Manuscript in press at Psychological Science: accepted July 29, 2020

Linking detail to temporal structure in naturalistic event recall

Nicholas B. Diamond^{1,2,4} and Brian Levine^{1,2,3}

¹Rotman Research Institute, Baycrest Health Sciences, Ontario, Canada, M6A2E1

²Department of Psychology, University of Toronto, Ontario, Canada, M5S3G3

³Department of Medicine (Neurology), University of Toronto, Ontario, Canada, M5S1A1

⁴Department of Psychology, University of Pennsylvania, PA, USA, 19104

Corresponding authors:

Nicholas B. Diamond: Department of Psychology, University of Pennsylvania, Philadelphia, PA,

USA, 19104; 647-537-5377; diamondn@sas.upenn.edu

Brian Levine: Rotman Research Institute at Baycrest, 3560 Bathurst St, Toronto, Ontario,

Canada, M6A 2E1; 416-785-2500 x.3593; blevine@research.baycrest.org

Abstract

Decades of memory research demonstrate the importance of temporal organization in recall dynamics, using laboratory stimuli (i.e. word lists) at seconds-to-minutes-long delays. Little is known, however, about such organization in recall of richer and more remote real-world experiences, where the focus is usually on memory content without reference to event order. Here, 119 younger and older adults freely recalled extended real-world experiences, for which the encoding sequence was controlled, after two days or one week. We paired analytical tools from the list-learning and autobiographical memory literatures to measure spontaneous contextual dynamics and details in these recall narratives. Recall dynamics were organized by temporal context (contiguity and forward asymmetry), and organization was reduced in older age, despite similar recall initiation and serial position effects across age groups. Across participants, organization was positively associated with episodic detail richness, providing evidence for a link between re-experiencing past events and reinstating their spatiotemporal context.

Linking detail to temporal structure in naturalistic event recall

“Time is what keeps everything from happening at once.” – Ray Cummings, 1921

We recall past experiences in the form of extended narratives, dwelling on certain details and then jumping in time and space to others. These memories are considered episodic to the degree that they are (1) populated by event-specific details (e.g. perceptions, thoughts and feelings), and (2) organized by their spatiotemporal relations (Tulving, 1972). Episodic memory is thus defined by both its content and its underlying organization.

Detail recovery and spatiotemporal organization both depend on the hippocampus (Palombo, Di Lascio, Howard, & Verfaellie, 2018; Sheldon et al., 2018), which declines in older age (Raz et al., 2005). Yet they have been explored in largely separate literatures using incompatible methods. Consequently, little is known about how the spatiotemporal structure of real-world experiences transforms into structure in memory, how this structure shapes the quantity and specificity of details we retrieve, and how these two dimensions jointly change as episodic memory declines with age.

Free recall dynamics, reflected in spontaneous recall transitions, reveal underlying structure in memory (Polyn, Norman, & Kahana, 2009). In word list learning studies, items encoded nearby in time tend to be recalled successively (the temporal contiguity effect) with a forward-going bias (Kahana, 1996) – these are considered universal organizational principles of episodic memory (Healey & Kahana, 2014). Retrieved context models hold that during encoding, items become associated to a gradually changing temporal context signal, such that items closer in time share more contextual overlap (e.g. Howard & Kahana, 2002; Polyn et al., 2009). Recalling an item triggers a “jump back in time” to an earlier state of context, cueing

items from proximal positions. Computational modeling of recall behavior suggests that aging, and to a greater extent hippocampal amnesia, impairs temporal context reinstatement, but does not affect measures that ignore the trajectory of recall through time (i.e. serial position effects and recall initiation; Healey & Kahana, 2016; Howard, Kahana, & Wingfield, 2006; Palombo et al., 2018).

Standard laboratory recall studies operationalize events as chains of discrete stimuli measured in binary fashion (i.e. recalled or not). Real-world episodes, on the other hand, are rich and continuous, and are recalled as extemporaneous narrative descriptions varying in detail and specificity (Koriat & Goldsmith, 1996; Manning, Fitzpatrick, & Heusser, 2018), and at delay intervals far exceeding those typical of laboratory experiments. Accordingly, the generalizability of contiguity effects to real life events has been questioned (Hintzman, 2016). Although there is evidence for macro-scale temporal organization across discrete events spanning individuals' autobiographical timelines (e.g. Friedman, 2004; Linton, 1986; Moreton & Ward, 2010; Nielson, Smith, Sreekumar, Dennis, & Sederberg, 2015; Uitvlugt & Healey, 2018), relatively little is known about micro-scale temporal organization in recall of extended real-world episodes, the basic units of episodic and autobiographical memory (Anderson & Conway, 1993).

In the autobiographical memory literature, as in word list learning, free recall (i.e. extemporaneous and self-governed generation of details) is a dominant retrieval task. The Autobiographical Interview scoring method, which has been used in over 200 studies (AutobiographicalInterview.com), decomposes recall narratives into their constituent details and classifies them as either internal (episodic; event-specific) or external (e.g. semantic, metacognitive, or unrelated) (Levine, Svoboda, Hay, Winocur, & Moscovitch, 2002). Here, older adults retrieve fewer internal details and more external details, a pattern that is exaggerated with

hippocampal dysfunction, reflecting reduced episodic re-experiencing (Levine et al., 2002; Sheldon et al., 2018). But as autobiographical events are typically sampled retrospectively, and are therefore heterogeneous and unverifiable, their recall dynamics typically cannot be mapped to the encoded event dynamics. One cannot, therefore, differentiate between two memories with similar detail counts but different contextual organization (but see e.g. Dede, Frascino, Wixted, & Squire, 2016; St-Laurent, Moscovitch, Tau, & McAndrews, 2011).

Thus the relationship between temporal context reinstatement and episodic detail generation remains unknown, despite their theoretical and presumed neurophysiological connection (Howard & Eichenbaum, 2013; Tulving, 1972). If they share underlying mechanisms, spontaneous temporal organization should be positively associated with the quantity or density of episodic details in recall narratives. To our knowledge, there is no direct evidence for this prediction (but see Anderson & Conway, 1993; Sadeh, Moran, & Goshen-Gottstein, 2014, for related evidence). On the other hand, the content and organization of episodic memories need not be related. For example, vivid or detailed memories can be fragmented and temporally disorganized, as has been observed in post-traumatic stress disorder and hippocampal amnesia (Brewin, 2014; Dede et al., 2016).

We paired methods from the list learning and autobiographical memory literatures to measure temporal organization and detail in single extended recall narratives. In Study 1, we assessed free recall of an immersive yet controlled real-world walking tour ('Baycrest Tour 1.0') in younger and older adults after a two-day delay. Control over the encoding sequence allowed us to bring to bear analytical tools for measuring recall dynamics from the list learning literature on naturalistic recall. We reasoned that if patterns of temporal organization in word list recall dynamics reflect core mechanisms underlying episodic memory retrieval, then similar patterns

should be observed in remote naturalistic event descriptions. In addition to the established effect of aging on internal detail density, we predicted that older adults would also show reduced temporal organization. In Study 2, we replicated our findings on recall dynamics in a larger independent younger adult sample recalling a different tour event ('Baycrest Tour 2.0') at a one-week delay. Having derived hallmark measures of episodic detail and temporal context reinstatement within memories, we tested the hypothesis that they would be positively related.

Study 1

Methods

Participants

There were 22 participants in both the younger group ($M_{\text{age}} = 23.81$ years, $SD_{\text{age}} = 3.92$, $M_{\text{education}} = 15.64$ years, $SD_{\text{education}} = 1.09$) and the older group ($M_{\text{age}} = 69.00$, $SD_{\text{age}} = 3.07$, $M_{\text{education}} = 16.56$, $SD_{\text{education}} = 3.73$). Two older participants were excluded for poor neuropsychological test performance, and one was excluded for revisiting the tour area between encoding and recall sessions. An additional older participant was excluded from analyses due to insufficient recall quantity for measuring recall dynamics (see below), leaving 18 older participants in the final analyzed sample. All participants were recruited via the Rotman Research Institute Participant Database at Baycrest Health Sciences and from advertisements in the Toronto community, and were screened for history of neurological or psychiatric illness, active significant medical illness, or substance abuse. Participants were fluent English speakers, had normal or corrected-to-normal vision and hearing, were not colour-blind and gave informed consent in accordance with institutional guidelines. We excluded participants who had been to Baycrest within the last month or more than five times in total. Data from Baycrest Tour 1.0 participants are included in

two other reports (Diamond, Abdi, & Levine, 2020; Diamond, Armson, & Levine, *in press*). The relationship of the present data to those reports is described in the Supplementary Material.

Materials and Procedure

The study consisted of two phases: a controlled real-world encoding phase, and a retrieval phase during which participants freely recalled their tour experience. Prior to encoding, participants completed a neuropsychological assessment battery, including the Rey Auditory Learning Verbal Test (RAVLT), Brief Visuospatial Memory Test (BVM-T-R), face-name associative memory, Symbol Digit Modalities Test (SDMT), Trail Making Test (TMT), verbal fluency (FAS), and the Shipley Vocabulary Test, with the expected age effects observed on tests of memory and executive functioning (see Supplementary Table S1).

Encoding Phase

Participants underwent an audio-guided walking tour of artwork and assorted items on the first floor of Baycrest Hospital (Baycrest Tour 1.0; Figure 1A). The route formed a generally unidirectional loop. Thus the physical structure of the tour route, along with the audio guide, controlled the sequence structure of the experience. Participants were instructed to approach and examine different target items (e.g. paintings, portraits, and exhibits) and occasionally identify specific items or features (e.g. locate a particular individual in a frame of portraits, or locate a particular item in the gift shop). In the middle of the tour, participants had a scripted interaction with a research confederate, during which the confederate asked a series of questions. Baycrest Tour 1.0 took an average of 23.0 minutes ($SD = 3.0$) for younger adults and 27.15 minutes ($SD = 4.32$) for older adults, likely reflecting differences in walking speed, as the audio guide controlled item viewing time.

The audio guide is publicly available on the Open Science Framework (<https://osf.io/yhm7n/>). It was recorded and edited by N.B.D. using Audacity (<http://audacity.sourceforge.net/>). It was narrated by four different speakers (two female and two male), each of whom narrated two sections of the tour. The order of speakers was different for the first four vs. last four sections of the tour, so that speaker order was decoupled from the sequence structure of the tour. The guide was broken down into multiple tracks, each associated with a target item. Each track was initiated by the participant by pressing a button on the MP3 player. Upon arrival at a target item, the guide instructed participants to examine the item, followed by a silent period in the recording, and then directed participants to the next item. This silent period controlled viewing time. For some items, the guide provided information (e.g. about the artist) or cued participants' attention to certain features. Participants were given extensive instructions before the tour began, and they were given an opportunity to practice using the MP3 player to control the audio guide. Specifically, participants were informed that their memory of the tour would be tested, and that they should pay close attention to what they see and hear. The experimenter unobtrusively observed participants to verify that they followed the audio guide's instructions. Participants exited (after the encoding session) and re-entered (for the retrieval session) the building through specific doors so as to minimize re-exposure to tour content.

Figure 1. *A and B*. Schematics of the two tour events. Red circles indicate locations of the target items and black dotted line depicts the tour route. *A*: Baycrest Tour 1.0 (Study 1). There were 27 target items with defined and universal ordinal positions. Participants were instructed, for example, to find the chef cookie jar in the gift shop (8th item; right photograph), examine a large curved painting called ‘Let There be Light’ (15th item; left photograph), and stand between the trees in the atrium (23rd item). *B*: Baycrest Tour 2.0 (Study 2) was split into two sections (13 universal items in section 1 and 18 in section 2); only Section 1 is depicted here. Participants

were instructed, for example, to examine a wall sculpture called ‘Head with Armstrong’ (2nd item), stand in the red number 8 in the shuffleboard game (5th item), and to examine a wall-mounted wood sculpture (8th item). *C.* Example recall narrative for Baycrest Tour 1.0 (younger participant). In this segment, the participant recalls 9 internal details and 1 external detail. Their recall vector is [4,6,7,8,9]. Note that they skipped the 5th item in the tour.

Retrieval Phase

Participants returned to the lab after 2 days. They were asked to freely recall their experience of the tour (instruction: “Tell me everything you can remember about the tour”). They completed a true/false memory test consisting of 40 true and 40 false statements about details from the tour (e.g., “The piano was black”) before performing free recall. False statements were created by altering the details of true statements. This true/false memory test was conducted for the purposes of another experiment (Diamond, Abdi, et al., 2020); in Study 2, we report recall data from participants who performed free recall for a different tour with no intervening true/false test. Participants in Study 1 were also asked to recall a time-matched personal event, with the order of recall (tour versus personal) counter-balanced across participants. Data from the time-matched personal events are not included in this report. Participants received the standard Autobiographical Interview administration, including a general probe (“Is there anything else you can tell me about this event”) following free recall for participants with limited output during free recall, as well as a subsequent specific probe for particular kinds of details. Given that our present interest is in spontaneous memory organization, only data from free recall and general probe are analyzed here. For participants who were administered the general probe, the transition from the last item in free recall to the

first item in general probe was masked from all analyses of recall dynamics (see below).

Participants' recall sessions were audio recorded and transcribed.

Analysis of details

To measure memory detail, we used the standard Autobiographical Interview (AI) scoring method (Levine et al., 2002). Transcribed recall narratives were broken down into discrete informational units/clauses, and categorized as either internal or external. Internal details are episodic and specific in space and time to the event being described. External details are not specific to the event being described – they may be semantic details (describing general features of oneself or the world that are not specific in space and time), repetitions, metacognitive statements (e.g. “I’m not sure”), or episodic details about different events. Internal details are further categorized as event, place, time, perceptual, or emotion/thought. Memories were scored by N.B.D. and research assistants, all of whom were trained on the method and achieved intraclass correlation coefficients of .90 or higher for the internal and external detail composite scores. Each scorer completed 20 transcripts from a reliability set, and ICCs were computed with reference to trained scorers' data. We measured episodic detail richness as the ratio of internal-to-total details, which measures the proportion of all details in a memory that refer to specific episodic information, unbiased by group differences in event content and individual differences in verbosity. This measure reliably differentiates age groups as well as memory-impaired groups from healthy comparison participants (Levine et al., 2002; Sheldon et al., 2018).

Analysis of temporal organization

We augmented the AI scoring method to investigate temporal organization. In recall of word lists or other standard laboratory stimuli, the items are discrete and occupy clearly defined

serial positions (i.e. 1st, 2nd, 3rd, ...). In recall of naturalistic episodes, particularly real-life experiences, perceptual experience is continuous rather than discrete, and the ‘stimuli’ include any attended feature of experience. We defined items as the elements in each tour to which the audio guide explicitly cued participants’ attention, ensuring that they were encoded by all participants in the first place, and in a specified order. These order-tagged items have clearly-defined and homogenous ordinal positions. There were 27 such items in Baycrest Tour 1.0. We coded participants’ first mention of any of these items with its ordinal position. Because a given naturalistic event can be described in myriad ways, ‘mentioning’ was defined as any reference to an item that would be unambiguous to a listener who was familiar with the tour. Thus for each memory, we derived a vector of order-tags, or ordinal positions, representing the items that person recalled and the order in which they were recalled. We note that this method can in principle be applied to any naturalistic memory for which the encoded sequence is known, making the data amenable to analytic techniques developed for word-list learning experiments.

To quantify temporal organization, we submitted the recall vectors to analysis of lag-conditional response probability (lag-CRP; Kahana, 1996), which is the canonical measure of temporal context reinstatement in recall. Lag-CRP measures the probability of transitioning from a recalled item i to the next-recalled item $i + 1$ as a function of their distance (lag) and order (positive = forward, negative = backward) at encoding. For instance, a lag of +1 represents a forward transition from a given item to the item that occurred next in the tour (e.g. from the 5th encoded item to the 6th encoded item), whereas a lag +2 represents a forward transition that skipped an intervening item (e.g. from the 5th encoded item to the 7th encoded item). Negative lags indicate recall transitions made in the backwards direction, opposite the encoded order.

The CRP is calculated, for each lag, as the number of transitions made divided by the number of transitions that were available. Repetitions are excluded and thus unavailable. The longest possible lag is $N - 1$, where N is the total number of order-tagged items (i.e. transitioning from the first item to the last; or $-(N - 1)$, if transitioning from the last item to the first). For each participant, values of zero for a given lag indicate that the participant had an opportunity to make that transition but did not. Transition lags that were never possible, given the preceding recall train and the total number of items, are excluded. For example, if a participant recalls every encoded item in perfect order, beginning at the first item, there was never an opportunity to make a transition in the backwards direction, and all negative lags would thus be unavailable and omitted for that participant. The analysis therefore considers at every transition which items have or have not already been recalled. This accounts for individual differences in the overall number of items recalled, as well as differences in the number of items in each event (i.e. the tours in Study 1 versus Study 2).

We also derived overall measures of temporal clustering (tendency to successively recall nearby items) and forward asymmetry (tendency to make forward recall transitions) for each participant. We measured temporal clustering using the temporal factor (Polyn et al., 2009), which quantifies, for each transition, the proportion of possible transition distances (in absolute lag) that are greater than the observed transition distance. Averaging over all transitions in a memory, it outputs a single proportion score representing the tendency to successively recall items that were nearer in time (and space, in our case). It is blind to transition direction (i.e. forward or backward). A score of 1 indicates that the participant always made the shortest transition available, and a score of 0.5 indicates chance-level temporal clustering. Forward

asymmetry was defined as the proportion of all transitions that moved forward in time with respect to the encoded order, excluding repetitions. It is blind to transition distance.

To derive stable measures of recall organization at the level of individual participants, we decided a priori to exclude recall trials with fewer than 5 unique order-tagged items (i.e. 4 transitions). This resulted in the exclusion of one older adult, leaving 18 older adults in the final analyzed sample. Lag-CRPs and temporal clustering scores were calculated using publicly available MATLAB scripts from the Behavioural Toolbox v1.01 from the Computational Memory Lab (<http://memory.psych.upenn.edu/Software>). For post-hoc group comparisons, we used Welch's *t*-tests to account for unequal variances. We report 95% confidence intervals around effect sizes (Cohen's *d* and Pearson's *r*).

Study 1 Results

Table 1 presents an overview of summary statistics and age effects on measures of detail and temporal organization.

Table 1

Measures of detail and temporal organization (* = significant age effect, $p < .05$).

Measure	Younger Mean[SD]	Older Mean [SD]	Cohen's d [95% CI]
Detail measures			
Internal detail count	92.45 [44.73]	72.44 [50.27]	.63 [-.03– 1.29]
External detail count	14.27 [15.74]	23.72 [19.57] *	.67 [.01 – 1.34]
Internal/total details	.89 [.06]	.74 [.15] *	1.35 [.64 – 2.07]
Temporal organization measures			
Temporal clustering	.87 [.11]	.75 [.15] *	.91 [.23 – 1.58]
Forward asymmetry	.84 [.12]	.72 [.15] *	.84 [.17, 1.51]
Explicit sequence errors (/transitions)	.04 [.06]	.06 [.08]	.19 [-.46, .83]

Details

Analyses of internal and external detail counts (see Table 1) were performed on log-transformed data to correct for significant positive skewness. One younger participant recalled 0 external details, so we artificially added 0.5 external details to each participant before log transformation. We replicated the interaction between age and detail type (internal vs. external) on detail counts ($F(1,38) = 17.29, p < .001$), previously established in autobiographical memory studies with self-selected events (e.g. Levine et al., 2002), with older adults reporting fewer internal details and more external details than younger adults (see Table 1; data also reported in Diamond, Armson, & Levine., *in press*). As expected, younger adults had considerably higher internal detail proportions than older adults ($t(22.03) = 3.97, p < .001, d = 1.35, 95\% \text{ CI } [.64,$

2.07]), replicating the established negative effect of age on episodic detail richness (Levine et al., 2002).

Recall dynamics

As described above, conditional response probability as a function of lag (lag-CRP) measures the probability of transitioning from an item i to the next-recalled item $i + 1$ as a function of their distance (lag) and order at encoding. Negative lags indicate recall transitions moving backward in time, opposite the encoded order (see “Analysis of recall dynamics”). Figure 2 presents the average lag-CRP curves for younger and older groups. Both groups exhibit the two canonical features of the lag-CRP curve indicating temporal context retrieval: (1) the contiguity effect, whereby the transition probability peaks for neighbouring items and declines as a function of distance in both directions, and (2) forward asymmetry, whereby forward transitions were more common than backwards transitions.

Figure 2. Lag-conditional response probabilities split by group. Dots represent group means, and error bars represent bootstrap-derived standard errors (1000 resamples).

Age differences in the lag-CRP curves are visually apparent, particularly at Lag +1 ($t(28.70) = 2.82, p = .009, d = .93, 95\% \text{ CI } [.26, 1.61]$); age differences were not significant at other lags, p 's $> .09$ uncorrected). To test the effect of age on the shape of the lag-CRP, we ran participant-wise linear regressions predicting CRP from lag. We did this separately for positive (1 to 5) and negative (-1 to -5) lags (Sadeh et al., 2014). This measure produced a coefficient for each participant, in each direction, representing the steepness of their lag-CRP curve (the change in recall probability as a function of increasing lag). Participants with no above-zero CRP values in either direction were excluded from analysis of that direction. In the positive direction, 1 older participant was excluded, and in the negative direction 3 younger and 4 older participants were excluded. We tested group-level differences in coefficients with t -tests. For positive lags,

younger adults ($M = -.113$, $SD = .04$) had steeper curves than older adults ($M = -.061$, $SD = .07$; $t(25.31) = 2.62$, $p = .015$, $d = .90$, 95% CI [.21, 1.58]). There was not a statistically significant age difference in the negative direction (younger: $M = -.040$, $SD = .03$; older: $M = -.028$, $SD = .03$; $t(28.55) = 1.19$, $p = .245$, $d = .42$, 95% CI [-.31, 1.14]). We note that previous studies took a similar approach to analyzing differences in lag-CRP curves, though they fit power functions to the curves rather than linear models (Sadeh et al., 2014). We opted for a more parsimonious approach, given the novelty of our encoding conditions and encoding-recall delay.

We next derived overall temporal clustering and forward asymmetry scores for each participant. We measured temporal clustering using the temporal factor (Polyn et al., 2009), which quantifies the tendency to successively recall items that were encoded nearby (in absolute lag) (see “Analysis of recall dynamics”). Consistent with the peaked lag-CRP curves, both groups exhibited greater-than-chance temporal clustering (p 's < .001), but there was a group difference in the degree of temporal clustering (Fig. 3A). Younger adults exhibited greater temporal clustering than older adults $t(29.38) = 2.75$, $p = .010$, $d = .91$, 95% CI [.23, 1.58]), indicating a large negative effect of age on temporal context reinstatement.

Figure 3. *A.* Temporal clustering. A score of .5 (dashed line) indicates chance-level temporal clustering, and a score of 1 indicates that every recall transition was the shortest available one. *B.* Forward asymmetry, measured as the proportion of all transitions that moved forward in time with respect to the encoded order. A score of .5 (dashed line) indicates recall transitions were made in backward and forward directions with equal probability, and a score of 1 indicates that only forward transitions were made. Black circles with white fill represent group means, and coloured dots represent individual subjects, and are slightly vertically jittered to reveal overlap. Error bars represent standard errors. The shaded regions in B are smoothed distributions.

Forward asymmetry was calculated as the proportion of all transitions that moved forward in time with respect to the encoded order. Younger and older adults both exhibited greater-than-chance forward asymmetry (p 's < .001), but groups differed here, too (Fig. 3B). Younger adults exhibited significantly higher forward asymmetry than older adults ($t(31.81) = 2.59, p = .014, d = .84, 95\% \text{ CI } [.17, 1.51]$), indicating that age was associated with a large reduction in the tendency to recall in chronological order.

We supplemented the analysis of forward asymmetry, which measures spontaneous recovery of the encoded temporal order in recall transitions, with analysis of explicit sequence errors, which were defined as any explicit reference to temporal order (using clauses such as “and then”, “after”, “before”, etc.) that were verifiably incorrect. These were rare (younger: $M = .73, SD = 1.12$, max = 4, 0 errors in 64% of participants; older: $M = .94, SD = 1.51$, max = 4, 0 errors in 61% of participants). In contrast to the deleterious effect of age on spontaneous forward asymmetry, there was not a significant difference between age groups in explicit sequence errors (Mann-Whitney U test: $U = 191, p = .838, d = .17, 95\% \text{ CI } [-.48, .81]$). To account for the fact that younger adults recalled more order-tagged items overall, and thus had more opportunities to make explicit sequence errors, we repeated this analysis dividing each participants' number of sequence errors by the number of transitions they made ($M_{\text{younger}} = .04, SD_{\text{younger}} = .06; M_{\text{older}} = .06, SD_{\text{younger}} = .08$). There was not a significant group difference on this measure either ($U = 187, p = .745, d = .19, 95\% \text{ CI } [-.46, .83]$).

Serial position effects

We have focused on group differences in the contextual dynamics of recall, as evidenced by the lag-CRP curves, temporal clustering, and forward asymmetry. The observed age effects, however, could be influenced by features of recall aside from its dynamics – for instance, which items are recalled overall, and from which ordinal position one initiates recall. Figure 4A shows serial position curves for each age group. One item (serial position 13) was removed because it was only recalled by two participants overall (.05), which is fewer than two standard deviations below the mean across groups ($M = .59$, $SD = .22$). Consistent with established findings, younger and older adults exhibit similar primacy and recency effects (Healey & Kahana, 2016; Howard et al., 2006), with older adults recalling fewer items overall ($M_{\text{younger}} = 18.00$, $SD_{\text{younger}} = 3.82$; $M_{\text{older}} = 13.61$, $SD_{\text{younger}} = 6.39$; $t(26.54) = 2.56$, $p = .016$, $d = .86$, 95% CI [.18, 1.53]). We note that the shape of these serial position curves should be interpreted with caution, as unlike laboratory stimuli, the items comprising the tour were not matched in their perceptual features, nor visual or environmental saliency, nor were they equidistant from each other. However, given that younger and older adults were exposed to the same event, the similarity in their serial position curves is noteworthy.

Figure 4B shows the proportion of participants in each group who began recall at each serial position (probability of first recall). Consistent with established findings, younger and older adults' probability of first recall curves are nearly identical (Healey & Kahana, 2016; Howard et al., 2006). Nearly all participants exhibit a strong primacy effect, initiating recall at the first or second tour item.

Figure 4. *A.* Serial position curves. Dots represent group means, and the dashed lines represent the quadratic fit for each group. *B.* Proportion of participants initiating recall at each serial position. Dots are slightly horizontally offset for each group to reveal overlap.

Interim summary

As predicted, age effects were observed for episodic detail richness and measures of spontaneous temporal organization (contiguity and forward asymmetry). While caution is warranted due to the small sample sizes, the pattern of observed age effects – shallower and less asymmetric lag-CRP functions in older relative to younger adults despite similar serial position and recall initiation curves – mirrors that observed in previous word list recall studies (Healey & Kahana, 2016; Howard et al., 2006).

Furthermore, we acknowledge that the true/false memory test may have contaminated subsequent free recall. In Study 2, we analyzed data from a larger younger adult sample who recalled a different controlled real-world event with no intervening testing. Leveraging this

larger sample to investigate individual differences, we tested the hypothesis that episodic detail richness would correlate with temporal contextual organization.

Study 2

Methods

Participants

The Study 2 sample included 90 younger participants ($M_{\text{age}} = 24.90$ years, $SD_{\text{age}} = 4.51$, $M_{\text{education}} = 16.46$ years, $SD_{\text{education}} = 2.87$, 65 females). 11 of these participants were excluded for insufficient recall quantity according to the threshold described in Study 1 (minimum 5 order-tagged items recalled). Participants were screened for the same exclusion criteria as in Study 1, except participants with any prior exposure to the tour area were excluded (as opposed to just those exposed within the last month or more than five times in total, as in Study 1).

Materials and Procedure

Encoding phase

Study 2 participants underwent a different audio-guided tour, this one on the second floor of Baycrest Hospital (Baycrest Tour 2.0; Figure 1B). Like the Baycrest Tour 1.0 audio guide, the Baycrest Tour 2.0 audio guide is publicly available on the Open Science Framework (<https://osf.io/j25y4/>). There was no confederate interaction, and the guide narrator was one male, but it was otherwise similar to Baycrest Tour 1.0. For the purposes of a different experiment, Baycrest Tour 2.0 was split into two sections. Participants completed one section of

the tour, were taken to a testing room to complete a battery of tests and questionnaires for approximately 45 minutes, and then completed the other section. The order of the sections was counter-balanced across participants. There were 13 order-tagged items in section 1 and 18 order-tagged items in section 2. Section 1 took on average 9.12 minutes ($SD = 1.27$), and section 2 took on average 10.17 minutes ($SD = 1.95$).

Retrieval phase

Participants performed free recall (they did not undergo general probe nor specific probe) after a 1 week delay. They neither completed an intervening true/false test nor a time-matched personal event recall as in Study 1. For the purposes of a separate experiment, these participants underwent eye-tracking during recall, using a head-mounted EyeLink system. They recalled each section of the tour separately, with the order of recall (section 1 versus section 2) counter-balanced across participants. During the first-recalled section, participants could move their eyes freely (free viewing). During the second-recalled section, participants were instructed to restrict their viewing patterns (fixed-viewing). Eye movements did occur in the fixed viewing condition, albeit within a restricted range. As a result, viewing condition had little effect on recall measures (Armson, Diamond, Levesque, Ryan, & Levine, *in revision*). Specifically, there was no detectable effect of viewing condition on measures of memory detail and temporal organization (see Supplementary Material), so we included data from both recalls in the present study.

Analysis

We used the same measures of detail and temporal organization from Study 1. As in Study 1, we excluded recall trials with fewer than five unique order-tagged items (i.e. four recall transitions). Here, this resulted in the exclusion of both recall trials for 11 participants, and one

recall trial for 17 participants. To clarify, after exclusions, there were 79 participants in Study 2, 62 with two recall trials (analyzed separately then averaged within participants) and 17 with one. Participants and trials excluded for this reason were also excluded from the analysis of details.

To investigate the relationship between recall organization and episodic detail across participants in Study 1 and 2, we ran mixed effects models and follow-up bivariate correlations predicting detail type from temporal clustering and forward asymmetry (mean-centered) while controlling for group. The total analyzed sample size of 119 exceeds Cohen's (1992) recommendation of $N = 85$ to reliably detect a medium sized population correlation at power = .8 and $\alpha = .05$.

Study 2 Results

Detail

Study 2 participants recalled on average 40.28 ($SD = 19.63$) internal details and 8.44 ($SD = 7.07$) external details (averaged over four sections, as described above). Their average internal-to-total detail proportion was .84 ($SD = .10$).

Temporal organization

The lag-CRP curve (Figure 5A) exhibited the canonical peaks at lags ± 1 with graded drop-offs as a function of lag, indicating that participants transitioned between items according to their spatiotemporal proximity and with a forward bias. In spite of the differences in events and testing methods, the lag-CRP curve obtained in this experiment was similar to that obtained for younger (but not older) participants in Study 1. As in Study 1, temporal clustering ($M = .82$, $SD = .09$; Figure 5B) and forward asymmetry ($M = .85$, $SD = .11$; Figure 5C) were greater than

chance (p 's $< .001$), and explicit sequence errors were rare (raw count: $M = .32$, $SD = .71$, max = 3, 0 errors in 85% of participants; as a proportion of transitions: $M = .02$, $SD = .05$). Post-hoc comparisons between the two tour events (restricted to younger participants from Study 1) indicated that forward asymmetry was not significantly different across the two tours ($t(32.11) = .35$, $p = .728$, $d = .09$, 95% CI $[-.39, .57]$), nor was temporal clustering ($t(29.24) = 1.97$, $p = .059$, $d = .53$, 95% CI $[-.05, 1.02]$), though Study 2 participants had numerically lower clustering, possibly reflecting longer retention interval or other cross-experiment differences.

Figure 5. Study 2 recall dynamics, following the same methods as in Study 1. A. Lag-conditional response probabilities. Error bars represent bootstrap-derived standard errors (1000 resamples). B. Temporal clustering. C. Forward asymmetry. In B and C, dashed lines indicate chance-level clustering and forward asymmetry, black circles with white fill represent group means, and coloured dots represent individual subjects, and are slightly vertically jittered to reveal overlap. Error bars (standard error) are not visible. The shaded regions are smoothed distributions.

Relating detail and temporal organization (combining Study 1 and 2)

We hypothesized that greater temporal context reinstatement, as measured by temporal clustering and forward asymmetry, would be associated with more episodically detail-rich recall. We tested this hypothesis by combining all three groups of participants across both studies. We ran separate linear mixed effects models predicting detail count from detail type (internal and external) and temporal clustering (Figure 6A) or forward asymmetry (Figure 7A), with each model also including group as a factor (Study 1 older, Study 1 younger, and Study 2), and all interactions. As above, internal and external detail counts were log transformed for analysis (after artificially adding 0.5 external details to each participant) to correct for positive skew.

There was a significant interaction between temporal clustering and detail type ($F(1,113) = 13.12, p < .001$), whereby temporal clustering was positively associated with internal details ($r(117) = .27, 95\% \text{ CI } [.10, .43], p = .003$), and exhibited a weak but statistically significant negative association with external details ($r(117) = -.19, 95\% \text{ CI } [-.01, -.36], p = .036$) (see Figure 6A). These coefficients were significantly different from each other ($Z = 5.30, p < .001$; Steiger Z-test). Critically, the absence of an interaction between group and temporal clustering ($F(2,113) = 0.47, p = .625$), or the three-way interaction including detail type ($F(2,113) = 0.25, p = .781$), suggests that the relationship between temporal clustering and details did not significantly vary across groups. To further clarify this finding, we tested the association between temporal clustering and the internal:total detail ratio, again including group in the model (Figure 6B). As expected, temporal clustering was significantly associated with internal:total detail proportion while modelling group ($F(1,113) = 12.53, p < .001$; $r(117) = .45, 95\% \text{ CI } [.30, .59], p < .001$). There was no interaction between temporal clustering and group ($F(2,113) =$

1.38, $p = .256$). For completeness, the correlation between temporal clustering and internal:total detail proportion is shown within each group in the Supplementary Material (Fig. S1).

Figure 6. *A*. Relationship between temporal clustering and internal versus external details, collapsed across groups. Note that raw details counts are visualized here but log-transformed detail counts were analyzed. *B*: Correlation between temporal clustering and internal detail proportion ($r(117) = .45, p < .001$). The shaded region represents the 95% confidence interval around the linear trendline.

We followed the same logic with forward asymmetry. As with temporal clustering, there was a significant interaction between forward asymmetry and detail type ($F(1,113) = 10.58, p = .002$), and no interaction between forward asymmetry and group ($F(2,113) = 1.76, p = .177$) nor forward asymmetry, group, and detail type ($F(2,113) = .74, p = .481$). However, unlike temporal clustering, forward asymmetry was not correlated with internal details ($r(117) = .09, 95\% \text{ CI } [-.10, .26], p = .355$), but rather was significantly negatively correlated with external details ($r(117) = -.29, 95\% \text{ CI } [-.11, -.45], p = .001$) (Fig. 7A). These coefficients were significantly

different from each other ($Z = 4.27, p < .001$). Comparing temporal clustering versus forward asymmetry directly, temporal clustering had a significantly greater association with internal details than forward asymmetry ($Z = 2.39, p = .017$), though they did not significantly differ in their relationship to external details ($Z = 1.25, p = .212$). Forward asymmetry, like temporal clustering, was significantly associated with internal:total detail proportion while modelling group ($F(1,113) = 10.44, p = .002$; $r(117) = .46, 95\% \text{ CI } [.30, .59], p < .001$) (Fig. 7B), and the interaction with group was not significant ($F(2,113) = 1.69, p = .188$). For completeness, the correlation between forward asymmetry and internal:total detail proportion is shown within each group in the Supplementary Material (Fig. S2).

Figure 7. **A.** Relationship between forward asymmetry and internal versus external details, collapsed across groups. Note that raw details counts are visualized, but log-transformed detail counts are analyzed. **B.** Correlation between forward asymmetry and internal detail proportion ($r(117) = .46, p < .001$). The shaded region represents the 95% confidence interval around the linear trendline.

Although temporal clustering and forward asymmetry were significantly correlated with each other ($r(117) = .63$, 95% CI [.51, .73], $p < .001$), they each explained unique variance in internal detail proportion when modelled together in a multiple regression (mean-centered; temporal clustering: $\beta = .27$, $t = 2.57$, $p = .011$; forward asymmetry: $\beta = .28$, $t = 2.62$, $p = .010$). This suggests that they capture different aspects of temporal structure, within single extended memories, that predict detail richness, which is consistent with their different relationships to internal and external details. They did not significantly interact ($\beta = -.01$, $t = .07$, $p = .942$).

One might be concerned that the internal detail proportion would necessarily be higher for participants who recalled more order-tagged items and thus made more recall transitions. However, our measures of temporal organization analytically controlled for the number of items recalled: lag-conditional response probabilities and temporal clustering are both computed on a transition-by-transition basis, adjusting for the number of available transitions at every point, and forward asymmetry was computed as a proportion of recalled items. Nonetheless, we regressed each measure on internal detail proportion while including the number of unique order-tagged items recalled in the model. In separate models, both temporal clustering ($\beta = .39$, $t = 4.47$, $p < .001$) and forward asymmetry ($\beta = .41$, $t = 5.08$, $p < .001$) significantly predicted internal detail proportion. As expected, the number of unique items recalled was also positively associated with internal detail proportion when modelled with temporal clustering (though not significantly; $\beta = .16$, $t = 1.88$, $p = .063$) or forward asymmetry ($\beta = .27$, $t = 3.82$, $p < .001$). Thus, recall dynamics are predictive of the density of episodic detail in a memory while controlling for the quantity of order-tagged items retrieved (i.e. the number of transitions made).

Lastly, to visualize the relationship between episodic detail richness and temporal context reinstatement, we re-plotted lag-CRP curves collapsing across group, binned by internal detail

proportion quintiles across (Fig. 8A). Quintiles line up in gradient-like fashion at lag +1, further highlighting the relationship between episodic detail richness and sequentially organized recall dynamics. This pattern may be driven in part by group differences, but the same general pattern obtained within the Study 2 sample (Figure 8B).

Figure 8. **A.** Lag-CRP curves binned by internal detail proportion quintiles, collapsing across all three groups ($N = 119$). **B.** Same as A, but with Study 2 participants only ($N = 79$). Error bars represent bootstrap-derived standard errors (1000 resamples).

General Discussion

We measured detail and temporal organization in free recall of extended real-world episodes. Across events, participants' recall dynamics revealed strong contiguity and forward asymmetry effects, extending established principles from laboratory paradigms to naturalistic recall at multi-day delays. Relative to younger adults, older adults exhibited temporally

disorganized memory as expressed in spontaneous recall transitions, but not in explicit sequence errors, with no age-related change in either serial position effects or recall initiation. Finally, internal detail proportion was positively correlated with contiguity and forward asymmetry, suggesting that memories unfolding with more sequentially organized recall dynamics are richer in episodic detail. These findings support the notion that episodic memory entails recovering not only snapshots of past experiences, but also spatiotemporal trajectories through them (Hasselman, 2012). They further suggest that the trajectory one takes to, or through, a memory is related to the quantity and kind of information retrieved.

The magnitudes of temporal clustering and forward asymmetry observed here are striking given the long delays (by laboratory standards) between encoding and recall (see also Diamond, Romero, Jeyakumar, & Levine, 2018). Furthermore, whereas organizational strategies develop over multiple encoding and recall trials in laboratory experiments (Tulving, 1962), we used one-shot events with no explicit instruction to encode sequence information (though participants were aware that their memory would be tested). These results add to existing evidence that temporal organization is not driven by relative differences in recency or trace strength among items, which should be rendered negligible by multi-day delays. Nor can such temporal organization be driven by schematic or script-like knowledge, as has been hypothesized for autobiographical memories (Anderson & Conway, 1993), given that the four items were idiosyncratic and arbitrarily ordered. Studies examining naturalistic events separated by months or years (Moreton & Ward, 2010; Uitvlugt & Healey, 2018) found temporal clustering only at the shortest lags, which may partly reflect direct event-to-event associations or reference to temporal landmarks (Friedman, 2004). Our finding of a temporally graded and forward-asymmetric contiguity effect extends principles from retrieved context models unambiguously to naturalistic event recall.

The positive relationship between temporal organization and detail richness builds on previous work suggesting that autobiographical memory organization shapes access to details (Anderson & Conway, 1993; Linton, 1986). More recent evidence from recognition memory tasks constrains temporal contiguity effects to items remembered with high confidence (Folkerts, Rutishauser, & Howard, 2018; Schwartz, Howard, Jing, & Kahana, 2005) or self-reported recollection (Sadeh et al., 2014), though participants may make these subjective judgements on the basis of retrieving temporal contextual information itself. Conversely, we objectively quantified episodic detail using a method that is blind to recall dynamics.

Temporal contiguity and forward asymmetry each explained unique variance in episodic detail density. Contiguity correlated positively with internal (episodic) detail quantity, and to a greater extent than forward asymmetry. Jumping back in time to an earlier moment from the encoding episode – an earlier ‘now’ – may bring into higher resolution moments that were nearby (Buzsáki & Moser, 2013; Howard & Kahana, 2002; Trope & Liberman, 2010). That contiguity related to episodic detail richness over and above the number of order-tagged items recalled (see Sederberg, Miller, Howard, & Kahana, 2010) suggests that it facilitated access to featural-level details, ambient environmental details, or journeys between items. Reduced temporal context binding and/or reinstatement in older adults may explain, in part, the established age-related reduction in internal details: despite initiating recall like younger adults, older adults may benefit less from iterative cueing through contextually-linked items (see also Howard et al., 2006). This would increase demands for multiple deliberate recall initiation attempts, with which older adults struggle (Craik, 1986), with initiation attempts jumping around more in space and time. The large effects of age on detail richness and temporal organization are not accompanied by effects on recall accuracy, which we explored in a related study using real-

world events (Diamond, Armson, & Levine, 2020). Mechanisms underlying detail recovery and temporal context reinstatement may be particularly susceptible to age-related decline.

Forward asymmetry was also positively associated with episodic detail richness, but this association was driven by reduced external details. Excessive external details can reflect over-reliance on semantic information or poor cognitive control (Sheldon et al., 2018). It is possible that external detail interjections interrupt the forward flow of temporal context, truncating memory search. Alternatively, participants with temporally disorganized memories may terminate memory search earlier and compensate with non-episodic information. In any case, we can only speculate about the causal direction, if there is one, between temporal organization and detail. It may be that temporal clustering is relatively automatic and dependent on hippocampal dynamics, whereas forward-biased search is more strategic and dependent on cognitive control processes coordinated by prefrontal cortex (Vriezen & Moscovitch, 1990). This interpretation is consistent with the associations between temporal clustering and internal detail generation on the one hand, and between forward asymmetry and external detail suppression on the other. It is also consistent with the decline of both contiguity and forward-bias in older age, with accompanying hippocampal and prefrontal atrophy (Raz et al., 2005), versus the decline in contiguity but preservation of forward-bias in medial temporal lobe amnesia (Palombo et al., 2018).

We acknowledge that the unidirectional structure of the tour events confounds spatial and temporal distance, which, when separated, can make dissociable contributions to recall organization (Miller, Lazarus, Polyn, & Kahana, 2012). As noted above, we use ‘temporal organization’ to refer to sequence, or ordinal structure, rather than absolute time. Such structure may shape the representation of episodes in memory more than space or time per se (Buzsáki & Tingley, 2018; Friedman, 2004), particularly for recall of real life experiences that flow

continuously through physical and semantic space (unlike artificially constructed stimuli that jump abruptly in these dimensions). Future work may determine how multiple dimensions (e.g. semantic associations, narrative structure, and boundaries) compete for influence on memory for complex episodes.

In conclusion, spatiotemporal proximity and chronological order shape the dynamics of naturalistic event recall. Both of these aspects of spontaneous temporal organization are compromised in older age, suggesting that aging is associated with a decline in the spatiotemporal organization of episodes in memory. Finally, recall organization relates to the content and specificity of retrieved details. These findings bridge a gap between detail richness and temporal context reinstatement, two influential yet disconnected behavioral hallmarks of episodic memory function, providing a more fully articulated description of naturalistic memory retrieval and how it declines in older age.

Acknowledgements

We thank Laryssa Levesque, Alissa Papadopolous, and Yarden Levy for assistance with memory scoring. This work was supported by CIHR grant MOP-148940 and the Ontario Graduate Scholarship to N.B.D.

References

- Anderson, S. J., & Conway, M. A. (1993). Investigating the structure of autobiographical memories. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 19(5), 1178–1196. <https://doi.org/10.1037/0278-7393.19.5.1178>
- Armson, M. J., Diamond, N. B., Levesque, L., Ryan, J. D., & Levine, B. (2019). The relationship between eye movements and autobiographical recollection is mediated by individual differences in autobiographical capacity. *PsyArxiv*.
<https://doi.org/10.1016/j.arthro.2011.05.004>
- Brewin, C. R. (2014). Episodic memory, perceptual memory, and their interaction: foundations for a theory of posttraumatic stress disorder. *Psychological Bulletin*, 140(1), 69–97.
<https://doi.org/10.1037/a0033722>
- Buzsáki, G., & Moser, E. I. (2013). Memory, navigation and theta rhythm in the hippocampal-entorhinal system. *Nature Neuroscience*, 16(2), 130–138. <https://doi.org/10.1038/nn.3304>
- Buzsáki, G., & Tingley, D. (2018). Space and Time: The Hippocampus as a Sequence Generator. *Trends in Cognitive Sciences*, 22(10), 853–869. <https://doi.org/10.1016/j.tics.2018.07.006>
- Craik, F. I. M. (1986). A functional account of age differences in memory. *Human Memory and Cognitive Capabilities: Mechanisms and Performances*, (April), 409–422.
- Cummings, R. (1921, January). The Time Professor. *Argosy All-Story Weekly*.
- Dede, A. J. O., Frascino, J. C., Wixted, J. T., & Squire, L. R. (2016). Learning and remembering real-world events after medial temporal lobe damage. *Proceedings of the National Academy*

of Sciences, 201617025. <https://doi.org/10.1073/pnas.1617025113>

Diamond, N. B., Abdi, H., & Levine, B. (2020). Different patterns of recollection for matched real-world and laboratory-based episodes in younger and older adults. *Cognition*, 202, 104309. <https://doi.org/10.1016/j.cognition.2020.104309>

Diamond, N. B., Armson, M. J., & Levine, B. (2020). The truth is out there: Accuracy and detail in recall of verifiable real-world events. *Psychological Science*.

Diamond, N. B., Romero, K., Jeyakumar, N., & Levine, B. (2018). Age-related decline in item but not spatiotemporal associative memory for a real-world event. *Psychology and Aging*, 33(7), 1079–1092. <https://doi.org/10.1037/pag0000303>

Folkerts, S., Rutishauser, U., & Howard, M. W. (2018). Human episodic memory retrieval is accompanied by a neural contiguity effect. *The Journal of Neuroscience*, 38(17), 2312–2317. <https://doi.org/10.1523/JNEUROSCI.2312-17.2018>

Friedman, W. J. (2004). Time in Autobiographical Memory. *Social Cognition*, 22(5), 591–605. <https://doi.org/10.1521/soco.22.5.591.50766>

Hasselmo, M. E. (2012). How We Remember: Brain Mechanisms of Episodic Memory. In *Philosophical Psychology* (Vol. 28). <https://doi.org/10.1080/09515089.2013.877243>

Healey, M. K., & Kahana, M. J. (2014). Is memory search governed by universal principles or idiosyncratic strategies? *Journal of Experimental Psychology: General*, 143(2), 575–596. <https://doi.org/10.1037/a0033715>

Healey, M. K., & Kahana, M. J. (2016). A four-component model of age-related memory

- change. *Psychological Review*, 123(1), 23–69. <https://doi.org/10.1037/rev0000015>
- Hintzman, D. L. (2016). Is memory organized by temporal contiguity? *Memory & Cognition*, 44(3), 365–375. <https://doi.org/10.3758/s13421-015-0573-8>
- Howard, M. W., & Eichenbaum, H. (2013). The hippocampus, time, and memory across scales. *Journal of Experimental Psychology. General*, 142(4), 1211–1230. <https://doi.org/10.1037/a0033621>
- Howard, M. W., & Kahana, M. J. (2002). A Distributed Representation of Temporal Context. *Journal of Mathematical Psychology*, 46(3), 269–299. <https://doi.org/10.1006/jmps.2001.1388>
- Howard, M. W., Kahana, M. J., & Wingfield, A. (2006). Aging and contextual binding: Modeling recency and lag recency effects with the temporal context model. *Psychonomic Bulletin and Review*, 13(3), 439–445. <https://doi.org/10.3758/BF03193867>
- Kahana, M. J. (1996). Associative retrieval processes in free recall. *Memory & Cognition*, 24(1), 103–109. <https://doi.org/10.3758/BF03197276>
- Koriat, A., & Goldsmith, M. (1996). Memory metaphors and the real-life/laboratory controversy: Correspondence versus storehouse conceptions of memory. *Behavioral and Brain Sciences*, 19(02), 167. <https://doi.org/10.1017/S0140525X00042114>
- Levine, B., Svoboda, E., Hay, J. F., Winocur, G., & Moscovitch, M. (2002). Aging and autobiographical memory: Dissociating episodic from semantic retrieval. *Psychology and Aging*, 17(4), 677–689. <https://doi.org/10.1037//0882-7974.17.4.677>

- Linton, M. (1986). Ways of searching and the contents of memory. In D. C. Rubin (Ed.), *Autobiographical memory* (pp. 50–68). <https://doi.org/10.1017/cbo9780511558313.007>
- Manning, J. R., Fitzpatrick, P. C., & Heusser, A. C. (2018). How is experience transformed into memory? *BioRxiv*, 409987. <https://doi.org/10.1101/409987>
- Miller, J. F., Lazarus, E. M., Polyn, S. M., & Kahana, M. J. (2012). Spatial clustering during memory search. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 39(3), 773–781. <https://doi.org/10.1037/a0029684>
- Moreton, B. J., & Ward, G. (2010). Time scale similarity and long-term memory for autobiographical events. *Psychonomic Bulletin & Review*, 17(4), 510–515. <https://doi.org/10.3758/PBR.17.4.510>
- Nielson, D. M., Smith, T. A., Sreekumar, V., Dennis, S., & Sederberg, P. B. (2015). Human hippocampus represents space and time during retrieval of real-world memories. *Proceedings of the National Academy of Sciences*, 112(35), 11078–11083. <https://doi.org/10.1073/pnas.1507104112>
- Palombo, D. J., Di Lascio, J. M., Howard, M. W., & Verfaellie, M. (2018). Medial temporal lobe amnesia is associated with a deficit in recovering temporal context. *Journal of Cognitive Neuroscience*, 31(2), 236–248. <https://doi.org/10.1162/jocn>
- Polyn, S. M., Norman, K. A., & Kahana, M. J. (2009). A context maintenance and retrieval model of organizational processes in free recall. *Psychological Review*, 116(1), 129–156. <https://doi.org/10.1037/a0014420>

- Raz, N., Lindenberger, U., Rodrigue, K. M., Kennedy, K. M., Head, D., Williamson, A., ...
Acker, J. D. (2005). Regional brain changes in aging healthy adults: general trends,
individual differences and modifiers. *Cerebral Cortex (New York, N.Y. : 1991)*, *15*(11),
1676–1689. <https://doi.org/10.1093/cercor/bhi044>
- Sadeh, T., Moran, R., & Goshen-Gottstein, Y. (2014). When items ‘pop into mind’: variability in
temporal-context reinstatement in free-recall. *Psychonomic Bulletin & Review*, *22*(3), 779–
790. <https://doi.org/10.3758/s13423-014-0746-7>
- Schwartz, G., Howard, M. W., Jing, B., & Kahana, M. J. (2005). Shadows of the past: Temporal
retrieval effects in recognition memory. *Psychological Science*, *16*(11), 898–904.
<https://doi.org/10.1111/j.1467-9280.2005.01634.x>
- Sederberg, P. B., Miller, J. F., Howard, M. W., & Kahana, M. J. (2010). The temporal contiguity
effect predicts episodic memory performance. *Memory & Cognition*, *38*(6), 689–699.
<https://doi.org/10.3758/MC.38.6.689>
- Sheldon, S., Diamond, N. B., Armson, M. J., Palombo, D. J., Selarka, D., Romero, K., ...
Levine, B. (2018). Assessing Autobiographical Memory. In *Stevens' Handbook of
Experimental Psychology and Cognitive Neuroscience*.
<https://doi.org/10.1002/9781119170174.epcn111>
- St-Laurent, M., Moscovitch, M., Tau, M., & McAndrews, M. P. (2011). The temporal unraveling
of autobiographical memory narratives in patients with temporal lobe epilepsy or excisions.
Hippocampus, *21*(4), 409–421. <https://doi.org/10.1002/hipo.20757>
- Trope, Y., & Liberman, N. (2010). Construal-level theory of psychological distance.

Psychological Review, 117(2), 440–463. <https://doi.org/10.1037/a0018963>

Tulving, E. (1962). Subjective organization in free recall of “unrelated” words. *Psychological Review*, 69(4), 344–354. <https://doi.org/10.1037/h0043150>

Tulving, E. (1972). Episodic and Semantic Memory. In *Organization of memory* (pp. 382–403).

Uitvlugt, M. G., & Healey, M. K. (2018). Temporal Proximity links Unrelated News Events in Memory. *Psychological Science*, 1–29. <https://doi.org/10.1177/0956797618808474>

Vriezen, E. R., & Moscovitch, M. (1990). Memory for Temporal Associative-Learning in Patients With Parkinson’s Disease. *Neuropsychologia*, 28, 1283–1293.