spin times were used. There were 5 possible original pinwheel durations: 500, 600, 700, 800,

900 ms. In mismatch trials, the adjusted spin times were longer than the original spin times, with the adjusted pinwheel durations on each trial created by applying Weber's law to the original duration:

$$k = \frac{\Delta I}{I}$$

$$adjusted\ \ time = I + \Delta I$$

In this formula, I represents the original duration and ΔI represents the difference threshold or in other words, the difference between the original and adjusted durations. For the Sequence condition, four different levels of k were used (0.56, 0.68, 0.80. 0.92), to create adjusted durations with varying levels of difficulty. For example, at k = 0.56, an original spin time of 500 ms would lead to a difference threshold of 0.56 × 500 = 280, resulting in an adjusted spin time of 500 + 280 = 780 ms. A similar approach was used to determine the spin times for the Single Short and Single Long conditions, except that for the latter a summation of two durations (e.g., 800 + 900) was used as the original duration I. The k levels for the Single Short and Single Long conditions were established via behavioral piloting such that performance was similar to the Sequence condition, and were 0.43, 0.60, 0.67, and 0.64 for the former, and 0.50, 0.63, 0.76, and 0.89 for the latter. The presentation of the adjusted and original durations was counterbalanced across mismatch trials, such that half of the time the longer adjusted duration appeared in the study phase and the corresponding original duration in the test phase. This was done to ensure that on half of the mismatch trials the test pinwheel was longer in duration than that at study, and vice versa for the other half of mismatch trials. Adjusted durations were also counterbalanced across left and right presentations and all possible permutations of original durations (e.g., 500, 700) were counterbalanced across difficulty levels.

In the Single High Load condition, mismatch trials involved two test durations that were different to that at study. One test duration was determined using the same levels of k as the Sequence condition, and the other was 20–25% longer or shorter. On match trials, one duration was identical to the study duration while the other was 20–25% longer or shorter.

Finally, all trials in each experimental condition were pseudo-randomized with the constraint that (1) no more than four match or mismatch trials could be presented in a row, (2) no more than three of the same difficulty levels could be presented in a row, and (3) no more than three trials could be presented in a row where the adjusted duration was on the left or right. Each experimental condition contained 40 match trials and 20 mismatch trials, totaling 60 trials.

Statistical analyses

Analyses of overall performance on each condition of the event sequence and pinwheel tasks were conducted on hits minus false-alarms (i.e., adjusted accuracy), with hits being defined as correct responses on mismatch trials and false-alarms being defined as incorrect responses on match trials. For analyses that specifically examined performance on match trials in the pinwheel task Single High Load condition in which the 2nd pinwheel

matched the duration of the study pinwheel (i.e., trials in which participants had to hold three durations in memory), percent correct was used instead.

To examine differences in performance between OAs and YAs, analyses for both experiments involved using a mixed-effects ANOVA with a between-subjects factor of Group, and within-subjects factors of Condition and Difficulty. These were then followed up with planned independent samples t-tests. As adjusted accuracy scores were not normally distributed as assessed by the Shapiro-Wilks normality tests, all ANOVAs and independent-sample t-tests were conducted using a bootstrapping procedure. Specifically, differences and effect sizes were first calculated for the original data, and then recalculated for 10,000 resamples of the original dataset (resampling with replacement within each group and across conditions). The p-value was then computed by comparing the original difference with the bootstrapped (null) distribution and calculating the probability of obtaining a difference lower than the original value. To assess the reliability of the effect sizes, 95% confidence intervals (CI) were derived from the bootstrapped data.

Results

Event sequence task

A three-way mixed-effects ANOVA with factors of Group (OA, YA), Condition (Order, Duration) and Difficulty (Easy, Hard) conducted on adjusted accuracy scores revealed main effects of Group ($F(1,50) = 8.56$, $p = 0.031$, $\eta^2 = 0.07$, η^2 95% CI = [0.02, 0.14]), Condition ($F(1,50) = 134.58$, $p = 0.017$, $\eta^2 = 0.27$, η^2 95% CI = [0.22, 0.35]), and Difficulty ($F(1,50) = 72.68$, $p = 0.022$, $\eta^2 = 0.28$, η^2 95% CI = [0.19, 0.39]; Figure 3(a)). In both participant groups, performance was better on Order compared to Duration trials, as well as Easy compared to Hard trials (OA mean corrected accuracies (SD): Time Easy = 0.67 (0.12), Time Hard = 0.43 (0.19), Order Easy = 0.83 (0.12), Order Hard = 0.68 (0.12); YA mean corrected accuracies (SD): Time Easy = 0.76 (0.18), Time Hard = 0.53 (0.28), Order Easy = 0.92 (0.082), Order Hard = 0.75 (0.15)). There was no interaction between Difficulty and Group ($F(1,50) = 0.003$, $p = 0.63$, $\eta^2 = 0.00002$, η^2 95% CI = [0.000003, 0.02])), or Difficulty and Condition ($F(1,50) = 3.95$, $p = 0.19$, $\eta^2 = 0.01$, η^2 95% CI = [0.0007, 0.05]), and as such, adjusted accuracy scores were collapsed across easy and hard blocks for subsequent between-group comparisons. There was no interaction between Group and Condition ($F(1,50) = 0.14$, $p = 0.93$, $\eta^2 = 0.0003$, η^2 95% CI = [0.000001, 0.009])) and planned comparisons between OAs and YAs for each condition separately confirmed that OAs performed significantly poorer on the Order sequence condition ($t(50) = -3.03$, $p = 0.001$, $d = 0.84$, d 95% CI = [0.31, 1.49]) and the Duration sequence condition ($t(50) = -2.30$, $p = 0.006$, $d = 0.64$, d 95% CI = [0.11, 1.22]) relative to YAs. Collectively, these results suggest that there are age-related differences in both temporal order and duration memory for a sequence of events, in accordance with our hypotheses. Of note, there was a significant correlation between accuracy scores for the Order and Duration conditions in the YA group ($r = 0.79$, $p < 0.001$), but not the OA group ($r = 0.29$, $p = 0.20$), with the relationship between performance in the Order and Duration condition being significantly stronger in the YAs in comparison to the OAs ($z = 2.62$, $p = 0.004$).

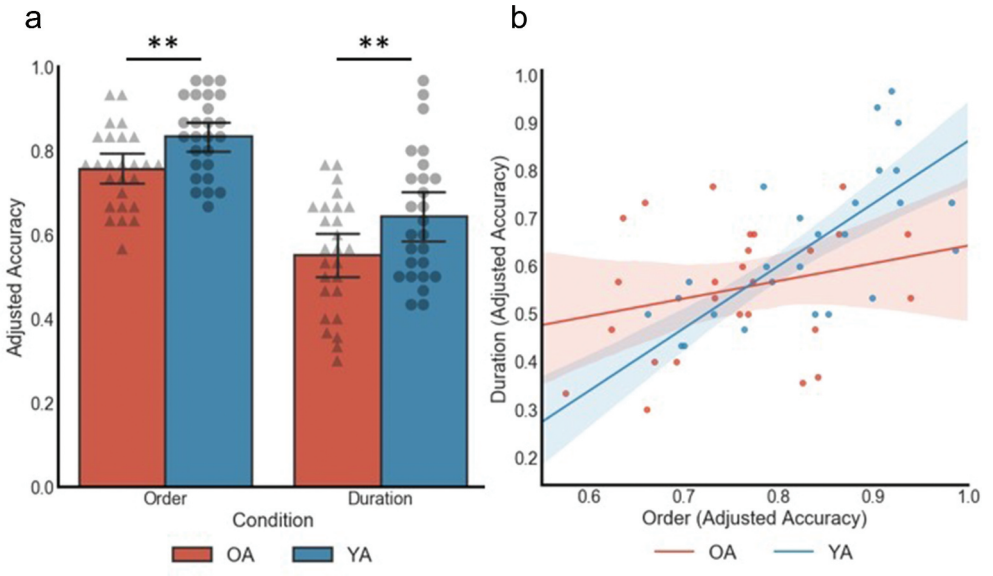

Figure 3. (a) Adjusted accuracy performance (± standard error) for OAs and YAs on the order and duration conditions of the event sequence task. Individual data points are shown as circles (OAs) or squares (YAs). Asterisks indicate significant differences at $p < 0.01$. (B) Correlation between adjusted accuracy performance for OAs and YAs on the order and duration conditions of the event sequence task. Shaded areas depict 95% confidence bands for the line of best fit.

Finally, in light of previous work demonstrating that older adults can be less successful at identifying and applying task strategies that are not explicitly provided (e.g., Murray et al., 2015), we examined whether OA and YA performance changed differentially throughout each of the event sequence task conditions. In other words, since each condition was administered separately in a blocked format, it is conceivable that YA participants were more strategic, for instance, by paying particular attention to the first image/duration in Easy blocks and the end of sequences in Hard blocks. To this end, a 2 × 3 repeated measures ANOVA was conducted for each condition, with one factor of group (YA vs. OA) and a second factor of time (first vs. middle vs. last 10 trials). There was a trend-level interaction between group and time on the Order Easy condition ($F(1, 50) = 3.00$, $p = 0.053$, $\eta^2 = 0.03$, η^2 95% CI = [0.007, 0.011])), with no significant interaction effect for any of the other conditions (all $F(1, 50) \leq 2.30$, $p \geq 0.14$, $\eta^2 \leq 0.01$, η^2 95% CI = [0.004–0.007, 0.04–0.08])). For the Order Easy condition, however, the pattern of performance was the opposite to what one would expect if a difference in strategy application was detrimentally impacting OA performance. Specifically, OA performance improved from beginning to end (M = 0.82 [SD = 0.16], M = 0.80 [SD = 0.19], M = 0.88 [SD = 0.21]) while that of YAs declined (M = 0.95 [SD = 0.09], M = 0.92 [SD = 0.15], M = 0.88 [SD = 0.13]). These findings suggest that it is unlikely that the YA participants benefitted from the application of strategies that were not explicitly provided.

Pinwheel task

In keeping with Palombo et al. (2020), the Sequence, Single Short and Single Long tasks were analyzed collectively, with the final control task (Single High Load) being analyzed separately. A three-way mixed-effects ANOVA with factors of Group (OA, YA), Condition (Sequence, Single Short, Single Long) and Difficulty (K1, K2, K3, K4) conducted on adjusted accuracy scores revealed a main effect of Condition ($F(2,100) = 17.64$, $p < 0.001$, $\eta^2 = 0.09$, η^2 95% CI = [0.06, 0.15]), a main effect of Difficulty ($F(3,150) = 121.86$, $p < 0.001$, $\eta^2 = 0.27$, η^2 95% CI = [0.23, 0.32]), and an interaction between Condition and Difficulty ($F(6,300) = 4.42$, $p < 0.026$, $\eta^2 = 0.03$, η^2 95% CI = [0.01, 0.05]; Figure 4). There was no significant main effect of Group ($F(1,50) = 1.59$, $p = 0.31$), $\eta^2 = 0.008$, η^2 95% CI = [0.00002, 0.04] and neither Difficulty ($F(3,50) = 1.98$, $p = 0.23$, $\eta^2 = 0.006$, η^2 95% CI = [0.002, 0.02]) nor Condition ($F(2,50) = 0.22$, $p = 0.82$, $\eta^2 = 0.001$, η^2 95% CI = [0.0002, 0.03]) interacted with Group. Despite the lack of a Group by Condition interaction, we explored the data further by conducting follow-up planned comparisons of adjusted accuracy scores collapsed across difficulty in OAs and YAs for each condition separately. These revealed a significant difference between groups on the Sequence ($t(50) = -2.37$, $p = 0.009$, $d = 0.66$, d 95% CI = [0.09, 1.19])) condition, whereas OAs performed similarly to YAs in the Single Short ($t(50) = -0.47$, $p = 0.34$, $d = 0.26$, d 95% CI = [−0.40, 0.67])) and Single Long ($t(50) = -0.56$, $p = 0.28$, $d = 0.30$, d 95% CI = [−0.37, 0.76])) conditions, suggesting poorer OA performance when temporal duration was processed in the context of a sequence compared to single durations. Notably, one of the YA participants was

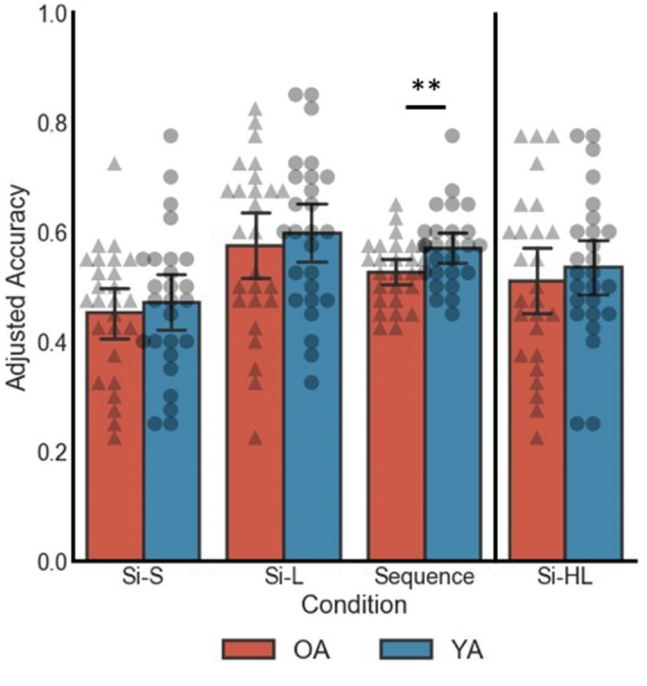

Figure 4. Adjusted accuracy performance (± standard error) for OAs and YAs on each of the pinwheel conditions. Individual data points are shown as circles (YAs) or triangles (OAs). Asterisks indicate significant between-group differences at $p < 0.01$.

a significant outlier on the Sequence condition, performing 2.5 SD above the YA group mean (Figure 4). Even after removing this participant's data, however, the comparison between OAs and YAs on the Sequence condition remained significant ($t(49) = -2.10$, $p = 0.016$, $d = 0.59$, d 95% CI = [0.08, 1.23]).

Next, we examined whether the age-related impairment in the Sequence condition was affected by the relative position of the divergent pinwheel at test. Specifically, we assessed whether the OA's performance was worse when it was the second pinwheel that was divergent (versus the first pinwheel) in the test phase of each trial for the Sequence condition. An ANOVA with Group and Position (1^{st} vs 2^{nd} pinwheel diverges) revealed a main effect of Group ($F(1,5) = 5.59$, $p = 0.022$, $\eta^2 = 0.06$, η^2 95% CI = [0.007, 0.14]) and Position ($F(1,50) = 19.79$, $p < 0.001$, $\eta^2 = 0.16$, η^2 95% CI = [0.07, 0.26]) but did not reveal a significant Group by Position interaction ($F(1,50) = 1.59$, $p = 0.21$, $\eta^2 = 0.01$, η^2 95% CI = [0.00006, 0.07]). Thus, the impairment in the Sequence condition was already present when performance necessitated 3 durations to be maintained in memory (i.e., two durations from the encoding phase, and the 1^{st} duration from the test phase).

Finally, to assess whether an age-related effect on the Sequence condition can be attributed to differences in memory load between the Sequence condition and the Single Short and Single Long control conditions, performance was assessed on the Single High Load control condition. A mixed-effects ANOVA on adjusted accuracy scores for the Single High Load condition, with factors of Group (OA, YA) and Difficulty (K1, K2, K3, K4) demonstrated a main effect of Difficulty ($F(3,50) = 26.33$, $p = 0.005$, $\eta^2 = 0.18$, η^2 95% CI = [0.12, 0.24]) with no significant effect of Group ($F(1,50) = 0.35$, $p = 0.40$, $\eta^2 = 0.004$, η^2 95% CI = [0.000007, 0.05]) or a Group by Difficulty interaction ($F(1,50) = 0.36$, $p = 0.53$, $\eta^2 = 0.002$, η^2 95% CI = [0.0005, 0.03]), indicating no difference in performance between OAs and YAs on the Single High Load control condition (Figure 4). Importantly, even when only considering trials on which the duration of the second test pinwheel matched the probe pinwheel duration (therefore requiring 3 durations to be maintained), there was similarly no difference between OAs and YAs ($t(50) = -0.09$, $p = 0.46$, $d = 0.04$, d 95% CI = [−0.41, 0.68]). However, a comparison of performance on these trials and Sequence trials in which the 1^{st} pinwheel was mismatched (which also required 3 durations to be maintained), did not reveal the expected interaction between group and condition ($F(1,50) = 0.48$, $p = 0.45$, $\eta^2 = 0.005$, η^2 95% CI = [0.00002, 0.05])). Thus, we cannot rule out that increased memory load (as compared to the Single Short and Single Long conditions) contributed to the age-related impairment in the Sequence condition.

Discussion

In this study, we sought to explore the impact of healthy aging on memory for temporal durations as well as order. To investigate this, we used two experimental tasks that were adapted (Barnett et al., 2014; Thavabalasingam et al., 2018) or taken directly (Palombo et al., 2020) from previous work. In summary, we found that both temporal order memory and memory for sequences of short durations were impaired in OAs in comparison to YAs.

Beginning with the event sequence task, the demonstration that OAs were impaired at remembering the relative order of scene images in comparison to YAs is consistent with the aging literature, with prior research typically demonstrating that healthy aging has a detrimental impact on temporal order memory (Allen et al., 2015; Blachstein et al., 2012;

Cabeza et al., 2000; Kessels et al., 2007; Newman et al., 2001; Old & Naveh-Benjamin, 2008; Roberts et al., 2014; Rotblatt et al., 2015; Tolentino et al., 2012; Ulbrich et al., 2009). Advancing beyond this prior work, however, we additionally observed that OAs were impaired relative to YAs in temporal duration memory in the same task. Considered together, therefore, these findings from the event sequence task support the idea that healthy aging can disrupt the processing of sequential information in regard to both temporal order and duration information. One possibility is that aging has a detrimental impact on the cognitive processes that are critical in supporting accurate memory for temporal sequences such as memory for the relationships between items (e.g., Davachi & DuBrow, 2015; Eichenbaum, 2004; Howard & Eichenbaum, 2015; Lee et al., 2020; Rolls, 2013). For example, OAs can demonstrate impaired associative memory between items but relatively intact memory for single items in the episodic and working memory domains (Castel & Craik, 2003; Mitchell et al., 2000; Naveh-Benjamin et al., 2004; Old & Naveh-Benjamin, 2008; Peterson & Naveh-Benjamin, 2016; Tsukiura et al., 2011).

Consistent with the findings from the duration condition of the event sequence task, a planned pairwise comparison between OAs and YAs on the Sequence condition of the pinwheel task revealed a significant difference between groups. It is important to acknowledge, however, that the overall group by condition interaction was not significant and that inspection of Figure 4 reveals that the within-group variance for the Sequence condition was much less compared to that for other conditions. As such, appropriate caution is necessary when interpreting this group effect in the pinwheel task. Similarly, in the absence of a significant interaction between group and performance on Sequence and Single High Load trials with equivalent memory load (i.e., Sequence trials in which the 1^{st} pinwheel duration was mismatched and Single High Load trials in which the 2^{nd} pinwheel was matched), one cannot conclude strongly that any OA deficit on the Sequence condition reflects an impairment in sequence processing rather than the extra demands associated with increased memory load. It is important, therefore, for future work to attempt to replicate the current pinwheel findings, ideally with a larger sample size.

Since previous timing studies have demonstrated that healthy aging can impact the processing of individual durations on the order of seconds and milliseconds (Xu & Church, 2017), for example, in the context of duration classification and discrimination tasks, it may be considered somewhat surprising that an age-related impairment for remembering single durations was not observed in the pinwheel task, which would have potentially led to an overall group effect on the pinwheel task. One possible explanation for this discrepancy is that an age-related impairment in processing single durations is only evident at higher levels of difficulty when participants are asked to perceive and discriminate very similar durations. In support of this possibility, previous timing studies that have reported age-related impairments in processing single durations have typically implemented K values ranging from 0.10 to 0.43 (Cheng et al., 2011; Lustig & Meck, 2011, 2001), which is in contrast to the current study's K values that ranged from 0.43 to 0.92. To explore this idea further, we conducted a post-hoc analysis to compare OA and YA performance at the most difficult K level for the different control conditions of the pinwheel task and found no significant differences between groups (all $t(50) \leq 1.67$ and all $ps \geq 0.063$). This finding is consistent with a previous study (Lustig & Meck, 2011) that found that OAs and YAs performed similarly when classifying durations that varied with

a K value equivalent to the most difficult K value used in the present study (i.e., 0.43). Of note, the current demonstration of intact single duration processing across a range of K values that is not typically associated with age-related impairment in timing studies suggests tentatively that the relatively poorer performance in the sequence duration conditions in the OAs may reflect a deficit in mnemonic processes, rather than an age-related impairment in timing (Turgeon et al. 2016).

In the absence of magnetic resonance imaging data from the current cohort of OAs, we are unable to make a definitive conclusion regarding the age-related brain changes that underlie the observed deficits on the event sequence and pinwheel tasks. Nevertheless, by taking into account current knowledge pertaining to the neural mechanisms of sequence memory and brain changes associated with healthy aging, it is possible to consider potential neural explanations for the OA profile of performance on the two tasks. Regarding temporal order memory, a large body of research has identified a specific role for the hippocampus in representing sequential relationships (Dede et al., 2016; Fortin et al., 2002; Kesner et al., 2002; Mayes et al., 2001; Wallenstein et al., 1998). In addition to this, there is evidence that other regions of the MTL such as the surrounding parahippocampal and perirhinal cortices are also involved. For instance, parahippocampal cortex activity has been observed to reflect the recall of sequence order pertaining to a variety of stimuli including words, spatial locations, and object and scene images (Jenkins and Ranganath, 2010; St Jacques et al., 2008; Hsieh & Ranganath, 2015; Thavabalasingam et al., 2018; Tubridy & Davachi, 2011; Turk-Browne et al., 2012) while the perirhinal cortex has been shown to signal temporal order information associated with objects (Naya et al., 2017). Lesions to the perirhinal cortex can also impair discriminations of the relative recency of objects (Hannesson et al., 2004) although, notably, it has been suggested this region may be preferentially involved in the processing of temporal information in relation to semantic, rather than episodic, memory (Hsieh & Ranganath, 2015; Wang & Diana, 2017). Concerning temporal duration, substantial rodent work has demonstrated that hippocampal and surrounding MTL neurons can represent information about short durations (e.g., MacDonald et al., 2011; MacDonald et al., 2013; Pastalkova et al, 2008; Heys & Dombeck, 2018; Tsao et al., 2018). Research in humans has complemented this work by implicating the hippocampus and other MTL regions including the perirhinal and entorhinal cortices in memory for durations (Barnett et al., 2014; Bellmund et al., 2019; Lositsky et al., 2016; Montchal et al., 2019; Thavabalasingam et al., 2018, 2019), particularly when such information is within the context of a sequence of events (Bellmund et al., 2020; Lee et al., 2020; Palombo et al., 2020). Considering this body of evidence highlighting the importance of the MTL for both order and duration memory, it is conceivable, therefore, that the observed OA deficits on the event sequence and pinwheel tasks stem from age-related changes in the MTL, which have been associated with episodic and working memory impairment (Daselaar & Cabeza, 2013; Grady, 2012; Sumida et al., 2016).

Beyond the MTL, it is important to note that lateral and medial regions of the prefrontal cortex have also been implicated in memory for temporal order and duration processing. Lesions to the prefrontal cortex have been demonstrated to impair temporal order memory (e.g., Kesner & Holbrook, 1987; Shimamura et al., 1990; McAndrews & Milner, 1991; Petrides, 1991), and prefrontal cortex activity has been shown to reflect the maintenance of temporal order information in working memory (e.g., Ninokura et al., 2004), as well as encoding and retrieval processes related to long-term order memory (e.g., Cabeza et al., 1997; Jenkins &

Ranganath, 2010; Tubridy & Davachi, 2011). In addition to this, prefrontal cortex damage has been associated with deficits in duration processing and memory (e.g., Jackson et al., 1998; Nichelli et al., 1995), and functional neuroimaging studies have reported prefrontal cortex involvement during tasks that involve single as well as sequences of durations (e.g., Barnett et al., 2014; Harrington et al., 2004, 2010; Lewis & Miall, 2003). Since there are significant projections from the MTL to the prefrontal cortex (Goldman-Rakic et al., 1984; Swanson, 1981), and healthy aging has also been associated with frontal lobe changes and dysfunction (e.g., Cabeza & Dennis, 2013), the potential contributions of atrophy/dysfunction to this region to the current age-related findings on the event sequence and pinwheel tasks must also be acknowledged.

Interestingly, suggestive of the possibility that temporal order and duration sequence memory are supported by partially overlapping mechanisms (Lee et al., 2020), we observed that performance on the temporal order and duration conditions of the event sequence task was correlated in the YAs. Such a relationship was not, however, present in the OAs indicating, perhaps, that while there may be overlapping mechanisms underlying temporal order and duration memory, these mechanisms may be impacted in varying ways as a function of the magnitude and extent of age-related MTL and/or frontal changes. In other words, within a group of neurologically healthy older adults, individual differences in brain changes may lead to variations in the manner in which order and duration memory are impacted, thereby disrupting a correlation in performance between the two. An important avenue of future work, therefore, would be to explore the relationship between MTL and frontal regional changes in older participant populations, and the ability to remember the order and duration of event sequences.

Finally, since the current experimental tasks used visual stimuli, an open question is whether similar results would be observed if auditory stimuli were used instead. Although the vast majority of the literature on MTL contributions to temporal memory has focused on the visual domain, there is evidence from a few studies to suggest that the hippocampus is involved in processing the order of auditory tones and letters (e.g., Kalm et al., 2013; Loo et al., 2021) as well duration information associated with successive auditory tones (e.g., Büchel et al., 1999). This, combined with the observation that the hippocampus is involved in memory for acoustic information (e.g., Kumar et al., 2016), suggests that the present results could generalize to the auditory domain, with age-related differences in memory for the order and duration of sequences of auditory stimuli.

In sum, we report evidence to suggest that temporal order and duration memory, particularly as pertaining to a sequence of events, can be impacted in healthy aging. Our results are consistent with research that has identified the importance of MTL structures and prefrontal regions to temporal memory and highlight the importance of future work that examines the relationship between aging-related brain changes and performance on tasks of temporal order and duration memory.

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