

¹ Memory for television episodes preserves event content
² while introducing new across-event similarities

³ Andrew C. Heusser^{1, 2, †}, Paxton C. Fitzpatrick^{1, †}, and Jeremy R. Manning^{1, *}

¹Department of Psychological and Brain Sciences

Dartmouth College, Hanover, NH 03755, USA

²Akili Interactive

Boston, MA 02110

[†]Denotes equal contribution

^{*}Corresponding author: jeremy.r.manning@dartmouth.edu

⁴ February 18, 2020

⁵ **Abstract**

⁶ Our experiences unfold over time defining unique *trajectories* through the relevant represen-
⁷ tational spaces. By casting our life events as temporally evolving trajectories, one can compare
⁸ the shape of the trajectory formed by an experience to that defined by our later remembering
⁹ of that experience. We propose a framework for mapping naturalistic experiences onto geomet-
¹⁰ ric spaces that characterize how experiences are segmented into discrete events, and how the
¹¹ contents of event sequences evolve over time. We apply this approach to a naturalistic memory
¹² experiment which had participants view and recount a television episode. The content of par-
¹³ ticipants' recounts of events from the original episode closely matched the original episode's
¹⁴ content. Further, we introduce two novel metrics for assessing memory quality (precision and
¹⁵ distinctiveness), both of which relate to participants' ability to recapitulate the experience. Lastly,
¹⁶ we identified a network of brain structures that are sensitive to the "shapes" of ongoing expe-

17 riences, and an overlapping network that is sensitive (at the time of encoding) to how people
18 later remembered those experiences in relation to other experiences. In this way, modeling the
19 content of richly structured experiences can reveal how (geometrically and conceptually) those
20 experiences are segmented into events and integrated into our memories of other experiences.

21 **Introduction**

22 What does it mean to *remember* something? In traditional episodic memory experiments (e.g.,
23 list-learning or trial-based experiments; Murdock, 1962; Kahana, 1996), remembering is often cast
24 as a discrete and binary operation: each studied item may be separated from all others, and la-
25 beled as having been recalled or forgotten. More nuanced studies might incorporate self-reported
26 confidence measures as a proxy for memory strength, or ask participants to discriminate between
27 “recollecting” the (contextual) details of an experience or having a general feeling of “familiarity”
28 (Yonelinas, 2002). Using well-controlled, trial-based experimental designs, the field has amassed
29 a wealth of valuable information regarding human episodic memory. However, there are funda-
30 mental properties of the external world and our memories that trial-based experiments are not well
31 suited to capture (for review also see Koriat and Goldsmith, 1994; Huk et al., 2018). First, our expe-
32 riences and memories are continuous, rather than discrete—removing a (naturalistic) event from
33 the context in which it occurs can substantially change its meaning. Second, the specific language
34 used to describe an experience has little bearing on whether the experience should be considered to
35 have been “remembered.” Asking whether the rememberer has precisely reproduced a specific set
36 of words to describe a given experience is nearly orthogonal to whether they were actually able to
37 remember it. In classic (e.g., list-learning) memory studies, by contrast, the number or proportion
38 of precise recalls is often a primary metric for assessing the quality of participants’ memories.
39 Third, one might remember the *essence* (or a general summary) of an experience but forget (or
40 neglect to recount) particular details. Capturing the essence of what happened is typically the
41 main “point” of recounting a memory to a listener, while the addition of highly specific details
42 may add comparatively little to successful conveyance of an experience.

43 How might one go about formally characterizing the “essence” of an experience, or whether
44 it has been recovered by the rememberer? Any given moment of an experience derives meaning
45 from surrounding moments, as well as from longer-range temporal associations (Lerner et al.,
46 2011; Manning, 2019). Therefore, the timecourse describing how an event unfolds is fundamental
47 to its overall meaning. Further, this hierarchy formed by our subjective experiences at different
48 timescales defines a *context* for each new moment (e.g., Howard and Kahana, 2002; Howard et al.,
49 2014), and plays an important role in how we interpret that moment and remember it later (for
50 review see Manning et al., 2015). Our memory systems can leverage these associations to form
51 predictions that help guide our behaviors (Ranganath and Ritchey, 2012). For example, as we
52 navigate the world, the features of our subjective experiences tend to change gradually (e.g., the
53 room or situation we are in at any given moment is strongly temporally autocorrelated), allowing
54 us to form stable estimates of our current situation and behave accordingly (Zacks et al., 2007;
55 Zwaan and Radvansky, 1998).

56 Occasionally, this gradual “drift” of our ongoing experience is punctuated by sudden changes,
57 or “shifts” (e.g., when we walk through a doorway; Radvansky and Zacks, 2017). Prior research
58 suggests that these sharp transitions (termed *event boundaries*) help to discretize our experiences
59 (and their mental representations) into *events* (Radvansky and Zacks, 2017; Brunec et al., 2018;
60 Heusser et al., 2018a; Clewett and Davachi, 2017; Ezzyat and Davachi, 2011; DuBrow and Davachi,
61 2013). The interplay between the stable (within-event) and transient (across-event) temporal
62 dynamics of an experience also provides a potential framework for transforming experiences
63 into memories that distill those experiences down to their essence. For example, prior work
64 has shown that event boundaries can influence how we learn sequences of items (Heusser et al.,
65 2018a; DuBrow and Davachi, 2013), navigate (Brunec et al., 2018), and remember and understand
66 narratives (Zwaan and Radvansky, 1998; Ezzyat and Davachi, 2011). Prior research has implicated
67 a network of brain regions (including the hippocampus and the medial prefrontal cortex) as playing
68 a critical role in transforming experiences into structured and consolidated memories (Tomparry
69 and Davachi, 2017).

70 Here we sought to examine how the temporal dynamics of a “naturalistic” experience were

71 later reflected in participants' memories. We analyzed an open dataset that comprised behavioral
72 and functional Magnetic Resonance Imaging (fMRI) data collected as participants viewed and then
73 verbally recounted an episode of the BBC television series *Sherlock* (Chen et al., 2017). We developed
74 a computational framework for characterizing the temporal dynamics of the moment-by-moment
75 content of the episode, and of participants' verbal recalls. Specifically, we use topic modeling (Blei
76 et al., 2003) to characterize the thematic conceptual (semantic) content present in each moment of
77 the episode and recalls, and Hidden Markov Models (Rabiner, 1989; Baldassano et al., 2017) to
78 discretize this evolving semantic content into events. In this way, we cast naturalistic experiences
79 (and recalls of those experiences) as geometric *trajectories* that describe how the experiences evolve
80 over time. Under this framework, successful remembering entails verbally "traversing" the content
81 trajectory of the episode, thereby reproducing the shape (or essence) of the original experience.
82 Comparing the shapes of the topic trajectories of the episode and of participants' retellings of
83 the episode then reveals which aspects of the episode were preserved (or lost) in the translation
84 into memory. We further introduce two novel metrics for assessing memory quality: the *precision*
85 with which a participant recounts each event and 2) the *distinctiveness* of each recall event (relative
86 to other recalled events). We examine how these metrics relate to participants' overall memory
87 performance, and discuss the ways in which they improve upon classic "proportion-recalled"
88 measures for analyzing naturalistic memory. Last, we utilize our framework to identify networks
89 of brain structures whose responses (as participants watched the episode) reflected the temporal
90 dynamics of the episode, and how participants would later recount it.

91 Results

92 To characterize the temporally dynamic contents of the *Sherlock* episode and participants' subse-
93 quent recounts, we used a topic model (Blei et al., 2003) to discover the latent themes. Topic
94 models take as inputs a vocabulary of words to consider and a collection of text documents, and
95 return two output matrices. The first of these is a *topics matrix* whose rows are topics (latent
96 themes) and whose columns correspond to words in the vocabulary. The entries of the topics ma-

97 trix define how each word in the vocabulary is weighted by each discovered topic. For example,
98 a detective-themed topic might weight heavily on words like “crime,” and “search.” The second
99 output is a *topic proportions matrix*, with one row per document and one column per topic. The topic
100 proportions matrix describes what mixture of discovered topics is reflected in each document.

101 Chen et al. (2017) collected hand-annotated information about each of 1000 (manually identified)
102 time segments spanning the roughly 50 minute video used in their experiment. This information
103 included: a brief narrative description of what was happening, the location where the scene
104 took place, the names of any characters on the screen, and other similar details (for a full list of
105 annotated features, see *Methods*). We took from these annotations the union of all unique words
106 (excluding stop words, such as “and,” “or,” “but,” etc.) across all features and scenes as the
107 “vocabulary” for the topic model. We then concatenated the sets of words across all features
108 contained in overlapping, sliding windows of (up to) 50 scenes, and treated each window as a
109 single “document” for the purpose of fitting the topic model. Next, we fit a topic model with (up
110 to) $K = 100$ topics to this collection of documents. We found that 32 unique topics (with non-zero
111 weights) were sufficient to describe the time-varying content of the video (see *Methods*; Figs. 1, S2).
112 Note that our approach is similar in some respects to Dynamic Topic Models (Blei and Lafferty,
113 2006) in that we sought to characterize how the thematic content of the episode evolved over
114 time. However, whereas Dynamic Topic Models are designed to characterize how the properties
115 of *collections* of documents change over time, our sliding window approach allows us to examine
116 the topic dynamics within a single document (or video). Specifically, our approach yielded (via the
117 topic proportions matrix) a single *topic vector* for each sliding window of annotations transformed
118 by the topic model. We then stretched (interpolated) the resulting windows-by-topics matrix to
119 match the time series of the 1976 fMRI volumes collected as participants viewed the episode.

120 The 32 topics we found were heavily character-focused (i.e., the top-weighted word in each
121 topic was nearly always a character) and could be roughly divided into themes centered around
122 Sherlock Holmes (the titular character), John Watson (Sherlock’s close confidant and assistant),
123 supporting characters (e.g., Inspector Lestrade, Sergeant Donovan, or Sherlock’s brother Mycroft),
124 or the interactions between various pairs of these characters (see Fig. S2). Several of the identified

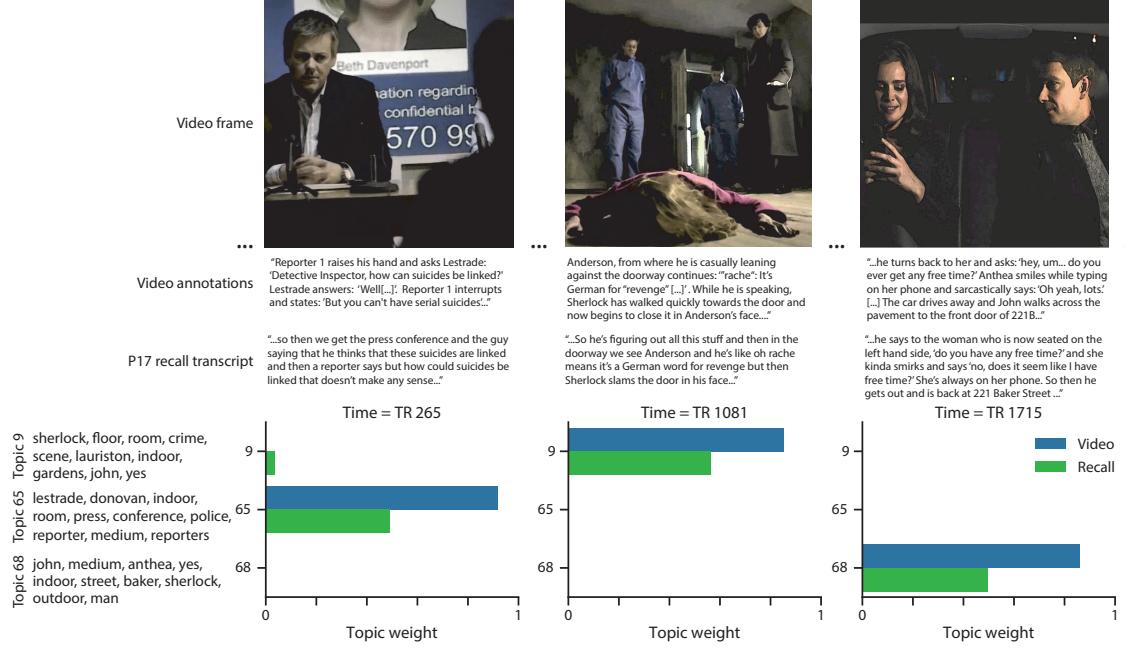


Figure 1: Methods overview. We used hand-annotated descriptions of each moment of video to fit a topic model. Three example video frames and their associated descriptions are displayed (top two rows). Participants later recalled the video (in the third row, we show example recalls of the same three scenes from participant 17). We used the topic model (fit to the annotations) to estimate topic vectors for each moment of video and each sentence the participants recalled. Example topic vectors are displayed in the bottom row (blue: video annotations; green: example participant’s recalls). Three topic dimensions are shown (the highest-weighted topics for each of the three example scenes, respectively). We also show the 10 highest-weighted words for each topic. Figure S2 provides a full list of the top 10 words from each of the discovered topics.

125 topics were highly similar, which we hypothesized might allow us to distinguish between subtle
126 narrative differences if the distinctions between those overlapping topics were meaningful. The
127 topic vectors for each timepoint were *sparse*, in that only a small number (usually one or two) of
128 topics tended to be “active” in any given timepoint (Fig. 2A). Further, the dynamics of the topic
129 activations appeared to exhibit *persistence* (i.e., given that a topic was active in one timepoint, it was
130 likely to be active in the following timepoint) along with *occasional rapid changes* (i.e., occasionally
131 topics would appear to spring into or out of existence). These two properties of the topic dynamics
132 may be seen in the block diagonal structure of the timepoint-by-timepoint correlation matrix
133 (Fig. 2B) and reflect the gradual drift and sudden shifts fundamental to the temporal dynamics of
134 real-world experiences. Given this observation, we adapted an approach devised by Baldassano
135 et al. (2017), and used a Hidden Markov Model (HMM) to identify the *event boundaries* where the
136 topic activations changed rapidly (i.e., at the boundaries of the blocks in the correlation matrix;
137 event boundaries identified by the HMM are outlined in yellow in Fig. 2B). Part of our model fitting
138 procedure required selecting an appropriate number of “events” into which the topic trajectory
139 should be segmented. To accomplish this, we used an optimization procedure that maximized the
140 difference between the topic weights for timepoints within an event and across multiple events
141 (see *Methods* for additional details). We then created a stable “summary” of the content within
142 each video event by averaging the topic vectors across timepoints each event spanned (Fig. 2C).

143 Given that the time-varying content of the video could be segmented cleanly into discrete
144 events, we wondered whether participants’ recalls of the video also displayed a similar structure.
145 We applied the same topic model (already trained on the video annotations) to each participant’s
146 recalls. Analogous to how we parsed the time-varying content of the video, to obtain similar esti-
147 mates for each participant’s recall, we treated each overlapping “window” of (up to 10) sentences
148 from their transcript as a “document,” and computed the most probable mix of topics reflected in
149 each timepoint’s sentences. This yielded, for each participant, a number-of-windows by number-
150 of-topics topic proportions matrix that characterized how the topics identified in the original video
151 were reflected in the participant’s recalls. Note that an important feature of our approach is that it
152 allows us to compare participants’ recalls to events from the original video, despite different par-



Figure 2: Modelling naturalistic stimuli and recalls. All panels: darker colors indicate greater values; range: [0, 1]. **A.** Topic vectors ($K = 100$) for each of the 1976 video timepoints. **B.** Timepoint-by-timepoint correlation matrix of the topic vectors displayed in Panel A. Event boundaries discovered by the HMM are denoted in yellow (30 events detected). **C.** Average topic vectors for each of the 30 video events. **D.** Topic vectors for each of 265 sliding windows of sentences spoken by an example participant while recalling the video. **E.** Timepoint-by-timepoint correlation matrix of the topic vectors displayed in Panel D. Event boundaries detected by the HMM are denoted in yellow (22 events detected). For similar plots for all participants see Figure S4. **F.** Average topic vectors for each of the 22 recalled events from the example participant. **G.** Correlations between the topic vectors for every pair of video events (Panel C) and recalled events (from the example participant; Panel F). For similar plots for all participants, see Figure S5. **H.** Average correlations between each pair of video events and recalled events (across all 17 participants). To create the figure, each recalled event was assigned to the video event with the most correlated topic vector (yellow boxes in panels G and H).

¹⁵³ ticipants using widely varying language to describe the same event, and that those descriptions
¹⁵⁴ may not match the original annotations. This is a substantial benefit of projecting the video and
¹⁵⁵ recalls into a shared “topic” space. An example topic proportions matrix from one participant’s
¹⁵⁶ recalls is shown in Figure 2D.

¹⁵⁷ Although the example participant’s recall topic proportions matrix has some visual similarity to
¹⁵⁸ the video topic proportions matrix, the time-varying topic proportions for the example participant’s
¹⁵⁹ recalls are not as sparse as those for the video (compare Figs. 2A and D). Similarly, although there do
¹⁶⁰ appear to be periods of stability in the recall topic dynamics (i.e., most topics are active or inactive
¹⁶¹ over contiguous blocks of time), the individual topics’ overall timecourses are not as cleanly
¹⁶² delineated as the video topics’. To examine these patterns in detail, we computed the timepoint-
¹⁶³ by-timepoint correlation matrix for the example participant’s recall topic trajectory (Fig. 2E). As in
¹⁶⁴ the video correlation matrix (Fig. 2B), the example participant’s recall correlation matrix has a strong
¹⁶⁵ block diagonal structure, indicating that their recalls are discretized into separated events. As for
¹⁶⁶ the video correlation matrix, we leveraged an HMM-based optimization procedure (see *Methods*)
¹⁶⁷ to determine how many events are reflected in the participant’s recalls and where specifically the
¹⁶⁸ event boundaries fall (outlined in yellow). We carried out a similar analysis on all 17 participants’
¹⁶⁹ recall topic proportions matrices (Fig. S4).

¹⁷⁰ Two clear patterns emerged from this set of analyses. First, although every individual partic-
¹⁷¹ ipant’s recalls could be segmented into discrete events (i.e., every individual participant’s recall
¹⁷² correlation matrix exhibited clear block diagonal structure; Fig. S4), each participant appeared to
¹⁷³ have a unique *recall resolution*, reflected in the sizes of those blocks. While, some participants’ recall
¹⁷⁴ topic proportions segmented into just a few events (e.g., Participants P4, P5, and P7), others’ seg-
¹⁷⁵ mented into many shorter duration events (e.g., Participants P12, P13, and P17). This suggests that
¹⁷⁶ different participants may be recalling the video with different levels of detail— e.g., some might
¹⁷⁷ touch on just the major plot points, whereas others might attempt to recall every minor scene or ac-
¹⁷⁸ tion. The second clear pattern present in every individual participant’s recall correlation matrix is
¹⁷⁹ that, unlike in the video correlation matrix, there are substantial off-diagonal correlations. Whereas
¹⁸⁰ each event in the original video was (largely) separable from the others (Fig. 2B), in transforming

¹⁸¹ those separable events into memory, participants appear to be integrating across multiple events,
¹⁸² blending elements of previously recalled and not-yet-recalled content into each newly recalled
¹⁸³ event (Figs. 2E, S4; also see Manning et al., 2011; Howard et al., 2012).

¹⁸⁴ The above results indicate that both the structure of the original video and participants' recalls
¹⁸⁵ of the video exhibit event boundaries that can be identified automatically by characterizing the
¹⁸⁶ dynamic content using a shared topic model and segmenting the content into events via HMMs.
¹⁸⁷ Next, we asked whether some correspondence might be made between the specific content of the
¹⁸⁸ events the participants experienced in the video, and the events they later recalled. One approach
¹⁸⁹ to linking the experienced (video) and recalled events is to label each recalled event as matching
¹⁹⁰ the video event with the most similar (i.e., most highly correlated) topic vector (Figs. 2G, S5). This
¹⁹¹ yields a sequence of "presented" events from the original video, and a (potentially differently
¹⁹² ordered) sequence of "recalled" events for each participant. Analogous to classic list-learning
¹⁹³ studies, we can then examine participants' recall sequences by asking which events they tended
¹⁹⁴ to recall first (probability of first recall; Fig. 3A; Atkinson and Shiffrin, 1968; Postman and Phillips,
¹⁹⁵ 1965; Welch and Burnett, 1924); how participants most often transition between recalls of the
¹⁹⁶ events as a function of the temporal distance between them (lag-conditional response probability;
¹⁹⁷ Fig. 3B; Kahana, 1996); and which events they were likely to remember overall (serial position
¹⁹⁸ recall analyses; Fig. 3C; Murdock, 1962). Interestingly, for two of these analyses (probability of first
¹⁹⁹ recall and lag-conditional response probability curves) we observe patterns comparable to classic
²⁰⁰ effects from the list-learning literature: namely, a higher probability of initiating recall with the
²⁰¹ first event in the sequence (Fig. 3A) and a higher probability of transitioning to neighboring events
²⁰² with an asymmetric forward bias (Fig. 3B). In contrast, we do not observe a pattern comparable to
²⁰³ the serial position effect (Fig. 3C), but rather we see higher memory for specific events distributed
²⁰⁴ somewhat evenly throughout the video.

²⁰⁵ We can also apply two list-learning-native analyses that describe how participants group items
²⁰⁶ in their recall sequences: temporal clustering and semantic clustering (Polyn et al., 2009, see
²⁰⁷ *Methods* for details). Temporal clustering refers to the extent to which participants group their
²⁰⁸ recall responses according to encoding position. Overall, we found that sequentially viewed video

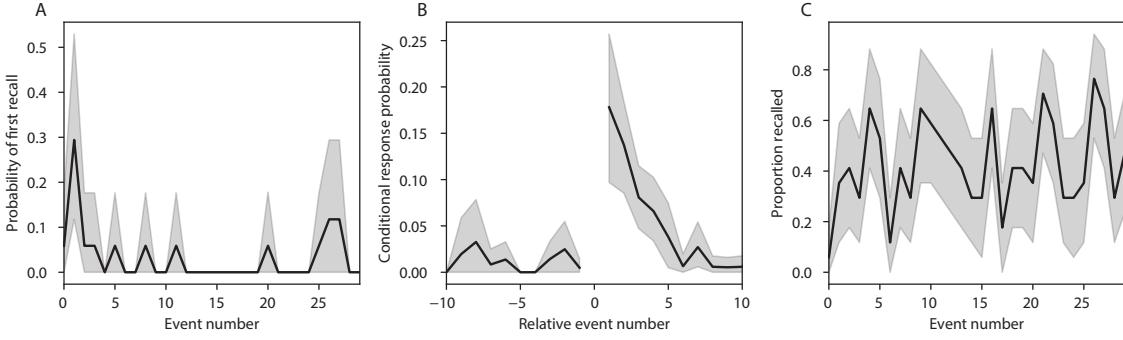


Figure 3: Naturalistic extensions of classic list-learning memory analyses. A. The probability of first recall as a function of the serial position of the event in the video. B. The probability of recalling each event, conditioned on having most recently recalled the event *lag* events away in the video. C. The proportion of participants who recalled each event, as a function of the serial position of the events in the video. All panels: error bars denote bootstrap-estimated standard error of the mean.

events were clustered heavily in participants' recall event sequences (mean clustering score: 0.767, SEM: 0.029), and that participants with higher temporal clustering scores tended to perform better according to both Chen et al. (2017)'s hand-annotated memory scores (Pearson's $r(15) = 0.62$, $p = 0.008$) and our model's estimate (Pearson's $r(15) = 0.54$, $p = 0.024$). Semantic clustering measures the extent to which participants cluster their recall responses according to semantic similarity. We found that participants tended to recall semantically similar video events together (mean clustering score: 0.787, SEM: 0.018), and that semantic clustering score was also related to both hand-annotated (Pearson's $r(15) = 0.65$, $p = 0.004$) and model-derived (Pearson's $r(15) = 0.63$, $p = 0.007$) memory performance.

Statistical models of memory studies often treat recall success as binary (i.e., an item either was or was not recalled), or occasionally categorical (e.g., to distinguish familiarity from recollection; Yonelinas et al., 2002). Such approaches are tenable in classical list-learning or recognition memory paradigms, as the presented stimuli tend to be very simple (e.g., a sequence of individual words or items). However, the feature-rich content of a naturalistic experiences may later be described with many, highly variable levels of success. Our framework produces a content-based model of individual stimulus and recall events by projecting the dynamic content of the video and participants' recalls into a shared topic space. This allows for direct, quantitative comparison

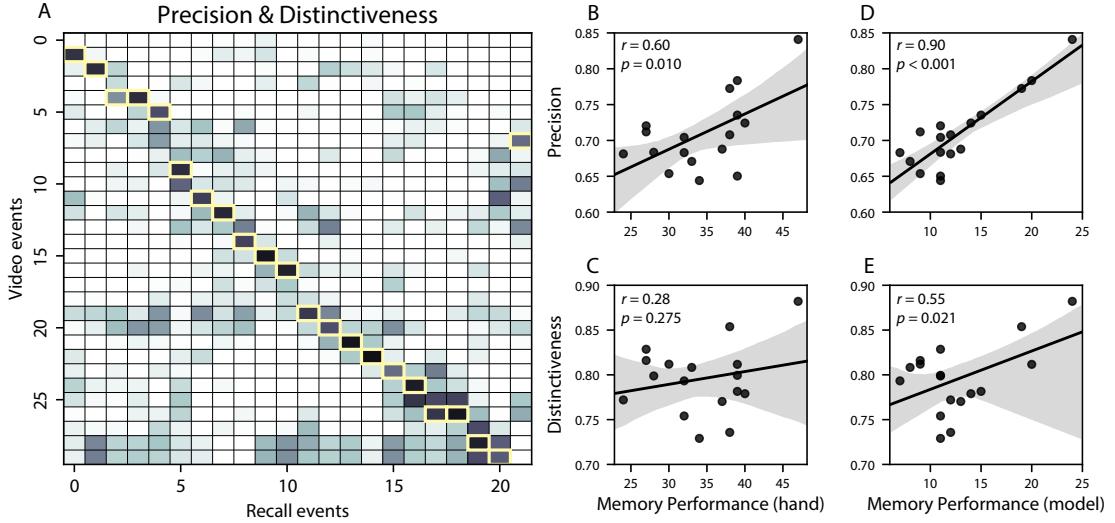


Figure 4: Novel content-based metrics of naturalistic memory: precision and distinctiveness. A. The video-recall correlation matrix for a representative participant (17). The yellow boxes highlight the maximum correlation in each column. The example participant's overall precision score was computed as the average across correlation values in the yellow boxes. Their distinctiveness score was computed as the average (over recall events) of 1 minus the average correlation between each recall event and all other recall events that do not display a box in the same row. B. The (Pearson's) correlation between precision and hand-annotated memory performance. C. The correlation between distinctiveness and hand-annotated memory performance. D. The correlation between precision and the number of video events successfully recalled, as determined by our model. E. The correlation between distinctiveness and the number of video events successfully recalled, as determined by our model.

226 between all stimulus and recall events, as well as between the recall events themselves. Leveraging
 227 these content-based models of the stimulus/recall events, we developed two novel, *continuous*
 228 metrics for analyzing naturalistic memory: *precision* and *distinctiveness*. We define precision as
 229 the “completeness” of recall, or how fully the presented content was recapitulated in memory.
 230 Under our framework, we quantify this for a given recall event as the correlation between the
 231 topic proportions of the recall event and the maximally correlated video event (Fig. 4). A second
 232 novel metric we introduce here is *distinctiveness*, which we define as the “specificity” of recall,
 233 or how unique the description of a given section of content was, compared to descriptions for
 234 other sections of content. We quantify this for each recall event as 1 minus the average correlation
 235 between the given recall event and all other recall events not matched to the same video event.

236 In addition to individual events, one may also use these metrics to describe each participant's
237 overall performance (i.e., by averaging across a participant's event-wise precision or distinctiveness
238 scores). Participants whose recall events are more veridical descriptions of what happened in the
239 video event will presumably have higher precision scores. We find that, across participants,
240 a higher precision score is correlated to both hand-annotated memory performance (Pearson's
241 $r(15) = 0.60, p = 0.010$) and the number of video events successfully remembered, as determined
242 by our model (Pearson's $r(15) = 0.90, p < 0.001$). We also hypothesized that participants who
243 recounted events in a more distinctive way would display better overall memory. We find that
244 this distinctiveness score is related to our model's estimated number of recalled events (Pearson's
245 $r(15) = 0.55, p = 0.021$), and while we do not find distinctiveness to be related to hand-annotated
246 memory performance (Pearson's $r(15) = 0.28, p = 0.275$), this is not entirely surprising given how
247 the hand-annotated memory scores were computed (see *Methods* and *Discussion* for details).

248 Further intuition for the behaviors captured by these two metrics may be gained by directly
249 examining the content of the video and recalls our framework models. In Figure 5, we contrast
250 recalls for the same video event (event 22) from two participants: one with a high precision score
251 (P17), the other with a low precision score (P6). From the HMM-identified event boundaries,
252 we recovered the set of annotations describing the content of an example video event (Fig. 5B),
253 and divided them into different color-coded sections for each action or feature described. We
254 then similarly recovered the set of sentences comprising the corresponding recall event for each
255 of the two example participants. Because the recall sliding windows overlap heavily, and each
256 recall event spans multiple recall timepoints (i.e., windows), we have stripped any sentences from
257 the beginning and end that describe earlier or later video events for the sake of readability. In
258 other words, Fig. 5C shows a subset of the full recall event text, comprising sentences between
259 the first and last descriptions of content from the example video event. We then colored all words
260 describing actions and features coded in panel B by their corresponding color. Visual comparison
261 of the transcripts reveals that the most precise participant's recall both captures more of the video
262 event's content, and does so with far more detail.

263 Figure 6 similarly contrasts two example participants' recalls for a common video event (event

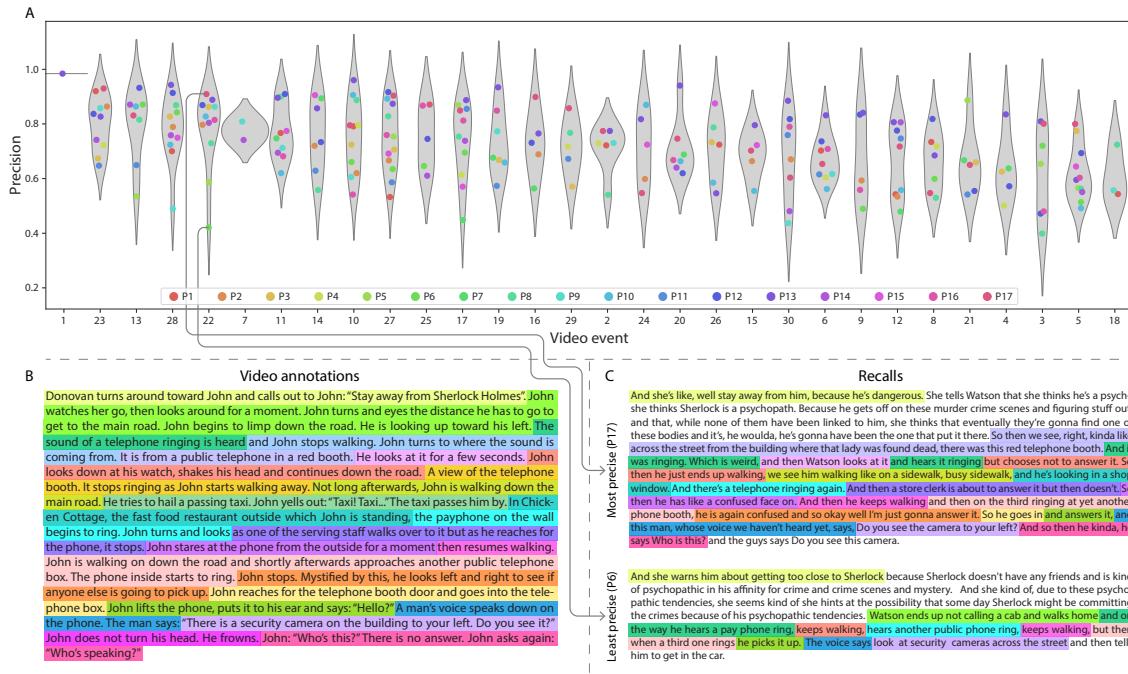


Figure 5: Precision metric reflects completeness of recall. **A.** Recall precision by video event. Grey violin plots display kernel density estimates for the distribution of recall precision scores for a single video event. Colored dots within each violin plot represent individual participants' recall precision for the given event. Video events are ordered along the *x*-axis by the average precision with which they were remembered. **B.** The set of "Narrative Details" video annotations (generated by Chen et al., 2017) for scenes comprising an example video event (22) identified by the HMM. Each action or feature is highlighted in a different color. **C.** A subset of the sentences comprising the most precise (P17) and least precise (P6) participants' recalls of video event 22. Descriptions of specific actions or features reflecting those highlighted in panel B are highlighted in the corresponding color.

19) to illustrate the tangible differences between high and low distinctiveness scores. Here, we
 20) have extracted the full set of sentences comprising the most distinctive recall event (P13) and least
 21) distinctive recall event (P11) matched to the example video event (Fig. 6C). We also extracted the
 22) annotations for the example video event, as well as those from each other video event whose content
 23) the example participants' single recall events described (Fig. 6B). We then shaded the annotation
 24) text for each video event with a different color, and shaded each word of the example participants'
 25) recall text by the color of the video event it describes. The majority of the most distinctive recall
 26) event text describes video event 19's content, with the first five and last one sentence describing
 27) the video events immediately preceding and succeeding the current one, respectively. In contrast,

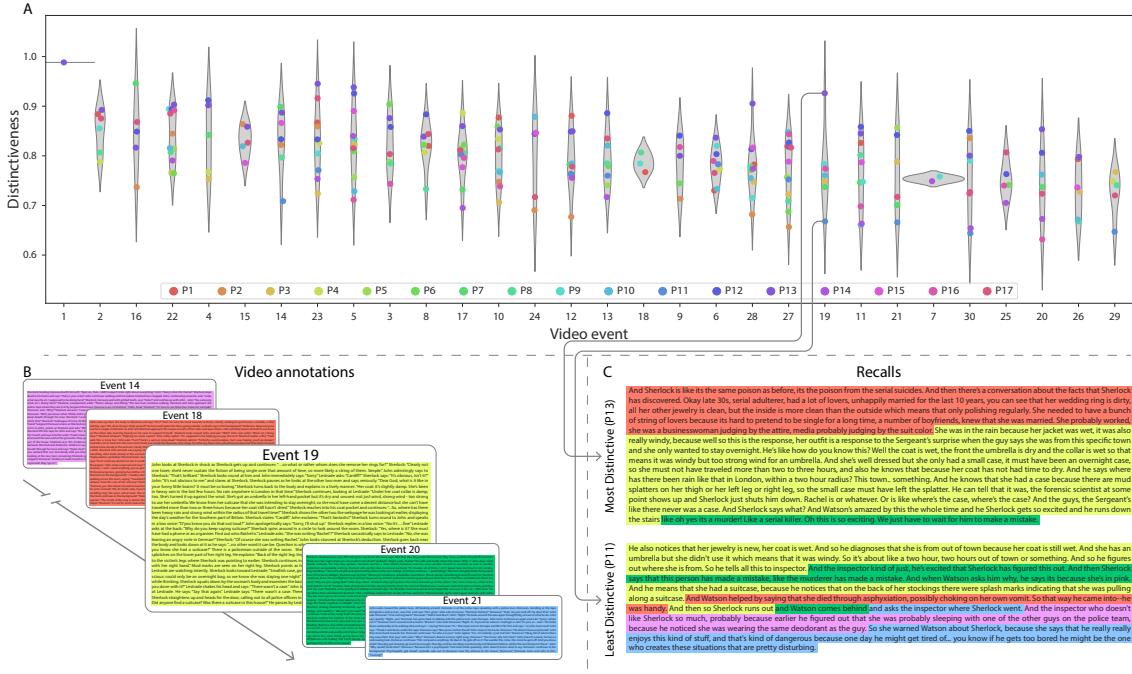


Figure 6: Distinctiveness metric reflects specificity of recall. A. Recall distinctiveness by video event. Kernel density estimates for each video event’s distribution of recall distinctiveness scores, analogous to Fig. 5A. B. The sets of “Narrative Details” video annotations (generated by Chen et al., 2017) for scenes comprising video events described by the example participants in panel C. Each event’s text is highlighted in a different color. C. The sentences comprising the most distinctive (P13) and least distinctive (P11) participants’ recalls of video event 19. Sections of recall describing each video event in panel B are highlighted with the corresponding color.

273 the least precise participant's recall for video event 19 blends the content from five separate video
274 events, does not transition between them in order, and often combines descriptions of two video
275 events' content in the same sentence.

The prior analyses leverage the correspondence between the 100-dimensional topic proportion matrices for the video and participants' recalls to characterize recall. However, it is difficult to gain deep insights into the content of (or relationships between) experiences and memories solely by examining these topic proportions (e.g., Figs. 2A, D) or the corresponding correlation matrices (Figs. 2B, E, S4). And while we can directly examine the original text underlying these topic vectors (e.g., Figs. 5, 6) to show how relationships between them reflect real-world behavior, this comparison becomes prohibitively cumbersome at larger timescales. To visualize the time-varying

283 high-dimensional content in a more intuitive way (Heusser et al., 2018b), we projected the topic
284 proportions matrices onto a two-dimensional space using Uniform Manifold Approximation and
285 Projection (UMAP; McInnes et al., 2018). In this lower-dimensional space, each point represents a
286 single video or recall event, and the distances between the points reflect the distances between the
287 events' associated topic vectors (Fig. 7). In other words, events that are nearer to each other in this
288 space are more semantically similar, and those that are farther apart are less so.

289 Visual inspection of the video and recall topic trajectories reveals a striking pattern. First, the
290 topic trajectory of the video (which reflects its dynamic content; Fig. 7A) is captured nearly perfectly
291 by the averaged topic trajectories of participants' recalls (Fig. 7B). To assess the consistency of these
292 recall trajectories across participants, we asked: given that a participant's recall trajectory had
293 entered a particular location in the reduced topic space, could the position of their *next* recalled
294 event be predicted reliably? For each location in the the reduced topic space, we computed the set of
295 line segments connecting successively recalled events (across all participants) that intersected that
296 location (see *Methods* for additional details). We then computed (for each location) the distribution
297 of angles formed by the lines defined by those line segments and a fixed reference line (the *x*-
298 axis). Rayleigh tests revealed the set of locations in topic space at which these across-participant
299 distributions exhibited reliable peaks (blue arrows in Fig. 7B reflect significant peaks at $p < 0.05$,
300 corrected). We observed that the locations traversed by nearly the entire video trajectory exhibited
301 such peaks. In other words, participants exhibited similar trajectories that also matched the
302 trajectory of the original video (Fig. 7C). This is especially notable when considering the fact that
303 the number of events participants recalled (dots in Fig. 7C) varied considerably across people, and
304 that every participant used different words to describe what they had remembered happening in
305 the video. Differences in the numbers of remembered events appear in participants' trajectories
306 as differences in the sampling resolution along the trajectory. We note that this framework also
307 provides a means of disentangling classic "proportion recalled" measures (i.e., the proportion
308 of video events described in participants' recalls) from participants' abilities to recapitulate the
309 overall unfolding of the original video's content (i.e., the similarity between the shapes of the
310 original video trajectory and that defined by each participant's recounting of the video).

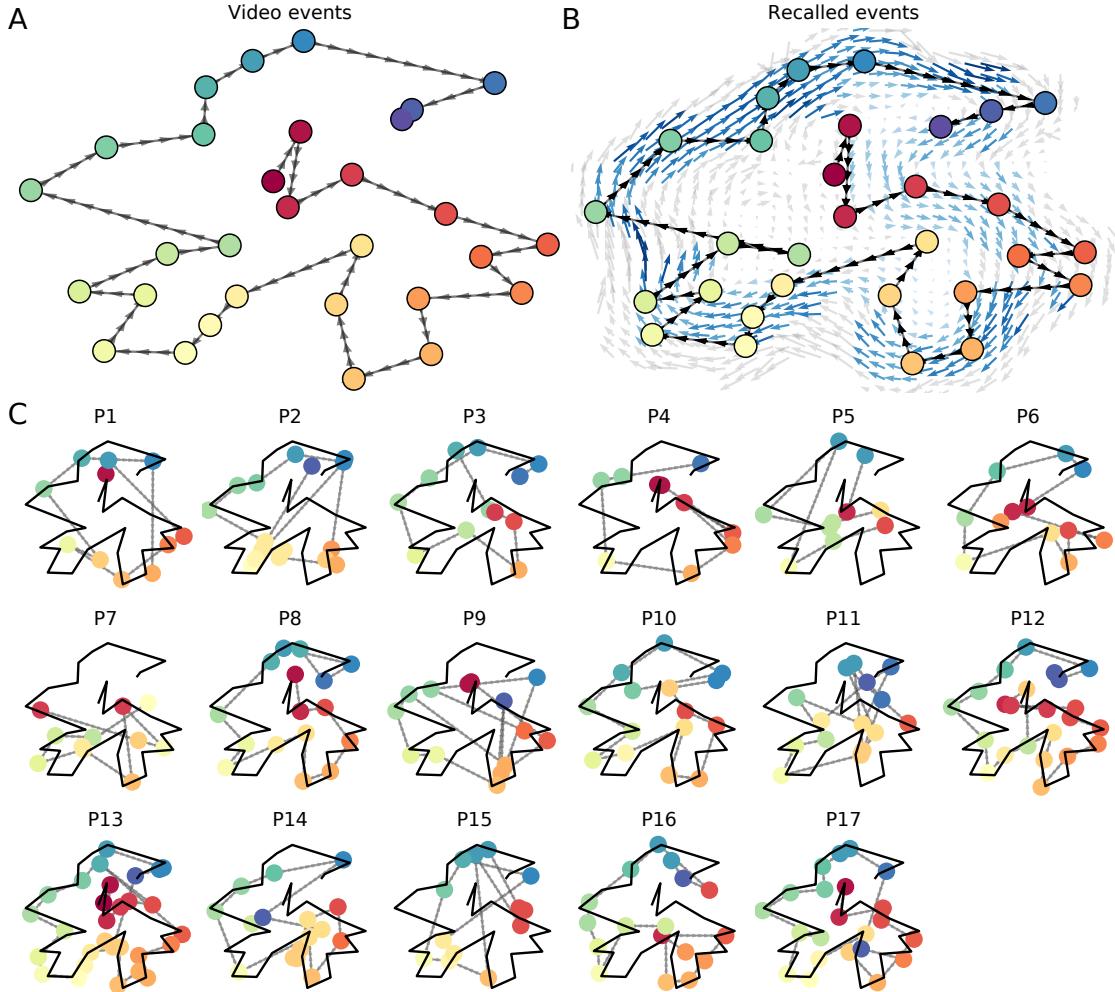


Figure 7: Trajectories through topic space capture the dynamic content of the video and recalls. All panels: the topic proportion matrices have been projected onto a shared two-dimensional space using UMAP. **A.** The two-dimensional topic trajectory taken by the episode of *Sherlock*. Each dot indicates an event identified using the HMM (see *Methods*); the dot colors denote the order of the events (early events are in red; later events are in blue), and the connecting lines indicate the transitions between successive events. **B.** The average two-dimensional trajectory captured by participants' recall sequences, with the same format and coloring as the trajectory in Panel A. To compute the event positions, we matched each recalled event with an event from the original video (see *Results*), and then we averaged the positions of all events with the same label. The arrows reflect the average transition direction through topic space taken by any participants whose trajectories crossed that part of topic space; blue denotes reliable agreement across participants via a Rayleigh test ($p < 0.05$, corrected). **C.** The recall topic trajectories (gray) taken by each individual participant (P1–P17). The video's trajectory is shown in black for reference. Here, events (dots) are colored by their matched video event (Panel A).

311 In addition to the more “holistic” measure of memory described in the previous section, our
312 framework also affords the ability to drill down to individual words and quantify how each word
313 relates to the memorability of each event. The results displayed in Figures 3C and 5A suggest that
314 certain events were remembered better than others. Given this, we next asked whether the
315 events were generally remembered well or poorly tended to reflect particular content. Because
316 our analysis framework projects the dynamic video content and participants’ recalls into a shared
317 space, and because the dimensions of that space represent topics (which are, in turn, sets of weights
318 over words in the vocabulary), we are able to recover the weighted combination of words that make
319 up any point (i.e., topic vector) in this space. We first computed the average precision with which
320 participants recalled each of the 30 video events (Fig. 8A; note that this result is analogous to a serial
321 position curve created from our continuous recall quality metric). We then computed a weighted
322 average of the topic vectors for each video event, where the weights reflected how reliably each
323 event was recalled. To visualize the result, we created a “wordle” image (Mueller et al., 2018) where
324 words weighted more heavily by better-remembered topics appear in a larger font (Fig. 8B, green
325 box). Across the full video, content that reflected topics necessary to convey the central focus of the
326 video (e.g., the names of the two main characters, “Sherlock” and “John”, and the address of a major
327 recurring location, “221B Baker Street”) were best remembered. An analogous analysis revealed
328 which themes were poorly remembered. Here in computing the weighted average over events’
329 topic vectors, we weighted each event in *inverse* proportion to how well it was remembered (Fig. 8B,
330 red box). The least well-remembered video content reflected information not necessary to later
331 convey a general summary of the video, such as the proper names of relatively minor characters
332 (e.g., “Mike,” “Molly,” and “Lestrade”) and locations (e.g., “St. Bartholomew’s Hospital”).

333 A similar result emerged from assessing the topic vectors for individual video and recall events
334 (Fig. 8C). Here, for each of the three best- and worst-remembered video events, we have constructed
335 two wordles: one from the original video event’s topic vector (left) and a second from the average
336 recall topic vector for that event (right). The three best-remembered events (circled in green)
337 correspond to scenes important to the central plot-line: a mysterious figure spying on John in a
338 phone booth; John meeting Sherlock at Baker St. to discuss the murders; and Sherlock laying

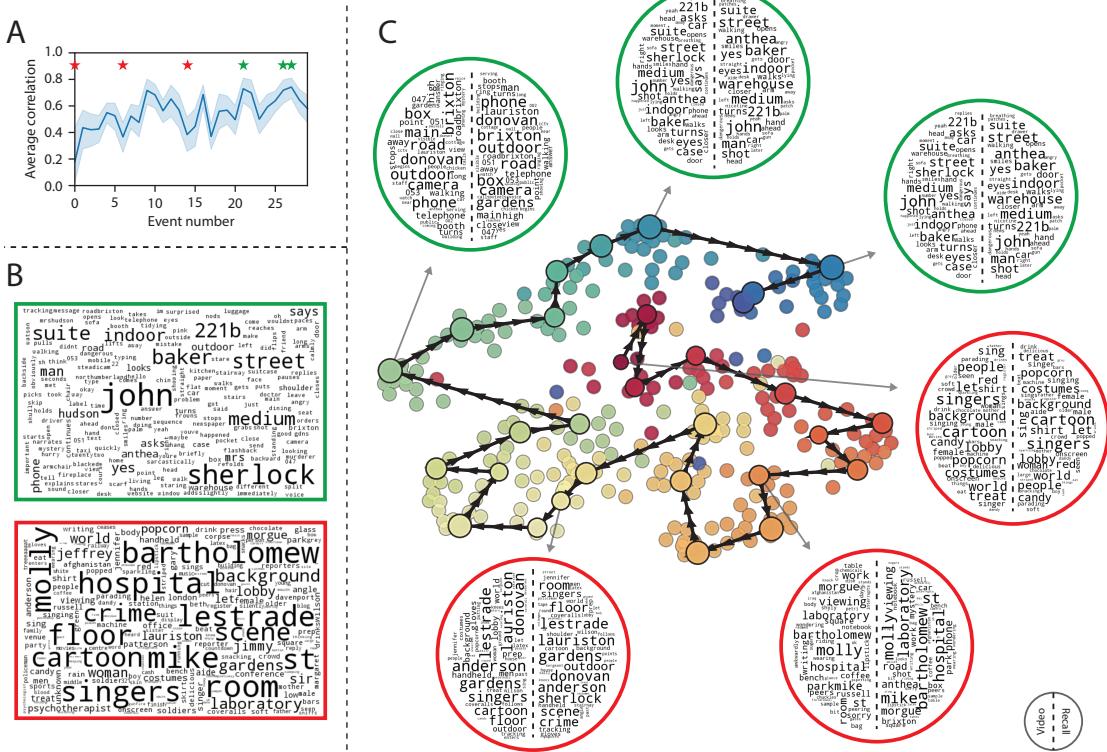


Figure 8: Language used in the most and least memorable events. **A.** Average precision (video event-recall event topic vector correlation) across participants for each video event. Error bars denote bootstrap-derived across-participant 95% confidence intervals. The stars denote the three best-remembered events (green) and worst-remembered events (red). **B.** Wordles comprising the top 200 highest-weighted words reflected in the weighted-average topic vector across video events. Green: video events were weighted by how well the topic vectors derived from recalls of those events matched the video events' topic vectors (Panel A). Red: video events were weighted by the inverse of how well their topic vectors matched the recalled topic vectors. **C.** The set of all video and recall events is projected onto the two-dimensional space derived in Figure 7. The dots outlined in black denote video events (dot size reflects the average correlation between the video event's topic vector and the topic vectors from the closest matching recalled events from each participant; bigger dots denote stronger correlations). The dots without black outlines denote recalled events. All dots are colored using the same scheme as Figure 7A. Wordles for several example events are displayed (green: three best-remembered events; red: three worst-remembered events). Within each circular wordle, the left side displays words associated with the topic vector for the video event, and the right side displays words associated with the (average) recall event topic vector, across all recall events matched to the given video event.

339 a trap to catch the killer. Meanwhile, the three worst-remembered events (circled in red) reflect
340 scenes that are non-essential to summarizing the narrative's structure: the video of singing cartoon
341 characters participants viewed prior to the main episode; John asking Molly about Sherlock's habit
342 of over-analyzing people; and Sherlock noticing evidence of Anderson's and Donovan's affair.

343 The results thus far inform us about which aspects of the dynamic content in the episode partic-
344 ipants watched were preserved or altered in participants' memories. We next carried out a series
345 of analyses aimed at understanding which brain structures might facilitate these preservations
346 and transformations between the external world and memory. In the first analysis, we sought
347 to identify brain structures that were sensitive to the dynamic unfolding of the video's content,
348 as characterized by its topic trajectory. We used a searchlight procedure to identify clusters of
349 voxels whose activity patterns displayed a proximal temporal correlation structure (as participants
350 watched the video) matching that of the original video's topic proportions (Fig. 9A; see *Methods* for
351 additional details). In a second analysis, we sought to identify brain structures whose responses
352 (during video viewing) reflected how each participant would later structure their recounting of the
353 video. We used an analogous searchlight procedure to identify clusters of voxels whose proximal
354 temporal correlation matrices matched that of the topic proportions for each individual's recall
355 (Figs. 9B; see *Methods* for additional details). To ensure our searchlight procedure identified re-
356 gions *specifically* sensitive to the temporal structure of the video or recalls (i.e., rather than those
357 with a temporal autocorrelation length similar to that of the video/recalls), we performed a phase
358 shift-based permutation correction (see *Methods* for additional details). As shown in Figure 9C, the
359 video-driven searchlight analysis revealed a distributed network of regions that may play a role in
360 processing information relevant to the narrative structure of the video. Similarly, the recall-driven
361 searchlight analysis revealed a second network of regions (Fig. 9D) that may facilitate a person-
362 specific transformation of one's experience into memory. In identifying regions whose responses
363 to ongoing experiences reflect how those experiences will be remembered later, this latter analysis
364 extends classic *subsequent memory analyses* (e.g., Paller and Wagner, 2002) to domain of naturalistic
365 stimuli.

366 The searchlight analyses described above yielded two distributed networks of brain regions,

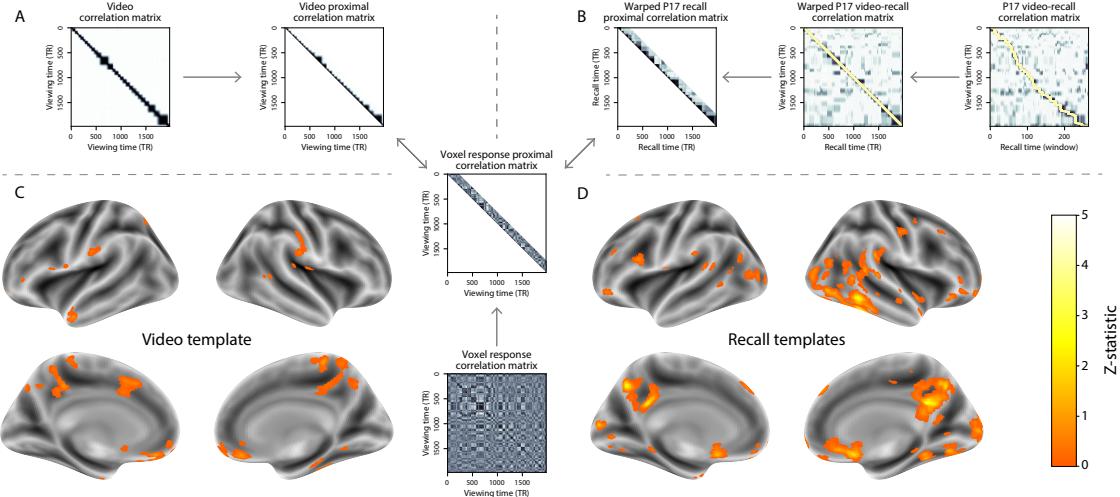


Figure 9: Brain structures that underlie the transformation of experience into memory. **A.** We isolated the proximal diagonals from the upper triangle of the video correlation matrix, and applied this same diagonal mask to the voxel response correlation matrix for each cube of voxels in the brain. We then searched for brain regions whose activation timeseries consistently exhibited a similar proximal correlational structure to the video model, across participants. **B.** We used dynamic time warping (Berndt and Clifford, 1994) to align each participant's recall timeseries to the TR timeseries of the video. We then applied the same diagonal mask used in Panel A to isolate the proximal temporal correlations and searched for brain regions whose activation timeseries for an individual consistently exhibited a similar proximal correlational structure to each individual's recall. **C.** We identified a network of regions sensitive to the narrative structure of participants' ongoing experience. The map shown is thresholded at $p < 0.05$, corrected. **D.** We also identified a network or regions sensitive to how individuals would later structure the video's content in their recalls. The map shown is thresholded at $p < 0.05$, corrected.

whose activity timecourses mirrored to the temporal structure of the video (Fig. 9C) or participants' eventual recalls (Fig. 9D). We next sought to gain greater insight into the structures and functional networks our results reflected. To accomplish this, we performed an additional, exploratory analysis using Neurosynth (Yarkoni et al., 2011). Given an arbitrary statistical map as input, Neurosynth performs a massive automated meta-analysis, returning a ranked list of terms reported in papers with similar significance maps. We ran Neurosynth on the significance maps for the video- and recall-driven searchlight analyses. These maps, along with the 10 terms with maximally similar meta-analysis images identified by Neurosynth are shown in Figure 10.

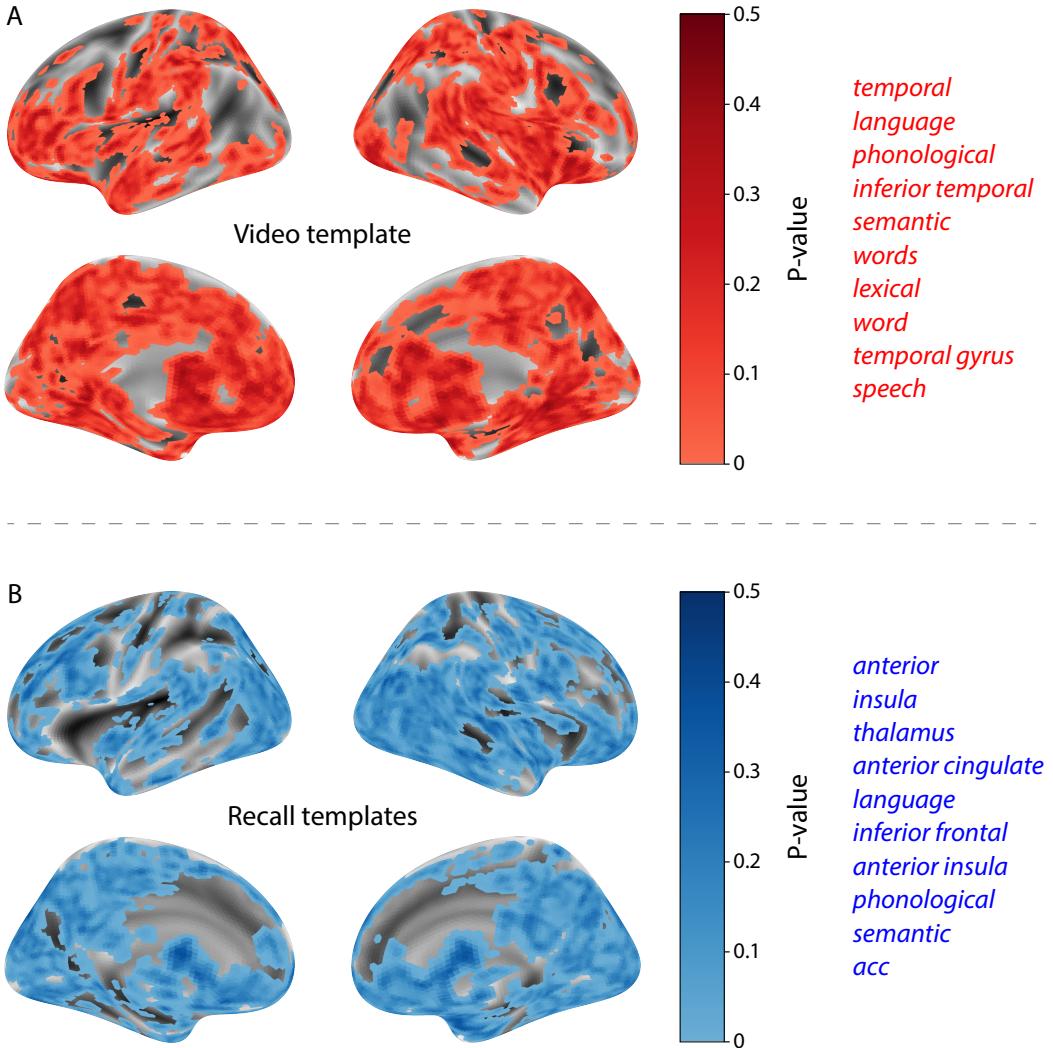


Figure 10: Decoding distributed statistical maps via Neurosynth meta-analyses. **A.** Video-searchlight significance and top 10 decoded terms. We constructed a map of the permutation-derived p -values for the video-driven searchlight analysis (Fig. 9A, C) at each voxel with a positive permutation-derived z -score. The top 10 terms decoded from this significance map are shown in red. **B.** Recall-searchlight significance and top 10 decoded terms. We constructed a map of the permutation-derived p -values for the recall-driven searchlight analysis (Fig. 9A, C) at each voxel with a positive permutation-derived z -score. The top 10 terms decoded from this significance map are shown in blue.

375 **Discussion**

376 Our work casts remembering as reproducing (behaviorally and neurally) the topic trajectory, or
377 shape, of an experience. This view draws inspiration from prior work aimed at elucidating
378 the neural and behavioral underpinnings of how we process dynamic naturalistic experiences
379 and remember them later. One approach to identifying neural responses to naturalistic stimuli
380 (including experiences) entails building a model of the stimulus and searching for brain regions
381 whose responses are consistent with the model. In prior work, a series of studies from Uri Hasson's
382 group (Lerner et al., 2011; Simony et al., 2016; Chen et al., 2017; Baldassano et al., 2017; Zadbood
383 et al., 2017) have extended this approach with a clever twist: rather than building an explicit
384 stimulus model, these studies instead search for brain responses (while experiencing the stimulus)
385 that are reliably similar across individuals. So called *inter-subject correlation* (ISC) and *inter-subject*
386 *functional connectivity* (ISFC) analyses effectively treat other people's brain responses to the stimulus
387 as a "model" of how its features change over time. By contrast, in our present work, we use topic
388 models to construct an explicit content model directly from the stimulus (i.e., the topic trajectory
389 of the video). Projecting each participant's recall into a space shared by both the stimulus and
390 other participants then allows us to compare recalls both directly to the stimulus and to each other.
391 Similarly, prior work introducing the use of HMMs to discover latent event structure in naturalistic
392 stimuli and recall (Baldassano et al., 2017) used between-subjects cross-validation to identify event
393 boundaries shared across participants, and between stimulus and recall. Our framework allows
394 us to break from the restriction of a common, shared event-timeseries and identify the unique
395 *resolution* of each participant's recall event structure, and how that may differ from the video and
396 that of other participants.

397 While a large number of language models exist (e.g., WAS, LSA, word2vec, universal sentence
398 encoder; Steyvers et al., 2004; Landauer et al., 1998; Mikolov et al., 2013; Cer et al., 2018), here
399 we use latent dirichlet allocation (LDA)-based topic models for a few reasons. First, topic models
400 capture the *essence* of a text passage devoid of the specific set and order of words used. This was
401 an important feature of our model since different people may accurately recall a scene using very

402 different language. Second, words can mean different things in different contexts (e.g. “bat” may
403 be the act of hitting a baseball, the object used for that action, or as a flying mammal). Topic
404 models are robust to this, allowing words to exist as part of multiple topics. Last, topic models
405 provide a straightforward means to recover the weights for the particular words comprising a topic,
406 enabling easy interpretation of an event’s contents (e.g. Fig. 8). Other models such as Google’s
407 Universal Sentence Encoder offer a context-sensitive encoding of text passages, but the encoding
408 space is complex and non-linear, and thus recovering the original words used to fit the model is
409 not straightforward. However, it’s worth pointing out that our framework is divorced from the
410 particular choice of language model. Moreover, many of the aspects of our framework could be
411 swapped out for other choices. For example, the language model, the timeseries segmentation
412 model and the video-recall matching function could all be customized for the particular problem.
413 Indeed for some problems, recovery of the particular recall words may not be necessary, and thus
414 other text-modeling approaches (such as universal sentence encoder) may be preferable. Future
415 work will explore the influence of particular model choices on the framework’s efficacy.

416 In extending classical free recall analyses to our naturalistic memory framework, we recovered
417 two patterns of recall dynamics central to list-learning studies: a heightened probability of initiating
418 recall with the first presented “item” (in our case, video events; Fig. 3A) and a strong bias toward
419 transitioning from recalling a given event to recalling the one immediately following it (Fig. 3B).
420 However, equally noteworthy are the typical free recall results *not* recovered in these analyses,
421 as each highlights a fundamental difference between the list-learning paradigm and naturalistic
422 memory paradigms like the one employed in the present study. The most noticeable departure
423 from hallmark free recall dynamics in these findings is the apparent lack of a serial position effect in
424 Figure 3C, which instead shows greater and lesser recall probabilities for events distributed across
425 the video. Stimuli in free recall experiments most often comprise lists of simple, common words,
426 presented to participants in a random order. (In fact, numerous word pools have been developed
427 based on these criteria; e.g., Friendly et al., 1982). These stimulus qualities enable two assumptions
428 that are central to word list analyses, but frequently do not hold for real-world experiences. First,
429 researchers conducting list-learning studies may assume that the content at each presentation index

430 is essentially equal, and does not possess attributes that would render it, on average, more or less
431 memorable than others. Such is rarely the case with real-world experiences or experiments meant
432 to approximate them, and the effects of both intrinsic and observer-dependent factors on stimulus
433 memorability are well established (for review see Chun and Turk-Browne, 2007; Bylinskii et al.,
434 2015; Tyng et al., 2017). Second, the random ordering of list items ensures that (across participants,
435 on average) there is no relationship between the thematic similarity of individual stimuli and their
436 presentation positions—in other words, two successively presented items are no more likely to be
437 highly semantically similar than they are to be highly dissimilar. In most cases, the exact opposite
438 is true of real-world episodes. Our internal thoughts, our actions, and the physical state of the
439 world around us all tend to follow a direct, causal progression. As a result, each moment of our
440 experience tends to be inherently more similar to surrounding moments than to those in the distant
441 past or future. Memory literature has termed this strong temporal autocorrelation “context,” and
442 in various media that depict real-world events (e.g., movies or written stories), we recognize
443 it as a *narrative structure*. While a random word list (by definition) has no such structure, the
444 logical progression between ideas and actions in a naturalistic stimulus prompts the rememberer
445 to recount presented events in order, starting with the beginning. This tendency is reflected in our
446 findings’ second departure from typical free recall dynamics: a lack of increased probability of first
447 recall for end-of-sequence events (Fig. 3A).

448 Because they disregard presentation order-dependent variability in the stimulus content, anal-
449 yses such as those in Figure 3 enable a more sensitive analysis of presentation order-dependent
450 temporal dynamics in free recall. Yet by the same token, they paint a wholly incomplete picture of
451 memory for naturalistic episodes. In an attempt to address this shortcoming, we have developed a
452 framework in the present study that characterizes the explicit semantic content of the stimulus and
453 subsequent recalls. However, sensitivity to stimulus and recall content introduces a new challenge:
454 distinguishing between levels of recall quality for a stimulus (e.g., an event) that is considered to
455 have been “remembered.” When modeling memory in an experimental setting, recall quality for
456 individual events is often cast as binary (e.g., a given list item was simply either remembered or
457 not remembered). Various models of memory (e.g., Yonelinas, 2002) attempt to improve upon this

458 by including confidence ratings, rendering this binary judgement instead categorical. To better
459 evaluate naturalistic memory quality, we introduce a continuous metric (*precision*), which reflects
460 the level of completeness of a participant’s recall for a feature-rich experience. Additionally, recall
461 quality for a single event is typically assessed independently from that for all other events (e.g., it
462 is difficult to “compare” a participant’s binary recall success for list item 1 to that of list item 10).
463 The second novel metric we introduce (*distinctiveness*) is based on analyzing of the correlational
464 structure of an individual’s full set of recall events, and reflects the specificity of their memory
465 for a single experienced event. We find that both of these metrics relate to the overall number of
466 video events participants successfully recalled, and that our precision metric additionally relates to
467 Chen et al. (2017)’s hand-annotated memory scores. Though we do not find participants’
468 average recall distinctiveness related to the hand-annotated memory scores, this is not entirely
469 surprising given the divergence of behavior they capture. In hand-scoring each participant’s ver-
470 bal recall for each of 50 (manually-delimited) scenes, “[a] scene was counted as recalled if the
471 participant described any part of the scene” (Chen et al., 2017). In other words, both an extensive
472 description of a scene’s content and a brief mention of some subset of its content were (binarily)
473 considered equally successful recalls. By contrast, we identify the event structure in participants’
474 recalls in an unsupervised manner, independent of the video event-timeseries, prior to mapping
475 between video and recall content. Our HMM-based event-segmentation produces boundaries
476 between timepoints where the topic proportions shift in a substantial way, and because a small
477 handful of words is unlikely to contribute significantly to the topic proportions for any sliding win-
478 dow, such brief scene descriptions will most often not begat a sufficiently large shift in the resulting
479 topic proportions for the HMM to identify an event boundary. Instead, they will be grouped with
480 a neighboring event, consequently lowering that event’s distinctiveness score and by extension,
481 the participant’s overall distinctiveness score. This is in essence the qualitative difference between
482 distinctive and indistinctive recall, and reflects the comparison shown in Figure 6C. Intriguingly,
483 prior studies show that pattern separation, or the ability to cleanly discriminate between similar
484 experiences, is impaired in many cognitive disorders as well as natural aging (Stark et al., 2010;
485 Yassa et al., 2011; Yassa and Stark, 2011). Future work might explore whether and how these

486 metrics compare between cognitively impoverished groups and healthy controls.

487 In the analyses outlined in Figure 9, we identified two networks of brain regions whose re-
488 sponses during video viewing were consistent with the temporal structure of the video and recall
489 topic trajectories, respectively. The network identified by the video trajectory analysis included the
490 ventromedial prefrontal cortex, left anterior temporal lobe, superior parietal and dorsal anterior
491 cingulate cortex. The network from the video-recall trajectory analysis also included the ventro-
492 medial prefrontal and superior parietal cortices, in addition to the posterior medial cortex (PMC)
493 and the inferior temporal regions. Notably, Chen et al. (2017) also observed the PMC in a number
494 of analyses including one that searched for regions whose activity patterns during encoding were
495 reinstated during free recall. The PMC has been consistently identified in studies involving stimuli
496 with meaningfully structured events Cohn-Sheely and Ranganath (2017). Further, the PMC is part
497 of the “posterior medial” system, a network of brain regions thought to represent situation models
498 Zacks et al. (2007) in support of memory, spatial navigation and social cognition (Ranganath and
499 Ritchey, 2012). Given that we constructed our video-recall searchlight model to capture temporal
500 structure in the episode’s semantic content (and how one’s later recall aligns with that structure),
501 we speculate that the PMC may play a role in constructing mnemonic events from meaningfully
502 structured experiences.

503 Decoding the associated significance maps with Neurosynth revealed two intriguing results.
504 First, the top 10 terms returned for the video-driven searchlight significance map were centered
505 around themes of language and semantic meaning (Fig. 10A). In other words, the voxels identified
506 as more reflective of the video’s temporal structure (i.e., voxels with lower permutation correction-
507 derived p -values), as defined by our model, were most likely to be reported as active in studies
508 focused on the the neural underpinnings of semantic processing. This finding is interesting, as our
509 model specifically captures the temporal structure of the video’s *semantic* content (e.g., as opposed
510 to that of the visual, auditory, or affective content). This suggests that the network of structures
511 displayed in Figure 9C may play a roll in processing the evolving semantic structure of ongoing
512 experiences.

513 Our second searchlight analysis identified a largely separate network of regions (Fig. 9D)

whose patterns of activity as participants viewed the video reflected the idiosyncratic structure of each individual's later recall. Decoding the associated significance map yielded a set of terms that primarily reflected names of specific structural regions (such as "thalamus," "anterior insula," "anterior cingulate" and "inferior frontal"; Fig. 10B). Interestingly, these regions share membership in a common, large-scale functional network (termed the "salience network") involved in detecting and processing affective cues. In particular, the latter three regions have been implicated in functions relevant to assigning personal meaning to an experience, including: ascribing subjective value to raw, sensory input (Medford and Critchley, 2010); modulating semantic and phonological processing in response to personally salient stimuli (Kelly et al., 2007); and directing and reallocating attention and working memory resources towards the most relevant stimuli (Menon and Uddin, 2010). This suggests that the network of structures displayed in Figure 9D may play a role in transforming and restructuring ongoing experiences through the lens of one's own personal values as they are encoded in memory.

Our work has broad implications for how we characterize and assess memory in real-world settings, such as the classroom or physician's office. For example, the most commonly used classroom evaluation tools involve simply computing the proportion of correctly answered exam questions. Our work indicates that this approach is only loosely related to what educators might really want to measure: how well did the students understand the key ideas presented in the course? Under this typical framework of assessment, the same exam score of 50% could be ascribed to two very different students: one who attended the full course but struggled to learn more than a broad overview of the material, and one who attended only half of the course but understood the material perfectly. Instead, one could apply our computational framework to build explicit content models of the course material and exam questions. This approach would provide a more nuanced and specific view into which aspects of the material students had learned well (or poorly). In clinical settings, memory measures that incorporate such explicit content models might also provide more direct evaluations of patients' memories.

540 **Methods**

541 **Experimental design and data collection**

542 Data were collected by Chen et al. (2017). In brief, participants ($n = 22$) viewed the first 48 minutes
543 of “A Study in Pink”, the first episode of the BBC television series *Sherlock*, while fMRI volumes
544 were collected (TR = 1500 ms). Participants were pre-screened to ensure they had never seen any
545 episode of the show before. The stimulus was divided into a 23 min (946 TR) and a 25 min (1030 TR)
546 segment to mitigate technical issues related to the scanner. After finishing the clip, participants
547 were instructed to (quoting from Chen et al., 2017) “describe what they recalled of the [episode]
548 in as much detail as they could, to try to recount events in the original order they were viewed
549 in, and to speak for at least 10 minutes if possible but that longer was better. They were told that
550 completeness and detail were more important than temporal order, and that if at any point they
551 realized they had missed something, to return to it. Participants were then allowed to speak for
552 as long as they wished, and verbally indicated when they were finished (e.g., ‘I’m done’).” Five
553 participants were dropped from the original dataset due to excessive head motion (2 participants),
554 insufficient recall length (2 participants), or falling asleep during stimulus viewing (1 participant),
555 resulting in a final sample size of $n = 17$. For additional details about the experimental procedure
556 and scanning parameters, see Chen et al. (2017). The experimental protocol was approved by
557 Princeton University’s Institutional Review Board.

558 After preprocessing the fMRI data and warping the images into a standard (3 mm³ MNI) space,
559 the voxel activations were z-scored (within voxel) and spatially smoothed using a 6 mm (full width
560 at half maximum) Gaussian kernel. The fMRI data were also cropped so that all video-viewing
561 data were aligned across participants. This included a constant 3 TR (4.5 s) shift to account for the
562 lag in the hemodynamic response. (All of these preprocessing steps followed Chen et al., 2017,
563 where additional details may be found.)

564 The video stimulus was divided into 1,000 fine-grained “scenes” and annotated by an inde-
565 pendent coder. For each of these 1,000 scenes, the following information was recorded: a brief
566 narrative description of what was happening, the location where the scene took place, whether

567 that location was indoors or outdoors, the names of all characters on-screen, the name(s) of the
568 character(s) in focus in the shot, the name(s) of the character(s) currently speaking, the camera
569 angle of the shot, a transcription of any text appearing on-screen, and whether or not there was
570 music present in the background. Each scene was also tagged with its onset and offset time, in
571 both seconds and TRs.

572 **Data and code availability**

573 The fMRI data we analyzed are available online [here](#). The behavioral data and all of our analysis
574 code may be downloaded [here](#).

575 **Statistics**

576 All statistical tests performed in the behavioral analyses were two-sided. All statistical tests per-
577 formed in the neural data analyses were two-sided, except for the permutation-based thresholding,
578 which was one-sided. In this case, we were specifically interested in identifying voxels whose ac-
579 tivation time series reflected the temporal structure of the video and recall trajectories to a *greater*
580 extent than that of the phase-shifted trajectories.

581 **Modeling the dynamic content of the video and recall transcripts**

582 **Topic modeling**

583 The input to the topic model we trained to characterize the dynamic content of the video comprised
584 998 hand-generated annotations of short (mean: 2.96s) scenes spanning the video clip (Chen et al.,
585 2017 generated 1000 annotations total; we removed two referring to the break between the first
586 and second scan sessions, during which no fMRI data was collected). We concatenated the text
587 for all of the annotated features within each segment, creating a “bag of words” describing each
588 scene and performed some minor preprocessing (e.g., stemming possessive nouns and removing
589 punctuation). We then re-organized the text descriptions into overlapping sliding windows span-
590 ning (up to) 50 scenes each. In other words, we created a “context” for each scene comprising the

591 text descriptions of the preceding 25 scenes, the present scene, and the following 24 scenes. To
592 model the “context” for scenes near the beginning and end of the video (i.e., within 25 scenes of
593 the beginning or end), we created overlapping sliding windows that grew in size from one scene
594 to the full length, then similarly tapered their length at the end. This additionally ensured that
595 each scene’s content was represented in the text corpus an equal number of times.

596 We trained our model using these overlapping text samples with `scikit-learn` (version 0.19.1;
597 Pedregosa et al., 2011), called from our high-dimensional visualization and text analysis software,
598 `HyperTools` (Heusser et al., 2018b). Specifically, we used the `CountVectorizer` class to transform
599 the text from each window into a vector of word counts (using the union of all words across all
600 scenes as the “vocabulary,” excluding English stop words); this yielded a number-of-windows
601 by number-of-words *word count* matrix. We then used the `LatentDirichletAllocation` class
602 (`topics=100, method='batch'`) to fit a topic model (Blei et al., 2003) to the word count matrix,
603 yielding a number-of-windows (1047) by number-of-topics (100) *topic proportions* matrix. The
604 topic proportions matrix describes the gradually evolving mix of topics (latent themes) present in
605 each scene. Next, we transformed the topic proportions matrix to match the 1976 fMRI volume
606 acquisition times. We assigned each topic vector to the timepoint (in seconds) midway between the
607 beginning of the first scene and the end of the last scene in its corresponding sliding text window.
608 By doing so, we warped the linear temporal distance between consecutive topic vectors to align
609 with the inconsistent temporal distance between consecutive annotations (whose durations varied
610 greatly). We then rescaled these timepoints to 1.5s TR units, and used linear interpolation to
611 estimate a topic vector for each TR. This resulted in a number-of-TRs (1976) by number-of-topics
612 (100) matrix.

613 We created similar topic proportions matrices using hand-annotated transcripts of each par-
614 ticipant’s recall of the video (annotated by Chen et al., 2017). We tokenized the transcript into a
615 list of sentences, and then re-organized the list into overlapping sliding windows spanning (up
616 to) 10 sentences each, analogously to how we parsed the video annotations. In turn, we trans-
617 formed each window’s sentences into a word count vector (using the same vocabulary as for the
618 video model), then used the topic model already trained on the video scenes to compute the most

probable topic proportions for each sliding window. This yielded a number-of-windows (range: 83–312) by number-of-topics (100) topic proportions matrix for each participant. These reflected the dynamic content of each participant’s recalls. Note: for details on how we selected the video and recall window lengths and number of topics, see *Supporting Information* and Figure S1.

623 Parsing topic trajectories into events using Hidden Markov Models

624 We parsed the topic trajectories of the video and participants’ recalls into events using Hidden
625 Markov Models (Rabiner, 1989). Given the topic proportions matrix (describing the mix of topics
626 at each timepoint) and a number of states, K , an HMM recovers the set of state transitions that
627 segments the timeseries into K discrete states. Following Baldassano et al. (2017), we imposed an
628 additional set of constraints on the discovered state transitions that ensured that each state was
629 encountered exactly once (i.e., never repeated). We used the BrainIAK toolbox (Capota et al., 2017)
630 to implement this segmentation.

631 We used an optimization procedure to select the appropriate K for each topic proportions
632 matrix. Prior studies on narrative structure and processing have shown that we both perceive
633 and internally represent the world around us at multiple, hierarchical timescales (e.g., Hasson
634 et al., 2008; Lerner et al., 2011; Hasson et al., 2015; Chen et al., 2017; Baldassano et al., 2017, 2018).
635 However, for the purposes of our framework, we sought to identify the single timeseries of event-
636 representations that is emphasized *most heavily* in the temporal structure of the video and of each
637 participant’s recall. We quantified this as the set of K states that maximized the similarity between
638 topic vectors for timepoints comprising each state, while minimizing the similarity between topic
639 vectors for timepoints across different states. Specifically, we computed (for each matrix)

$$\operatorname{argmax}_K [W_1(a, b)],$$

640 where a was the distribution of within-state topic vector correlations, and b was the distribution of
641 across-state topic vector correlations . We computed the first Wasserstein distance (W_1 ; also known
642 as “earth mover’s distance”; Dobrushin, 1970; Ramdas et al., 2017) between these distributions for a

643 large range of possible K -values (range [2,50]), and selected the K that yielded the maximum value.
644 Figure 2B displays the event boundaries returned for the video, and Figure S4 displays the event
645 boundaries returned for each participant's recalls. See Figure S6 for the optimization functions
646 for the video and recalls. After obtaining these event boundaries, we created stable estimates of
647 the content represented in each event by averaging the topic vectors across timepoints between
648 each pair of event boundaries. This yielded a number-of-events by number-of-topics matrix for
649 the video and recalls from each participant.

650 **Naturalistic extensions of classic list-learning analyses**

651 In traditional list-learning experiments, participants view a list of items (e.g., words) and then recall
652 the items later. Our video-recall event matching approach affords us the ability to analyze memory
653 in a similar way. The video and recall events can be treated analogously to studied and recalled
654 "items" in a list-learning study. We can then extend classic analyses of memory performance and
655 dynamics (originally designed for list-learning experiments) to the more naturalistic video recall
656 task used in this study.

657 Perhaps the simplest and most widely used measure of memory performance is *accuracy*—i.e.,
658 the proportion of studied (experienced) items (in this case, video events) that the participant later
659 remembered. Chen et al. (2017) used this method to rate each participant's memory quality by
660 computing the proportion of (50, manually identified) scenes mentioned in their recall. We found a
661 strong across-participants correlation between these independent ratings and the proportion of (30,
662 HMM-identified) video events matched to participants' recalls (Pearson's $r(15) = 0.71, p = 0.002$).
663 We further considered a number of more nuanced memory performance measures that are typically
664 associated with list-learning studies. We also provide a software package, Quail, for carrying out
665 these analyses (Heusser et al., 2017).

666 **Probability of first recall (PFR).** PFR curves (Welch and Burnett, 1924; Postman and Phillips,
667 1965; Atkinson and Shiffrin, 1968) reflect the probability that an item will be recalled first as a
668 function of its serial position during encoding. To carry out this analysis, we initialized a number-

669 of-participants (17) by number-of-video-events (30) matrix of zeros. Then for each participant, we
670 found the index of the video event that was recalled first (i.e., the video event whose topic vector
671 was most strongly correlated with that of the first recall event) and filled in that index in the matrix
672 with a 1. Finally, we averaged over the rows of the matrix, resulting in a 1 by 30 array representing
673 the proportion of participants that recalled an event first, as a function of the order of the event's
674 appearance in the video (Fig. 3A).

675 **Lag conditional probability curve (lag-CRP).** The lag-CRP curve (Kahana, 1996) reflects the
676 probability of recalling a given item after the just-recalled item, as a function of their relative
677 encoding positions (or *lag*). In other words, a lag of 1 indicates that a recalled item was presented
678 immediately after the previously recalled item, and a lag of -3 indicates that a recalled item came
679 3 items before the previously recalled item. For each recall transition (following the first recall),
680 we computed the lag between the current recall event and the next recall event, normalizing by
681 the total number of possible transitions. This yielded a number-of-participants (17) by number-
682 of-lags (-29 to +29; 61 lags total) matrix. We averaged over the rows of this matrix to obtain a
683 group-averaged lag-CRP curve (Fig. 3B).

684 **Serial position curve (SPC).** SPCs (Murdock, 1962) reflect the proportion of participants that
685 remember each item as a function of the items' serial positions during encoding. We initialized
686 a number-of-participants (17) by number-of-video-events (30) matrix of zeros. Then, for each
687 recalled event, for each participant, we found the index of the video event that the recalled event
688 most closely matched (via the correlation between the events' topic vectors) and entered a 1 into
689 that position in the matrix. This resulted in a matrix whose entries indicated whether or not each
690 event was recalled by each participant (depending on whether the corresponding entires were
691 set to one or zero). Finally, we averaged over the rows of the matrix to yield a 1 by 30 array
692 representing the proportion of participants that recalled each event as a function of the events'
693 order appearance in the video (Fig. 3C).

694 **Temporal clustering scores.** Temporal clustering describes a participant’s tendency to organize
695 their recall sequences by the learned items’ encoding positions. For instance, if a participant
696 recalled the video events in the exact order they occurred (or in exact reverse order), this would
697 yield a score of 1. If a participant recalled the events in random order, this would yield an expected
698 score of 0.5. For each recall event transition (and separately for each participant), we sorted
699 all not-yet-recalled events according to their absolute lag (i.e., distance away in the video). We
700 then computed the percentile rank of the next event the participant recalled. We averaged these
701 percentile ranks across all of the participant’s recalls to obtain a single temporal clustering score
702 for the participant.

703 **Semantic clustering scores.** Semantic clustering describes a participant’s tendency to recall se-
704 mantically similar presented items together in their recall sequences. Here, we used the topic
705 vectors for each event as a proxy for its semantic content. Thus, the similarity between the seman-
706 tic content for two events can be computed by correlating their respective topic vectors. For each
707 recall event transition, we sorted all not-yet-recalled events according to how correlated the topic
708 vector of *the closest-matching video event* was to the topic vector of the closest-matching video event
709 to the just-recalled event. We then computed the percentile rank of the observed next recall. We
710 averaged these percentile ranks across all of the participant’s recalls to obtain a single semantic
711 clustering score for the participant.

712 **Novel naturalistic memory metrics**

713 **Precision.** We tested whether participants who recalled more events were also more *precise* in
714 their recollections. For each participant, we computed the average correlation between the topic
715 vectors for each recall event and those of its closest-matching video event. This gave a single value
716 per participant representing the average precision across all recalled events. We then correlated
717 these values with both hand-annotated and model-derived (i.e., the number of unique video events
718 matched by a participant’s recall events) memory performance.

719 **Distinctiveness.** We also considered the *distinctiveness* of each recalled event. That is, how unique
720 a participant’s description of a video event was, versus their descriptions of other video events.
721 We hypothesized that participants with high memory performance might describe each event in
722 a more distinctive way (relative to those with lower memory performance who might describe
723 events in a more general way). To test this hypothesis we define a distinctiveness score for each
724 recall event as

$$d(\text{event}) = 1 - \bar{c}(\mathbb{P} \setminus \{\text{event}\}),$$

725 where $\bar{c}(\mathbb{P} \setminus \{\text{event}\})$ is the average correlation between the given recall event’s topic vector and
726 the topic vectors from all other recall events not matched to the same video event (for a single
727 participant). We then averaged these distinctiveness scores across all of the events recalled by the
728 given participant and correlated resulting values with hand-annotated and model derived memory
729 performance scores across-subjects, as above.

730 Note: in all instances where we performed statistical tests involving precision or distinctiveness
731 scores, we used Fisher’s *z*-transformation (Fisher, 1925) to stabilize the variance across the dis-
732 tribution of correlation values prior to performing the test. Similarly, when averaging precision
733 or distinctiveness scores, we *z*-transformed the scores prior to computing the mean, and inverse
734 *z*-transformed the result.

735 Visualizing the video and recall topic trajectories

736 We used the UMAP algorithm (McInnes et al., 2018) to project the 100-dimensional topic space onto
737 a two-dimensional space for visualization (Figs. 7, 8). Importantly, to ensure that all of the trajec-
738 tories were projected onto the *same* lower dimensional space, we computed the low-dimensional
739 embedding on a “stacked” matrix created by vertically concatenating the events-by-topics topic
740 proportions matrices for the video, across-participants average recall and all 17 individual partici-
741 pants’ recalls. We then divided the rows of the result (a total-number-of-events by two matrix) back
742 into separate matrices for the video topic trajectory, across-participant average recall trajectory and

743 the trajectories for each individual participant's recalls (Fig. 7). This general approach for dis-
744 covering a shared low-dimensional embedding for a collections of high-dimensional observations
745 follows Heusser et al. (2018b).

746 We optimized the manifold space for visualization based on two criteria: First, that the 2D
747 embedding of the video trajectory should reflect its original 100-dimensional structure as faithfully
748 as possible. Second, that the path traversed by the embedded video trajectory should intersect
749 itself a minimal number of times. The first criteria helps bolster the validity of visual intuitions
750 about relationships between sections of video content, based on their locations in the embedding
751 space. The second criteria was motivated by the observed low off-diagonal values in the video
752 trajectory's temporal correlation matrix (suggesting that the same topic-space coordinates should
753 not be revisited; see Figure 2A in the main text). For further details on how we created this
754 low-dimensional embedding space, see *Supporting Information*.

755 **Estimating the consistency of flow through topic space across participants**

756 In Figure 7B, we present an analysis aimed at characterizing locations in topic space that dif-
757 ferent participants move through in a consistent way (via their recall topic trajectories). The
758 two-dimensional topic space used in our visualizations (Fig. 7) comprised a 60 x 60 (arbitrary
759 units) square. We tiled this space with a 50 x 50 grid of evenly spaced vertices, and defined a
760 circular area centered on each vertex whose radius was two times the distance between adjacent
761 vertices (i.e., 2.4 units). For each vertex, we examined the set of line segments formed by connecting
762 each pair successively recalled events, across all participants, that passed through this circle. We
763 computed the distribution of angles formed by those segments and the x -axis, and used a Rayleigh
764 test to determine whether the distribution of angles was reliably "peaked" (i.e., consistent across
765 all transitions that passed through that local portion of topic space). To create Figure 7B we drew
766 an arrow originating from each grid vertex, pointing in the direction of the average angle formed
767 by the line segments that passed within its circular radius. We set the arrow lengths to be inversely
768 proportional to the p -values of the Rayleigh tests at each vertex. Specifically, for each vertex we
769 converted all of the angles of segments that passed within 2.4 units to unit vectors, and we set

770 the arrow lengths at each vertex proportional to the length of the (circular) mean vector. We also
771 indicated any significant results ($p < 0.05$, corrected using the Benjamani-Hochberg procedure) by
772 coloring the arrows in blue (darker blue denotes a lower p -value, i.e., a longer mean vector); all
773 tests with $p \geq 0.05$ are displayed in gray and given a lower opacity value.

774 **Searchlight fMRI analyses**

775 In Figure 9, we present two analyses aimed at identifying brain regions whose responses (as par-
776 ticipants viewed the video) exhibited a particular temporal structure. We developed a searchlight
777 analysis wherein we constructed a $5 \times 5 \times 5$ cube of voxels (following Chen et al., 2017) centered on
778 each voxel in the brain, and for each of these cubes, computed the temporal correlation matrix of
779 the voxel responses during video viewing. Specifically, for each of the 1976 volumes collected dur-
780 ing video viewing, we correlated the activity patterns in the given cube with the activity patterns
781 (in the same cube) collected during every other timepoint. This yielded a 1976 by 1976 correlation
782 matrix for each cube. Note: participant 5's scan ended 75s early, and in Chen et al., 2017's publicly
783 released dataset, their scan data was padded to match the length of the other participants'. For
784 our searchlight analyses, we removed this padded data (i.e., the last 50 TRs), resulting in a 1925 by
785 1925 correlation matrix for each cube in participant 5's brain.

786 Next, we constructed a series of "template" matrices: the first reflecting the timecourse of
787 video's topic trajectory, and the others reflecting that of each participant's recall topic trajectory.
788 To construct the video template, we computed the correlations between the topic proportions
789 estimated for every pair of TRs (prior to segmenting the trajectory into discrete events; i.e., the
790 correlation matrix shown in Figs. 2B and 9A). We constructed similar temporal correlation matrices
791 for each participant's recall topic trajectory (Figs. 2D, S4). However, to correct for length differences
792 and potential non-linear transformations between viewing time and recall time, we first used
793 dynamic time warping (Berndt and Clifford, 1994) to temporally align participants' recall topic
794 trajectories with the video topic trajectory. An example correlation matrix before and after warping
795 is shown in Fig. 9B. This yielded a 1976 by 1976 correlation matrix for the video template and for
796 each participant's recall template.

797 The temporal structure of the video’s content (as described by our model) is captured in the
798 block-diagonal structure of the video’s temporal correlation matrix (e.g., Figs. 2B, 9A), with time
799 periods of thematic stability represented as dark blocks of varying sizes. Inspecting the video
800 correlation matrix suggests that the video’s semantic content is highly temporally specific (i.e.,
801 the correlations between topic vectors from distant timepoints are almost entirely near-zero).
802 By contrast, the activity patterns of individual (cubes of) voxels can encode relatively limited
803 information on their own, and their activity frequently contributes to multiple separate functions
804 (Freedman et al., 2001; Sigman and Dehaene, 2008; Charron and Koechlin, 2010; Rishel et al., 2013).
805 By nature, these two attributes give rise to similarities in activity across large timescales that may
806 not necessarily reflect a single task. To enable a more sensitive analysis of brain regions whose shifts
807 in activity patterns mirrored shifts in the semantic content of the video or recalls, we restricted the
808 temporal correlations we considered to timescale of semantic information captured by our model.
809 Specifically, we isolated the upper triangle of the video correlation matrix and created a “proximal
810 correlation mask” that included only diagonals from the upper triangle of the video correlation
811 matrix up to the first that contained no positive correlations. Applying this mask to the full video
812 correlation matrix was analogous to excluding diagonals beyond the corner of the largest diagonal
813 block. In other words, the timescale of temporal correlations we considered corresponded to the
814 longest period of thematic stability in the video, and by extension the longest expected period
815 of thematic stability in participants’ recalls and the longest period of stability we might expect
816 to see in voxel activity arising from processing or encoding video content. Figure 9 shows this
817 proximal correlation mask applied to the temporal correlation matrices for the video, an example
818 participant’s (warped) recall, and an example cube of voxels from our searchlight analyses.

819 To determine which (cubes of) voxel responses matched the video template, we correlated the
820 proximal diagonals from the upper triangle of the voxel correlation matrix for each cube with the
821 proximal diagonals from video template matrix (Kriegeskorte et al., 2008). This yielded, for each
822 participant, a voxelwise map of correlation values. We then performed a one-sample t -test on the
823 distribution of (Fisher z -transformed) correlations at each voxel, across participants. This resulted
824 in a value for each voxel (cube), describing how reliably its timecourse mirrored that of the video.

825 We further sought to ensure that our analysis identified regions where the activations' temporal
826 structure specifically reflected that of the video, rather than regions whose activity was simply
827 autocorrelated at a width similar to the video template's diagonal. To achieve this, we used a phase
828 shift-based permutation procedure, wherein we circularly shifted the video's topic trajectory by
829 a random number of timepoints, computed the resulting "null" video template, and re-ran the
830 searchlight analysis, in full. (For each of the 100 permutations, the same random shift was used for
831 all participants). We z -scored the observed (unshifted) result at each voxel against the distribution
832 of permutation-derived "null" results, and estimated a p -value by computing the proportion of
833 shifted results that yielded larger values. To create the map in Figure 9C, we thresholded out
834 any voxels whose similarity to the unshifted video's structure fell below the 95th percentile of the
835 permutation-derived similarity results.

836 We used an analogous procedure to identify which voxels' responses reflected the recall tem-
837 plates. For each participant, we correlated the proximal diagonals from the upper triangle of the
838 correlation matrix for each cube of voxels with the proximal diagonals from the upper triangle
839 of their (time-warped) recall correlation matrix. As in the video template analysis, this yielded a
840 voxelwise map of correlation coefficients per participant. However, whereas the video analysis
841 compared every participant's responses to the same template, here the recall templates were unique
842 for each participant. As in the analysis described above, we t -scored the (Fisher z -transformed)
843 voxelwise correlations, and used the same permutation procedure we developed for the video
844 responses to ensure specificity to the recall timeseries and assign significance values. To create the
845 map in Figure 9D we again thresholded out any voxels whose correspondence values fell below
846 the 95th percentile of the permutation-derived null distribution.

847 Neurosynth decoding analyses

848 Neurosynth parses a massive online database of over 14,000 neuroimaging studies and constructs
849 meta-analysis images for over 13,000 psychology- and neuroscience-related terms, based on NIfTI
850 images accompanying studies where those terms appear at a high frequency. Then, given a novel
851 image (tagged with its value type; e.g., t -, F - or p -statistics), Neurosynth returns a list of terms whose

meta-analysis images are most similar to this new data. Our permutation procedure yielded, for each of the two searchlight analyses, a voxelwise map of significance (p -statistic) values. These maps describe the extent to which each voxel *specifically* reflected the temporal structure of the video or individuals' recalls (i.e., for each voxel, the proportion of phase-shifted topic vector correlation matrices less similar to the voxel activity correlation matrix than the unshifted video's correlation matrix). We input the two statistical maps described above to Neurosynth to create a list of the 10 most representative terms for each map.

References

- Atkinson, R. C. and Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In Spence, K. W. and Spence, J. T., editors, *The psychology of learning and motivation*, volume 2, pages 89–105. Academic Press, New York.
- Baldassano, C., Chen, J., Zadbood, A., Pillow, J. W., Hasson, U., and Norman, K. A. (2017). Discovering event structure in continuous narrative perception and memory. *Neuron*, 95(3):709–721.
- Baldassano, C., Hasson, U., and Norman, K. A. (2018). Representation of real-world event schemas during narrative perception. *Journal of Neuroscience*, 38(45):9689–9699.
- Berndt, D. J. and Clifford, J. (1994). Using dynamic time warping to find patterns in time series. In *KDD workshop*, volume 10, pages 359–370.
- Blei, D. M. and Lafferty, J. D. (2006). Dynamic topic models. In *Proceedings of the 23rd International Conference on Machine Learning*, ICML '06, pages 113–120, New York, NY, US. ACM.
- Blei, D. M., Ng, A. Y., and Jordan, M. I. (2003). Latent dirichlet allocation. *Journal of Machine Learning Research*, 3:993 – 1022.
- Brunec, I. K., Moscovitch, M. M., and Barense, M. D. (2018). Boundaries shape cognitive representations of spaces and events. *Trends in Cognitive Sciences*, 22(7):637–650.

- 876 Bylinskii, Z., Isola, P., Bainbridge, C., Torralba, A., and Oliva, A. (2015). Intrinsic and extrinsic
877 effects on image memorability. *Vision Research*, 116:165–178.
- 878 Capota, M., Turek, J., Chen, P.-H., Zhu, X., Manning, J. R., Sundaram, N., Keller, B., Wang, Y., and
879 Shin, Y. S. (2017). Brain imaging analysis kit.
- 880 Cer, D., Yang, Y., Kong, S. Y., Hua, N., Limtiaco, N., John, R. S., Constant, N., Guajardo-Cespedes,
881 M., Yuan, S., Tar, C., Sung, Y.-H., Strope, B., and Kurzweil, R. (2018). Universal sentence encoder.
882 *arXiv*, 1803.11175.
- 883 Charron, S. and Koechlin, E. (2010). Divided representations of current goals in the human frontal
884 lobes. *Science*, 328(5976):360–363.
- 885 Chen, J., Leong, Y. C., Honey, C. J., Yong, C. H., Norman, K. A., and Hasson, U. (2017). Shared
886 memories reveal shared structure in neural activity across individuals. *Nature Neuroscience*,
887 20(1):115.
- 888 Chun, M. and Turk-Browne, N. (2007). Interactions between attention and memory. *Current opinion*
889 *in neurobiology*, 17(2):177–184.
- 890 Clewett, D. and Davachi, L. (2017). The ebb and flow of experience determines the temporal
891 structure of memory. *Curr Opin Behav Sci*, 17:186–193.
- 892 Cohn-Sheely, B. I. and Ranganath, C. (2017). Time regained: how the human brain constructs
893 memory for time. *Current Opinion in Behavioral Sciences*, 17:169–177.
- 894 Dobrushin, R. L. (1970). Prescribing a system of random variables by conditional distributions.
895 *Theory of Probability & Its Applications*, 15(3):458–486.
- 896 DuBrow, S. and Davachi, L. (2013). The influence of contextual boundaries on memory for the
897 sequential order of events. *Journal of Experimental Psychology: General*, 142(4):1277–1286.
- 898 Ezzyat, Y. and Davachi, L. (2011). What constitutes an episode in episodic memory? *Psychological*
899 *Science*, 22(2):243–252.

- 900 Fisher, R. A. (1925). *Statistical Methods for Research Workers*. Oliver and Boyd.
- 901 Freedman, D., Riesenhuber, M., Poggio, T., and Miller, E. (2001). Categorical representation of
902 visual stimuli in the primate prefrontal cortex. *Science*, 291(5502):312–316.
- 903 Friendly, M., Franklin, P. E., Hoffman, D., and Rubin, D. C. (1982). The Toronto Word Pool:
904 Norms for imagery, concreteness, orthographic variables, and grammatical usage for 1,080
905 words. *Behavior Research Methods and Instrumentation*, 14:375–399.
- 906 Hasson, U., Chen, J., and Honey, C. J. (2015). Hierarchical process memory: memory as an integral
907 component of information processing. *Trends in Cognitive Science*, 19(6):304–315.
- 908 Hasson, U., Yang, E., Vallines, I., Heeger, D. J., and Rubin, N. (2008). A hierarchy of temporal
909 receptive windows in human cortex. *Journal of Neuroscience*, 28(10):2539–2550.
- 910 Heusser, A. C., Ezzyat, Y., Shiff, I., and Davachi, L. (2018a). Perceptual boundaries cause mnemonic
911 trade-offs between local boundary processing and across-trial associative binding. *Journal of
912 Experimental Psychology Learning, Memory, and Cognition*, 44(7):1075–1090.
- 913 Heusser, A. C., Fitzpatrick, P. C., Field, C. E., Ziman, K., and Manning, J. R. (2017). Quail: a
914 Python toolbox for analyzing and plotting free recall data. *The Journal of Open Source Software*,
915 10.21105/joss.00424.
- 916 Heusser, A. C., Ziman, K., Owen, L. L. W., and Manning, J. R. (2018b). HyperTools: a Python
917 toolbox for gaining geometric insights into high-dimensional data. *Journal of Machine Learning
918 Research*, 18(152):1–6.
- 919 Howard, M. W. and Kahana, M. J. (2002). A distributed representation of temporal context. *Journal
920 of Mathematical Psychology*, 46:269–299.
- 921 Howard, M. W., MacDonald, C. J., Tiganj, Z., Shankar, K. H., Du, Q., Hasselmo, M. E., and H., E.
922 (2014). A unified mathematical framework for coding time, space, and sequences in the medial
923 temporal lobe. *Journal of Neuroscience*, 34(13):4692–4707.

- 924 Howard, M. W., Viskontas, I. V., Shankar, K. H., and Fried, I. (2012). Ensembles of human MTL
925 neurons “jump back in time” in response to a repeated stimulus. *Hippocampus*, 22:1833–1847.
- 926 Huk, A., Bonnen, K., and He, B. J. (2018). Beyond trial-based paradigms: continuous behavior, on-
927 going neural activity, and naturalistic stimuli. *Journal of Neuroscience*, 10.1523/JNEUROSCI.1920-
928 17.2018.
- 929 Kahana, M. J. (1996). Associative retrieval processes in free recall. *Memory & Cognition*, 24:103–109.
- 930 Kelly, S., Lloyd, D., Nurmikko, T., and Roberts, N. (2007). Retrieving autobiographical memories
931 of painful events activates the anterior cingulate cortex and inferior frontal gyrus. *THe Journal of
932 Pain*, 8(4):307–314.
- 933 Kriat, A. and Goldsmith, M. (1994). Memory in naturalistic and laboratory contexts: distin-
934 guishing accuracy-oriented and quantity-oriented approaches to memory assessment. *Journal of
935 Experimental Psychology: General*, 123(3):297–315.
- 936 Kriegeskorte, N., Mur, M., and Bandettini, P. (2008). Representational similarity analysis – con-
937 necting the branches of systems neuroscience. *Frontiers in Systems Neuroscience*, 2:1 – 28.
- 938 Landauer, T. K., Foltz, P. W., and Laham, D. (1998). Introduction to latent semantic analysis.
939 *Discourse Processes*, 25:259–284.
- 940 Lerner, Y., Honey, C. J., Silbert, L. J., and Hasson, U. (2011). Topographic mapping of a hierarchy
941 of temporal receptive windows using a narrated story. *Journal of Neuroscience*, 31(8):2906–2915.
- 942 Manning, J. R. (2019). Episodic memory: mental time travel or a quantum ‘memory wave’ function?
943 *PsyArXiv*, doi:10.31234/osf.io/6zjwb.
- 944 Manning, J. R., Norman, K. A., and Kahana, M. J. (2015). The role of context in episodic memory.
945 In Gazzaniga, M., editor, *The Cognitive Neurosciences, Fifth edition*, pages 557–566. MIT Press.
- 946 Manning, J. R., Polyn, S. M., Baltuch, G., Litt, B., and Kahana, M. J. (2011). Oscillatory patterns
947 in temporal lobe reveal context reinstatement during memory search. *Proceedings of the National
948 Academy of Sciences, USA*, 108(31):12893–12897.

- 949 McInnes, L., Healy, J., and Melville, J. (2018). UMAP: Uniform manifold approximation and
950 projection for dimension reduction. *arXiv*, 1802(03426).
- 951 Medford, N. and Critchley, H. D. (2010). Conjoint activity of anterior insular and anterior cingulate
952 cortex: awareness and response. *Brain Structure and Function*, 214(5-6):535–549.
- 953 Menon, V. and Uddin, L. Q. (2010). Saliency, switching, attention and control: a network model of
954 insula function. *Brain Structure and Function*, 214(5-6):655–667.
- 955 Mikolov, T., Chen, K., Corrado, G., and Dean, J. (2013). Efficient estimation of word representations
956 in vector space. *arXiv*, 1301.3781.
- 957 Mueller, A., Fillion-Robin, J.-C., Boidol, R., Tian, F., Nechifor, P., yoonsubKim, Peter, Rampin, R.,
958 Corvellec, M., Medina, J., Dai, Y., Petrushev, B., Langner, K. M., Hong, Alessio, Ozsvald, I.,
959 vkolmakov, Jones, T., Bailey, E., Rho, V., IgorAPM, Roy, D., May, C., foobuzz, Piyush, Seong,
960 L. K., Goey, J. V., Smith, J. S., Gus, and Mai, F. (2018). WordCloud 1.5.0: a little word cloud
961 generator in Python. *Zenodo*, <https://zenodo.org/record/1322068#.W4tPKZNKh24>.
- 962 Murdock, B. B. (1962). The serial position effect of free recall. *Journal of Experimental Psychology*,
963 64:482–488.
- 964 Paller, K. A. and Wagner, A. D. (2002). Observing the transformation of experience into memory.
965 *Trends in Cognitive Sciences*, 6(2):93–102.
- 966 Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Pretten-
967 hofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A., Cournapeau, D., Brucher, M., Perrot,
968 M., and Duchesnay, E. (2011). Scikit-learn: Machine learning in Python. *Journal of Machine
969 Learning Research*, 12:2825–2830.
- 970 Polyn, S. M., Norman, K. A., and Kahana, M. J. (2009). A context maintenance and retrieval model
971 of organizational processes in free recall. *Psychological Review*, 116(1):129–156.
- 972 Postman, L. and Phillips, L. W. (1965). Short-term temporal changes in free recall. *Quarterly Journal
973 of Experimental Psychology*, 17:132–138.

- 974 Rabiner, L. (1989). A tutorial on Hidden Markov Models and selected applications in speech
975 recognition. *Proceedings of the IEEE*, 77(2):257–286.
- 976 Radvansky, G. A. and Zacks, J. M. (2017). Event boundaries in memory and cognition. *Curr Opin*
977 *Behav Sci*, 17:133–140.
- 978 Ramdas, A., Trillos, N., and Cuturi, M. (2017). On wasserstein two-sample testing and related
979 families of nonparametric tests. *Entropy*, 19(2):47.
- 980 Ranganath, C. and Ritchey, M. (2012). Two cortical systems for memory-guided behavior. *Nature*
981 *Reviews Neuroscience*, 13:713 – 726.
- 982 Rishel, C. A., Huang, G., and Freedman, D. J. (2013). Independent category and spatial encoding
983 in parietal cortex. *Neuron*, 77(5):969–979.
- 984 Sigman, M. and Dehaene, S. (2008). Brain mechanisms of serial and parallel processing during
985 dual-task performance. *Journal of Neuroscience*, 28(30):7585–7589.
- 986 Simony, E., Honey, C. J., Chen, J., and Hasson, U. (2016). Uncovering stimulus-locked network
987 dynamics during narrative comprehension. *Nature Communications*, 7(12141):1–13.
- 988 Stark, S. M., Yassa, M. A., and Stark, C. E. L. (2010). Individual differences in spatial pattern
989 separation performance associated with healthy aging in humans. *Learning & Memory*, 17(6):284–
990 288.
- 991 Steyvers, M., Shiffrin, R. M., and Nelson, D. L. (2004). Word association spaces for predicting
992 semantic similarity effects in episodic memory. In Healy, A. F., editor, *Cognitive Psychology and*
993 *its Applications: Festschrift in Honor of Lyle Bourne, Walter Kintsch, and Thomas Landauer*. American
994 Psychological Association, Washington, DC.
- 995 Tompry, A. and Davachi, L. (2017). Consolidation promotes the emergence of representational
996 overlap in the hippocampus and medial prefrontal cortex. *Neuron*, 96(1):228–241.
- 997 Tyng, C. M., Amin, H. U., Saad, M. N. M., and S, M. A. (2017). The influences of emotion on
998 learning and memory. *Frontiers in psychology*, 8:1454.

- 999 Welch, G. B. and Burnett, C. T. (1924). Is primacy a factor in association-formation. *American Journal*
1000 *of Psychology*, 35:396–401.
- 1001 Yarkoni, T., Poldrack, R. A., Nichols, T. E., Van Essen, D. C., and Wager, T. D. (2011). Large-scale
1002 automated synthesis of human functional neuroimaging data. *Nature Methods*, 8(8):665.
- 1003 Yassa, M. A., Lacy, J. W., Stark, S. M., Albert, M. S., Gallagher, M., and Stark, C. E. L. (2011). Pattern
1004 separation deficits associated with increased hippocampal ca3 and dentate gyrus activity in
1005 nondemented older adults. *Hippocampus*, 21(9):968–979.
- 1006 Yassa, M. A. and Stark, C. E. L. (2011). Pattern separation in the hippocampus. *Trends In Neuro-*
1007 *sciences*, 34(10):515–525.
- 1008 Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research.
1009 *Journal of Memory and Language*, 46:441–517.
- 1010 Yonelinas, A. P., Kroll, N. E., Quamme, J. R., Lazzara, M. M., Sauvé, M. J., Widaman, K. F., and
1011 Knight, R. T. (2002). Effects of extensive temporal lobe damage or mild hypoxia on recollection
1012 and familiarity. *Nature Neuroscience*, 5(11):1236–41.
- 1013 Zacks, J. M., Speer, N. K., Swallow, K. M., Braver, T. S., and Reynolds, J. R. (2007). Event perception:
1014 a mind-brain perspective. *Psychological Bulletin*, 133:273–293.
- 1015 Zadbood, A., Chen, J., Leong, Y. C., Norman, K. A., and Hasson, U. (2017). How we transmit
1016 memories to other brains: Constructing shared neural representations via communication. *Cereb*
1017 *Cortex*, 27(10):4988–5000.
- 1018 Zwaan, R. A. and Radvansky, G. A. (1998). Situation models in language comprehension and
1019 memory. *Psychological Bulletin*, 123(2):162 – 185.

1020 **Supporting information**

- 1021 Supporting information is available in the online version of the paper.

1022 **Acknowledgements**

1023 We thank Luke Chang, Janice Chen, Chris Honey, Lucy Owen, Emily Whitaker, and Kirsten Ziman
1024 for feedback and scientific discussions. We also thank Janice Chen, Yuan Chang Leong, Kenneth
1025 Norman, and Uri Hasson for sharing the data used in our study. Our work was supported in part
1026 by NSF EPSCoR Award Number 1632738. The content is solely the responsibility of the authors
1027 and does not necessarily represent the official views of our supporting organizations.

1028 **Author contributions**

1029 Conceptualization: A.C.H. and J.R.M.; Methodology: A.C.H., P.C.F. and J.R.M.; Software: A.C.H.,
1030 P.C.F. and J.R.M.; Analysis: A.C.H., P.C.F. and J.R.M.; Writing, Reviewing, and Editing: A.C.H.,
1031 P.C.F. and J.R.M.; Supervision: J.R.M.

1032 **Author information**

1033 The authors declare no competing financial interests. Correspondence and requests for materials
1034 should be addressed to J.R.M. (jeremy.r.manning@dartmouth.edu).