

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

³ Andrew C. Heusser^{1,2}, Paxton C. Fitzpatrick¹, and Jeremy R. Manning^{1,*}

¹Department of Psychological and Brain Sciences

Dartmouth College, Hanover, NH 03755, USA

²Akili Interactive

Boston, MA 02110

*Corresponding author: jeremy.r.manning@dartmouth.edu

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⁵ **Abstract**

The ways our experiences unfold over time define unique *trajectories* through the relevant representational spaces. Within this geometric framework, one can compare the shape of the trajectory formed by an experience to that defined by our later remembering of that experience. We propose a framework for mapping naturalistic experiences onto geometric spaces that characterize how experiences are segmented into discrete events, and how the contents of event sequences evolve over time. We apply this approach to a naturalistic memory experiment which had participants view and recount a television episode. The content of participants' recounts of events from the original episode closely matched the original episode's content. However, the similarity patterns *across* events was much different in the original episode as compared with participants' recounts. We also identified a network of brain structures that are sensitive to the "shapes" of ongoing experiences, and an overlapping network that is sensitive (at the time of encoding) to how people later remembered those experiences in relation to other experiences.

18 In this way, modeling the content of richly structured experiences can reveal how (geometrically
19 and conceptually) those experiences are segmented into events and integrated into our memories
20 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-
beled as having been recalled or forgotten. More nuanced studies might incorporate self-reported
25 confidence measures as a proxy for memory strength, or ask participants to discriminate between
26 “recollecting” the (contextual) details of an experience or having a general feeling of “familiarity”
27 (Yonelinas, 2002). Using well-controlled, trial-based experimental designs, the field has amassed
28 a wealth of valuable information regarding human episodic memory. However, there are funda-
29 mental properties of the external world and our memories that trial-based experiments are not well
30 suited to capture (for review also see Koriat and Goldsmith, 1994; Huk et al., 2018). First, our expe-
31 riences and memories are continuous, rather than discrete—removing a (naturalistic) event from
32 the context in which it occurs can substantially change its meaning. Second, the specific language
33 used to describe an experience has little bearing on whether the experience should be considered to
34 have been “remembered.” Asking whether the rememberer has precisely reproduced a specific set
35 of words to describe a given experience is nearly orthogonal to whether they were actually able to
36 remember it. In classic (e.g., list-learning) memory studies, by contrast, the number or proportion
37 of precise recalls is often a primary metric for assessing the quality of participants’ memories.
38 Third, one might remember the *essence* (or a general summary) of an experience but forget (or
39 neglect to recount) particular details. Capturing the essence of what happened is typically the
40 main “point” of recounting a memory to a listener, while the addition of highly specific details
41 may add comparatively little to successful conveyance of an experience.
42

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 into
63 memories that distill those experiences down to their essence. For example, prior work has shown
64 that event boundaries can influence how we learn sequences of items (Heusser et al., 2018a; DuBrow
65 and Davachi, 2013), navigate (Brunec et al., 2018), and remember and understand narratives (Zwaan
66 and Radvansky, 1998; Ezzyat and Davachi, 2011). Prior research has implicated the hippocampus
67 and the medial prefrontal cortex as playing a critical role in transforming experiences into structured
68 and consolidated memories (Tompry and Davachi, 2017).

69 Here we sought to examine how the temporal dynamics of a “naturalistic” experience were
70 later reflected in participants’ memories. We analyzed an open dataset that comprised behavioral
71 and functional Magnetic Resonance Imaging (fMRI) data collected as participants viewed and then

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

90 Results

91 To characterize the "essence" of the *Sherlock* episode and participants' subsequent recounts of
92 its unfolding, we used a topic model (Blei et al., 2003) to discover the latent themes in the episode's
93 dynamic content. Topic models take as inputs a vocabulary of words to consider and a collection
94 of text documents, and return two output matrices. The first of these is a *topics matrix* whose rows
95 are topics (latent themes) and whose columns correspond to words in the vocabulary. The entries
96 of the topics matrix define how each word in the vocabulary is weighted by each discovered topic.
97 For example, a detective-themed topic might weight heavily on words like "crime," and "search."

98 The second output is a *topic proportions matrix*, with one row per document and one column per
99 topic. The topic proportions matrix describes what mixture of discovered topics is reflected in each
100 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 the resulting windows-by-topics matrix to match the time
119 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
125 topics were highly similar, which we hypothesized might allow us to distinguish between subtle

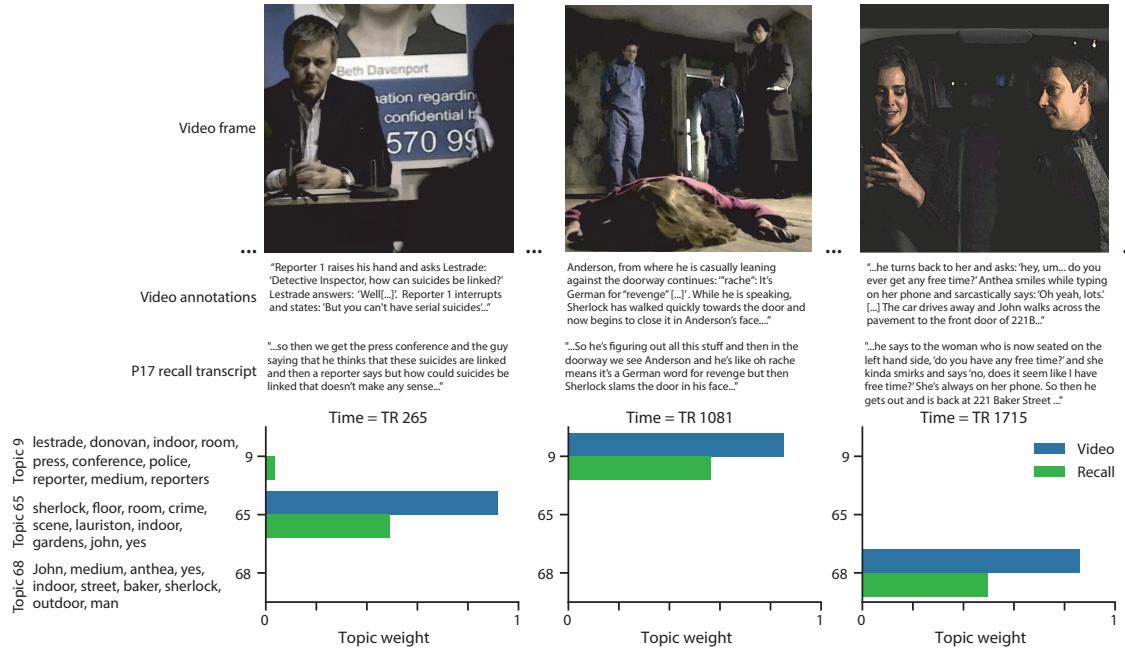


Figure 1: Methods overview. We used hand-annotated descriptions of each moment of video to fit a topic model. Three example video frames and their associated descriptions are displayed (top two rows). Participants later recalled the video (in the third row, we show example recalls of the same three scenes from participant 13). 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.

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-
153 ticipants using widely varying language to describe the same event, and that those descriptions



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). The heat maps in each panel were created using Seaborn (Waskom et al., 2016).

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
¹⁶⁴ in the video correlation matrix (Fig. 2B), the example participant’s recall correlation matrix has a
¹⁶⁵ strong block diagonal structure, indicating that their recalls are discretized into separated events.
¹⁶⁶ As for the video correlation matrix, we can use an HMM, along with the aforementioned number-
¹⁶⁷ of-events optimization procedure (also see *Methods*) to determine how many events are reflected
¹⁶⁸ in the participant’s recalls and where specifically the event boundaries fall (outlined in yellow).
¹⁶⁹ We carried out a similar analysis on all 17 participants’ 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. 2D, 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. 3C). 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
209 events were clustered heavily in participants' recall event sequences (mean: 0.767, SEM: 0.029),

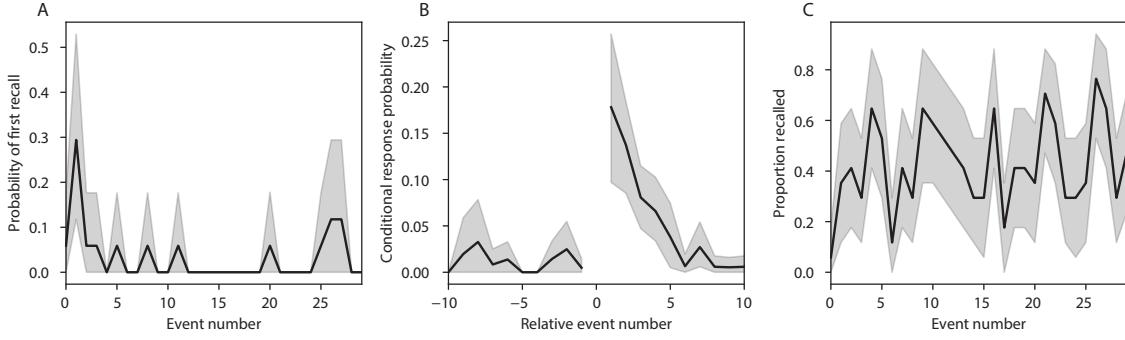


Figure 3: Naturalistic extensions of classic list-learning memory analyses. **A.** The probability of first recall as a function of the serial position of the event in the video. **B.** The probability of recalling each event, conditioned on having most recently recalled the event *lag* events away in 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.

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: 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 between all stimulus and recall events, as well as between the recall events themselves. Leveraging

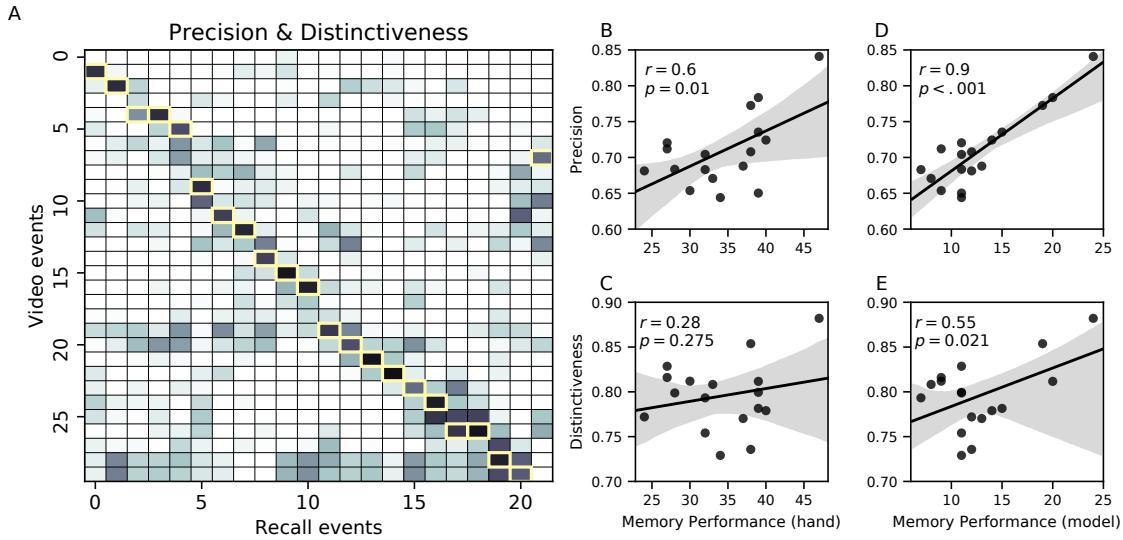


Figure 4: Novel content-based metrics of naturalistic memory: precision and distinctiveness. A. The video-recall correlation matrix for a representative participant (17). The yellow boxes highlight the maximum correlation in each column. The example participant's overall precision score was computed as the average across correlation values in the yellow boxes. Their distinctiveness score was computed as the 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.

these content-based models of the stimulus/recall events, we developed two novel, *continuous* metrics for analyzing naturalistic memory: *precision* and *distinctiveness*. We define precision as the “completeness” of recall, or how fully the presented content was recapitulated in memory. Under our framework, we quantify this for a given recall event as the correlation between the topic proportions of the recall event and the maximally correlated video event (Fig. 4). A second novel metric we introduce here is *distinctiveness*, which we define as the “specificity” of recall, or how unique the description of a given section of content was, compared to descriptions for other sections of content. We quantify this for each recall event as 1 minus the average correlation between the given recall event and all other recall events not matched to the same video event. 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 $r(15) = 0.56, p = 0.021$) and the number of video events successfully remembered, as determined
242 by our model (Pearson’s $r(15) = 0.88, p < 0.001$). 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*).

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
264 19) to illustrate the tangible differences between high and low distinctiveness scores. Here, we

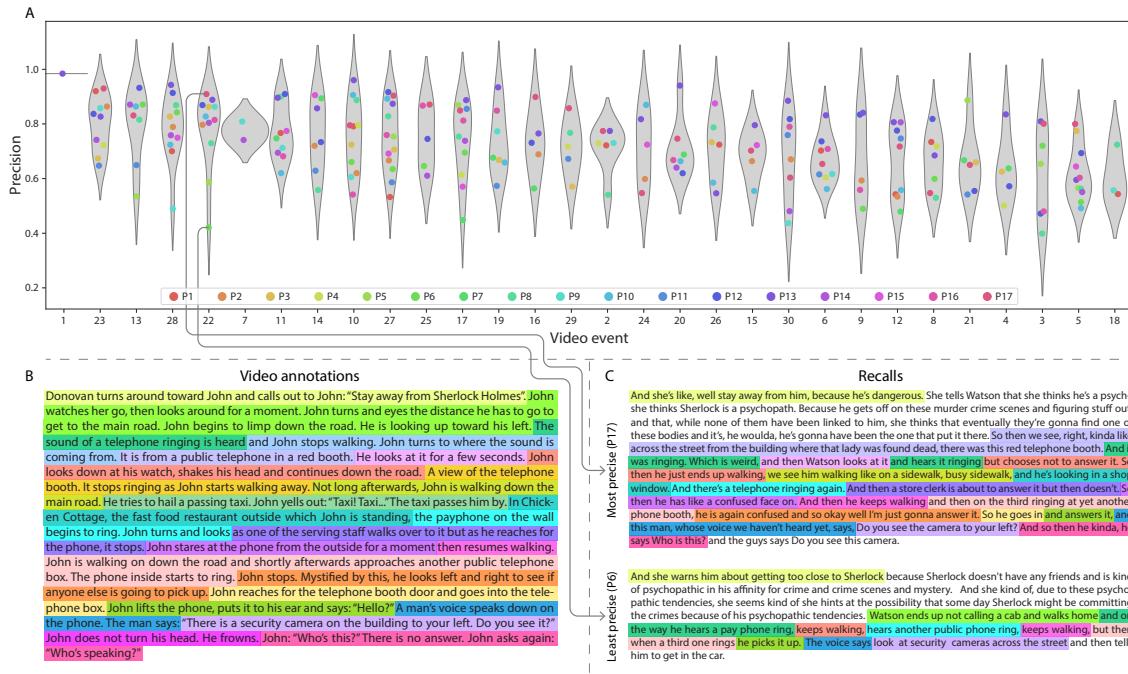


Figure 5: Precision metric reflects completeness of recall. **A.** Recall precision by video event. Grey violin plots display kernel density estimates for the distribution of recall precision scores for a single video event. Colored dots within each violin plot represent individual participants' recall 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.

265 have extracted the full set of sentences comprising the most distinctive recall event (P13) and least
 266 distinctive recall event (P11) recall event matched to the example video event (Fig. 6C). We also
 267 extracted the annotations for the example video event, as well as those from each other video
 268 event whose content the example participants' single recall events described (Fig. 6B). We then
 269 shaded the annotation text for each video event with a different color, and shaded each word of
 270 the example participants' recall text by the color of the video event it describes. The majority of
 271 the most distinctive recall event text describes video event 19's content, with the first five and last
 272 one sentence describing the video events immediately preceding and succeeding the current one,
 273 respectively. Meanwhile, the least precise participant's recall for video event 19 blends the content

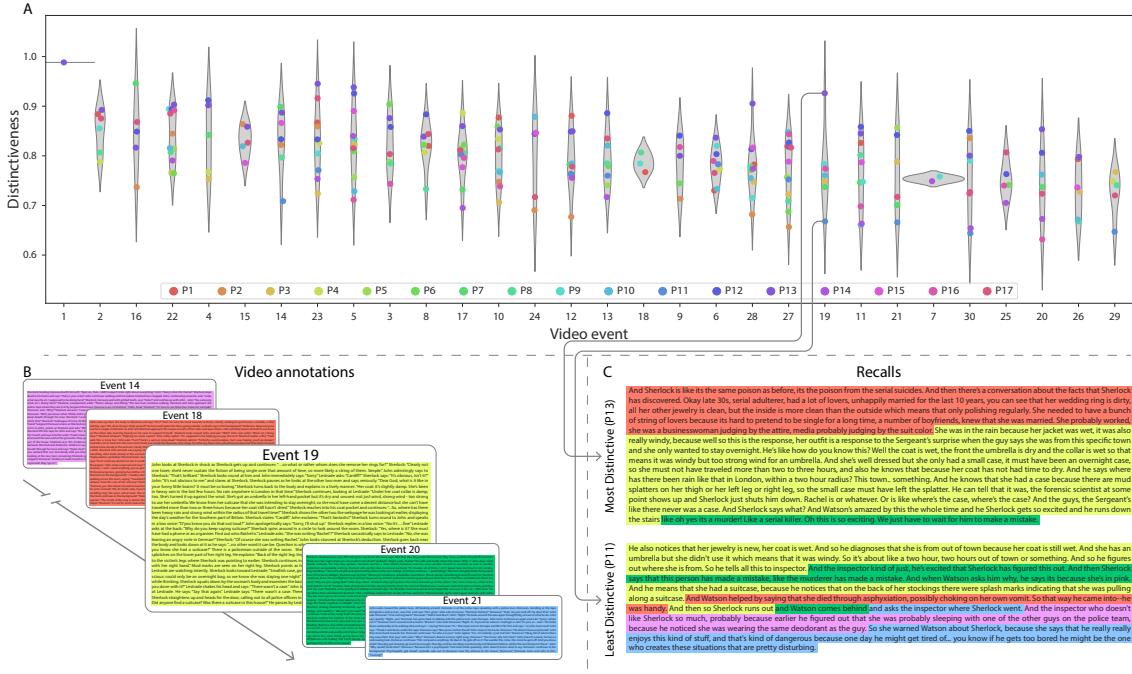


Figure 6: Distinctiveness metric reflects specificity of recall. A. Recall distinctiveness by video event. Kernel density estimates for each video event’s distribution of recall distinctiveness scores, analogous to Fig. 5A. B. The sets of “Narrative Details” video annotations (generated by Chen et al., 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.

from five separate video events, does not transition between them in order, and often combines descriptions of two video 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 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,
290 the topic trajectory of the video (which reflects its dynamic content; Fig. 7A) is captured nearly
291 perfectly by the averaged topic trajectories of participants' recalls (Fig. 7B). To assess the consistency
292 of these recall trajectories across participants, we asked: given that a participant's recall trajectory
293 had entered a particular location in topic space, could the position of their *next* recalled event
294 be predicted reliably? For each location in topic space, we computed the set of line segments
295 connecting successively recalled events (across all participants) that intersected that location (see
296 *Methods* for additional details). We then computed (for each location) the distribution of angles
297 formed by the lines defined by those line segments and a fixed reference line (the *x*-axis). Rayleigh
298 tests revealed the set of locations in topic space at which these across-participant distributions
299 exhibited reliable peaks (blue arrows in Fig. 7B reflect significant peaks at $p < 0.05$, corrected). We
300 observed that the locations traversed by nearly the entire video trajectory exhibited such peaks.
301 In other words, participants exhibited similar trajectories that also matched the trajectory of the
302 original video (Fig. 7C). This is especially notable when considering the fact that the number of
303 events participants recalled (dots in Fig. 7C) varied considerably across people, and that every
304 participant used different words to describe what they had remembered happening in the video.
305 Differences in the numbers of remembered events appear in participants' trajectories as differences
306 in the sampling resolution along the trajectory. We note that this framework also provides a
307 means of disentangling classic "proportion recalled" measures (i.e., the proportion of video events
308 described in participants' recalls) from participants' abilities to recapitulate the overall unfolding
309 of the original video's content (i.e., the similarity between the shapes of the original video trajectory
310 and that defined by each participant's recounting of the video).

311 The results displayed in Figures 3C and 5A suggest that certain events were remembered better

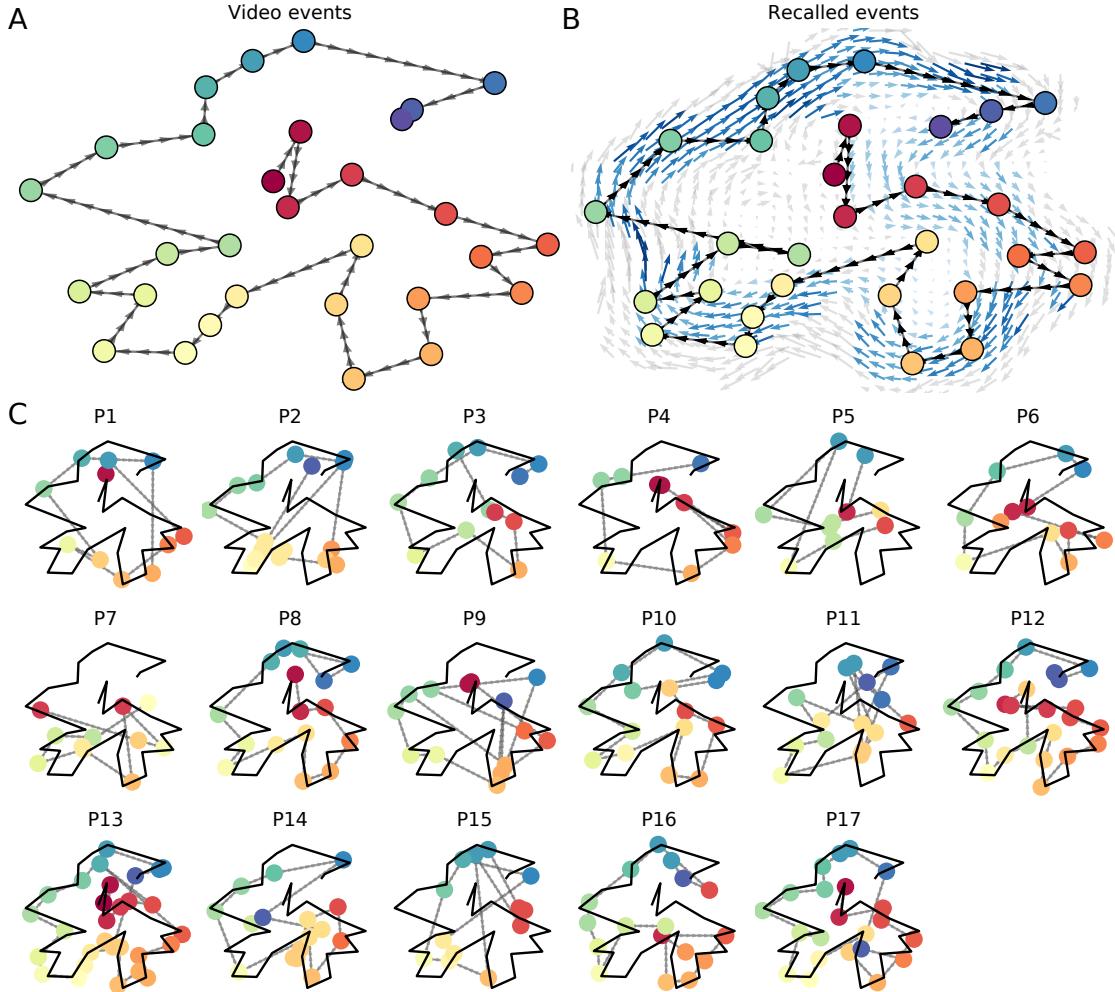


Figure 7: Trajectories through topic space capture the dynamic content of the video and recalls. All panels: the topic proportion matrices have been projected onto a shared two-dimensional space using UMAP. **A.** The two-dimensional topic trajectory taken by the episode of *Sherlock*. Each dot indicates 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).

than others. Given this, we next asked whether the events were generally remembered well or poorly tended to reflect particular content. Because our analysis framework projects the dynamic video content and participants' recalls into a shared space, and because the dimensions of that space represent topics (which are, in turn, sets of weights over words in the vocabulary), we are able to recover the weighted combination of words that make up any point (i.e., topic vector) in this space. We first computed the average precision with which participants recalled each of the 30 video events (Fig. 8A; note that this result is analogous to a serial position curve created from our continuous recall quality metric). We then computed a weighted average of the topic vectors for each video event, where the weights reflected how reliably each event was recalled. To visualize the result, we created a "wordle" image (Mueller et al., 2018) where words weighted more heavily by better-remembered topics appear in a larger font (Fig. 8B, green box). Across the full video, content that reflected topics necessary to convey the central focus of the video (e.g., the names of the two main characters, "Sherlock" and "John", and the address of a major recurring location, "221B Baker Street") were best remembered. An analogous analysis revealed which themes were poorly remembered. Here in computing the weighted average over events' topic vectors, we weighted each event in *inverse* proportion to how well it was remembered (Fig. 8B, red box). The least well-remembered video content reflected information not necessary to later convey a general summary of the video, such as the proper names of relatively minor characters (e.g., "Mike," "Molly," and "Lestrade") and locations (e.g., "St. Bartholomew's Hospital").

A similar result emerged from assessing the topic vectors for individual video and recall events (Fig. 8C). Here, for each of the three best- and worst-remembered video events, we have constructed two wordles: one from the original video event's topic vector (left) and a second from the average recall topic vector for that event (right). The three best-remembered events (circled in green) correspond to scenes important to the central plot-line: a mysterious figure spying on John in a phone booth; John meeting Sherlock at Baker St. to discuss the murders; and Sherlock laying a trap to catch the killer. Meanwhile, the three worst-remembered events (circled in red) reflect scenes that are non-essential to summarizing the narrative's structure: the video of singing cartoon characters participants viewed prior to the main episode; John asking Molly about Sherlock's habit

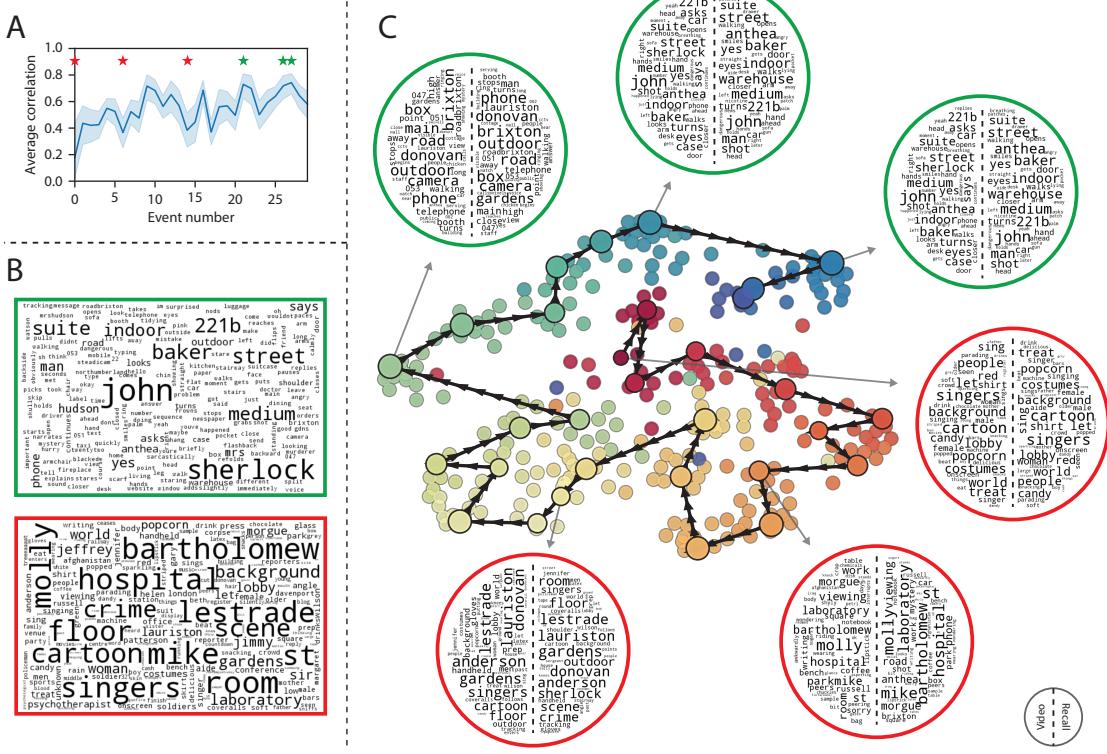


Figure 8: Transforming experience into memory. **A.** Average precision (video event-recall event topic vector correlation) across participants for each video event. Error bars denote bootstrap-derived across-participant 95% confidence intervals. The stars denote the three best-remembered events (green) 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.

340 of over-analyzing people; and Sherlock noticing evidence of Anderson's and Donovan's affair.

341 The results thus far inform us about which aspects of the dynamic content in the episode partic-
342 ipants watched were preserved or altered in participants' memories. We next carried out a series
343 of analyses aimed at understanding which brain structures might facilitate these preservations and
344 transformations between the external world and memory. In one analysis, we sought to identify
345 brain structures that were sensitive to the dynamic unfolding of the video's content, as character-
346 ized by its topic trajectory. We used a searchlight procedure to identify clusters of voxels whose
347 activity patterns displayed a proximal temporal correlation structure (as participants watched the
348 video) matching that of the original video's topic proportions (Fig. 9A; see *Methods* for additional
349 details). In a second analysis, we sought to identify brain structures whose responses (during
350 video viewing) reflected how each participant would later structure their *recalls* of the video. We
351 used an analogous searchlight procedure to identify clusters of voxels whose proximal temporal
352 correlation matrices matched that of the topic proportions for each individual's recall (Figs. 9B; see
353 *Methods* for additional details). To ensure our searchlight procedure identified regions *specifically*
354 sensitive to the temporal structure of the video or recalls (i.e., rather than those with a tempo-
355 ral autocorrelation length similar to that of the video/recalls), we performed a phase shift-based
356 permutation correction (see *Methods* for additional details). Specifically, we circularly shifted the
357 timeseries of the topic trajectory by a random number of timepoints, recomputed the shifted tra-
358 jectory's correlation matrix, and again performed our searchlight analysis on this permuted data.
359 We then z-scored the "real" searchlight results at each voxel against the null distribution of (100)
360 permuted results. In Figure 9, only voxels whose activity pattern reflected the "real" video/recall
361 timeseries more closely than 95% of the permuted results are shown. As shown in Figure 9C, the
362 video-driven searchlight analysis revealed a distributed network of regions that may play a role in
363 processing information relevant to the narrative structure of the video. Similarly, the recall-driven
364 searchlight analysis revealed a second diffuse network of regions (Fig. 9D) that may facilitate a
365 person-specific transformation of one's experience into memory. In identifying regions whose re-
366 sponses to ongoing experiences reflect how those experiences will be remembered later, this latter
367 analysis extends classic *subsequent memory analyses* (e.g., Paller and Wagner, 2002) to domain of

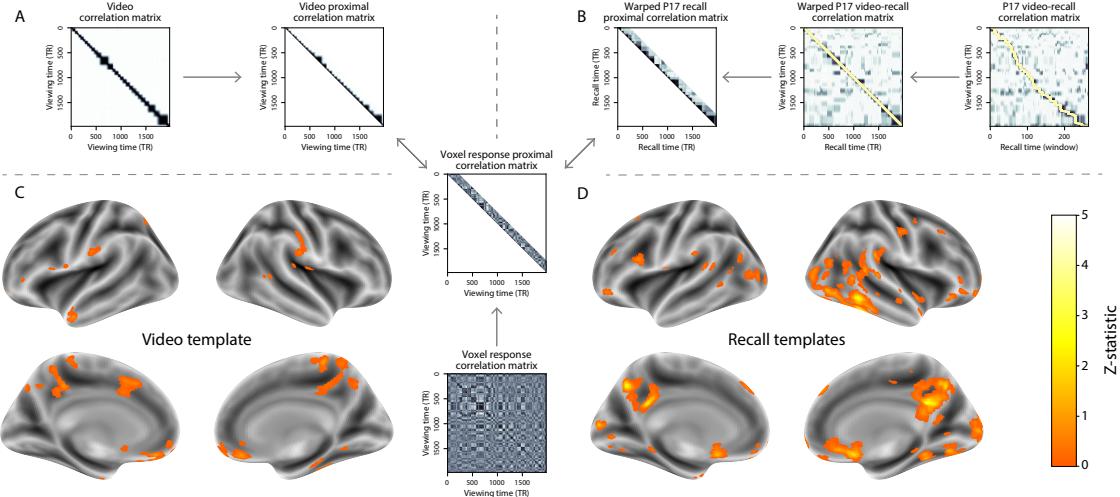


Figure 9: Brain structures that underlie the transformation of experience into memory. **A.** We isolated the proximal diagonals from the upper triangle of the video correlation matrix, and applied this same diagonal mask to the voxel response correlation matrix for each cube of voxels in the brain. 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.

368 naturalistic stimuli.

369 The searchlight analyses described above yielded two distributed networks of brain regions,
 370 whose activity timecourses mirrored to the temporal structure of the video (Fig. 9C) or participants'
 371 eventual recalls (Fig. 9D). We next sought to gain greater insight into the structures and
 372 functional networks our results reflected. To accomplish this in a blind, unbiased manner (i.e.,
 373 without reverse inference via visual observation) we performed an additional, exploratory analy-
 374 sis using Neurosynth (Yarkoni et al., 2011). Neurosynth parses a massive online database of over
 375 14,000 neuroimaging studies and constructs meta-analysis images for over 13,000 psychology-
 376 and neuroscience-related terms, based on NIfTI images accompanying studies where those terms
 377 appear at a high frequency. Then, given a novel image (tagged with its value type; e.g., t -, F - or

378 *p*-statistics), Neurosynth returns a list of terms whose meta-analysis images are most similar to this
379 new data. Our permutation procedure (described above) yielded, for each of the two searchlight
380 analyses, a voxelwise map of significance (*p*-statistic) values. These maps describe the extent to
381 which each voxel *specifically* reflected the temporal structure of the video or individuals' recalls (i.e.,
382 for each voxel, the proportion of phase-shifted topic vector correlation matrices less similar to the
383 voxel activity correlation matrix than the unshifted video's correlation matrix). These significance
384 maps for the video- and recall-driven searchlight analyses, along with the 10 terms with maximally
385 similar meta-analysis images identified by Neurosynth are shown in Figure 10.

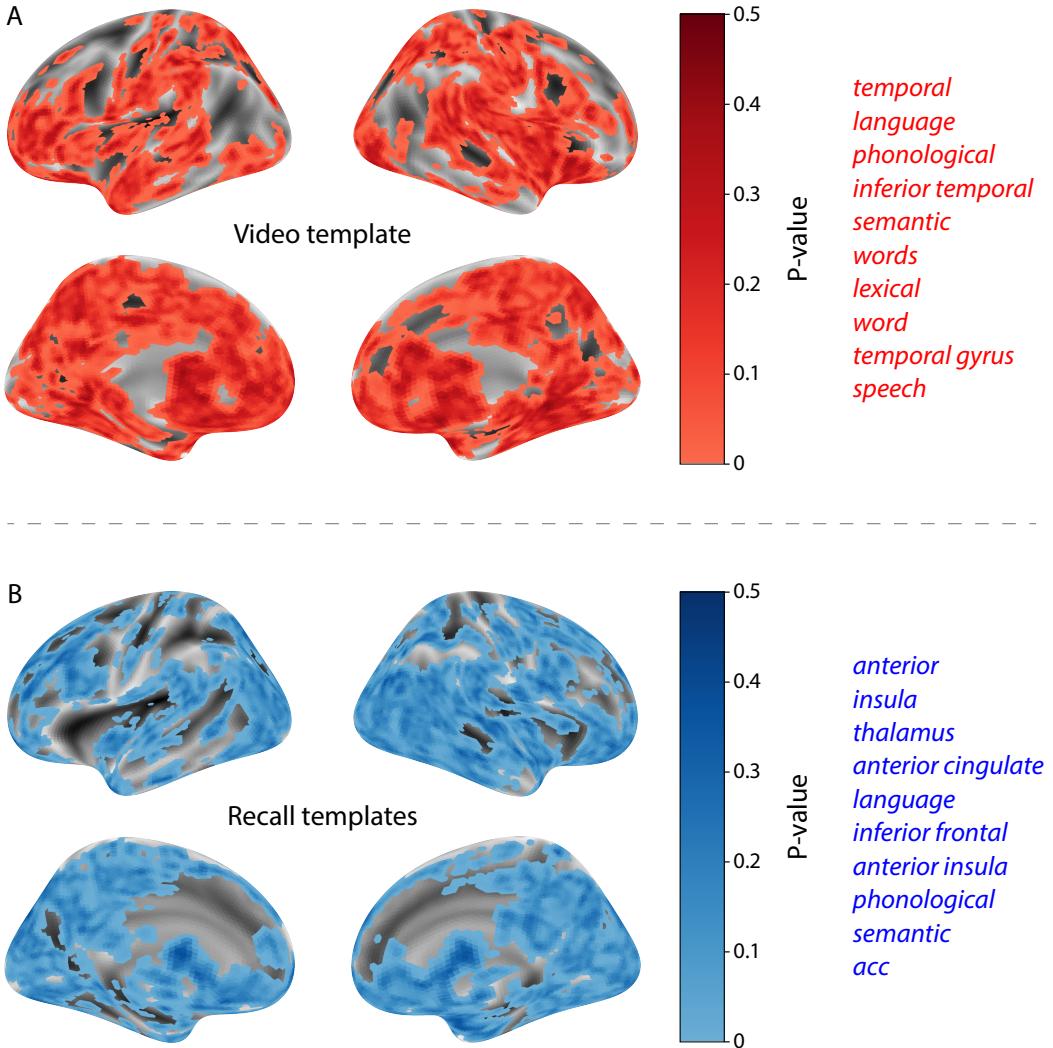


Figure 10: Decoding distributed statistical maps via Neurosynth meta-analyses. **A.** Video-searchlight significance and top 10 decoded terms. We constructed a map of the permutation-derived p -values for the video-driven searchlight analysis (Fig. 9A, C) at each voxel with a positive permutation-derived 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.

386 **Discussion**

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

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

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

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

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

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

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

497 metrics compare between cognitively impoverished groups and healthy controls.

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

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

523 Our work has broad implications for how we characterize and assess memory in real-world
524 settings, such as the classroom or physician's office. For example, the most commonly used

525 classroom evaluation tools involve simply computing the proportion of correctly answered exam
526 questions. Our work indicates that this approach is only loosely related to what educators might
527 really want to measure: how well did the students understand the key ideas presented in the
528 course? Under this typical framework of assessment, the same exam score of 50% could be
529 ascribed to two very different students: one who attended the full course but struggled to learn
530 more than a broad overview of the material, and one who attended only half of the course but
531 understood the material perfectly. Instead, one could apply our computational framework to build
532 explicit content models of the course material and exam questions. This approach would provide
533 a more nuanced and specific view into which aspects of the material students had learned well
534 (or poorly). In clinical settings, memory measures that incorporate such explicit content models
535 might also provide more direct evaluations of patients' memories.

536 Methods

537 Experimental design and data collection

538 Data were collected by Chen et al. (2017). In brief, participants ($n = 22$) viewed the first 48 minutes
539 of "A Study in Pink", the first episode of the BBC television series *Sherlock*, while fMRI volumes
540 were collected (TR = 1500 ms). Participants were pre-screened to ensure they had never seen any
541 episode of the show before. The stimulus was divided into a 23 min (946 TR) and a 25 min (1030 TR)
542 segment to mitigate technical issues related to the scanner. After finishing the clip, participants
543 were instructed to (quoting from Chen et al., 2017) "describe what they recalled of the [episode]
544 in as much detail as they could, to try to recount events in the original order they were viewed
545 in, and to speak for at least 10 minutes if possible but that longer was better. They were told that
546 completeness and detail were more important than temporal order, and that if at any point they
547 realized they had missed something, to return to it. Participants were then allowed to speak for
548 as long as they wished, and verbally indicated when they were finished (e.g., 'I'm done')." Five
549 participants were dropped from the original dataset due to excessive head motion (2 participants),

550 insufficient recall length (2 participants), or falling asleep during stimulus viewing (1 participant),
551 resulting in a final sample size of $n = 17$. For additional details about the experimental procedure
552 and scanning parameters, see Chen et al. (2017). The experimental protocol was approved by
553 Princeton University's Institutional Review Board.

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

560 The video stimulus was divided into 1,000 fine-grained “scenes” and annotated by an inde-
561 pendent coder. For each of these 1,000 scenes, the following information was recorded: a brief
562 narrative description of what was happening, the location where the scene took place, whether
563 that location was indoors or outdoors, the names of all characters on-screen, the name(s) of the
564 character(s) in focus in the shot, the name(s) of the character(s) currently speaking, the camera
565 angle of the shot, a transcription of any text appearing on-screen, and whether or not there was
566 music present in the background. Each scene was also tagged with its onset and offset time, in
567 both seconds and TRs.

568 **Data and code availability**

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

571 **Statistics**

572 All statistical tests performed in the behavioral analyses were two-sided. All statistical tests per-
573 formed in the neural data analyses were two-sided, except for the permutation-based thresholding,
574 which was one-sided. In this case, we were specifically interested in identifying voxels whose ac-

575 tivation time series reflected the temporal structure of the video and recall trajectories to a *greater*
576 extent than that of the phase-shifted trajectories.

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

578 **Topic modeling**

579 The input to the topic model we trained to characterize the dynamic content of the video comprised
580 998 hand-generated annotations of short (mean: 2.96s) scenes spanning the video clip (Chen et al.,
581 2017 generated 1000 annotations total; we removed two referring to the break between the first
582 and second scan sessions, during which no fMRI data was collected). We concatenated the text
583 for all of the annotated features within each segment, creating a “bag of words” describing each
584 scene and performed some minor preprocessing (e.g., stemming possessive nouns and removing
585 punctuation). We then re-organized the text descriptions into overlapping sliding windows span-
586 ning (up to) 50 scenes each. In other words, we created a “context” for each scene comprising the
587 text descriptions of the preceding 25 scenes, the present scene, and the following 24 scenes. To
588 model the “context” for scenes near the beginning and end of the video (i.e., within 25 scenes of
589 the beginning or end), we created overlapping sliding windows that grew in size from one scene
590 to the full length, then similarly tapered their length at the end. This additionally ensured that
591 each scene’s content was represented in the text corpus an equal number of times.

592 We trained our model using these overlapping text samples with `scikit-learn` (version 0.19.1;
593 Pedregosa et al., 2011), called from our high-dimensional visualization and text analysis software,
594 `HyperTools` (Heusser et al., 2018b). Specifically, we used the `CountVectorizer` class to transform
595 the text from each window into a vector of word counts (using the union of all words across all
596 scenes as the “vocabulary,” excluding English stop words); this yielded a number-of-windows
597 by number-of-words *word count* matrix. We then used the `LatentDirichletAllocation` class
598 (`topics=100, method='batch'`) to fit a topic model (Blei et al., 2003) to the word count matrix,
599 yielding a number-of-windows (1047) by number-of-topics (100) *topic proportions* matrix. The
600 topic proportions matrix describes the gradually evolving mix of topics (latent themes) present in

601 each scene. Next, we transformed the topic proportions matrix to match the 1976 fMRI volume
602 acquisition times. We assigned each topic vector to the timepoint (in seconds) midway between the
603 beginning of the first scene and the end of the last scene in its corresponding sliding text window.
604 By doing so, we warped the linear temporal distance between consecutive topic vectors to align
605 with the inconsistent temporal distance between consecutive annotations (whose durations varied
606 greatly). We then rescaled these timepoints to 1.5s TR units, and used linear interpolation to
607 estimate a topic vector for each TR. This resulted in a number-of-TRs (1976) by number-of-topics
608 (100) matrix.

609 We created similar topic proportions matrices using hand-annotated transcripts of each par-
610 ticipant’s recall of the video (annotated by Chen et al., 2017). We tokenized the transcript into a
611 list of sentences, and then re-organized the list into overlapping sliding windows spanning (up
612 to) 10 sentences each, analogously to how we parsed the video annotations. In turn, we trans-
613 formed each window’s sentences into a word count vector (using the same vocabulary as for the
614 video model), then used the topic model already trained on the video scenes to compute the most
615 probable topic proportions for each sliding window. This yielded a number-of-windows (range:
616 83–312) by number-of-topics (100) topic proportions matrix for each participant. These reflected
617 the dynamic content of each participant’s recalls. Note: for details on how we selected the video
618 and recall window lengths and number of topics, see *Supporting Information* and Figure S1.

619 **Parsing topic trajectories into events using Hidden Markov Models**

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

627 We used an optimization procedure to select the appropriate K for each topic proportions

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

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

636 where a was the distribution of within-state topic vector correlations, and b was the distribution of
637 across-state topic vector correlations . We computed the first Wasserstein distance (W_1 ; also known
638 as "earth mover's distance"; Dobrushin, 1970; Ramdas et al., 2017) between these distributions for a
639 large range of possible K -values (range [2,50]), and selected the K that yielded the maximum value.
640 Figure 2B displays the event boundaries returned for the video, and Figure S4 displays the event
641 boundaries returned for each participant's recalls. See Figure S6 for the optimization functions
642 for the video and recalls. After obtaining these event boundaries, we created stable estimates of
643 the content represented in each event by averaging the topic vectors across timepoints between
644 each pair of event boundaries. This yielded a number-of-events by number-of-topics matrix for
645 the video and recalls from each participant.

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

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

652 task used in this study.

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

662 **Probability of first recall (PFR).** PFR curves (Welch and Burnett, 1924; Postman and Phillips,
663 1965; Atkinson and Shiffrin, 1968) reflect the probability that an item will be recalled first as a
664 function of its serial position during encoding. To carry out this analysis, we initialized a number-
665 of-participants (17) by number-of-video-events (30) matrix of zeros. Then for each participant, we
666 found the index of the video event that was recalled first (i.e., the video event whose topic vector
667 was most strongly correlated with that of the first recall event) and filled in that index in the matrix
668 with a 1. Finally, we averaged over the rows of the matrix, resulting in a 1 by 30 array representing
669 the proportion of participants that recalled an event first, as a function of the order of the event’s
670 appearance in the video (Fig. 3A).

671 **Lag conditional probability curve (lag-CRP).** The lag-CRP curve (Kahana, 1996) reflects the
672 probability of recalling a given item after the just-recalled item, as a function of their relative
673 encoding positions (or *lag*). In other words, a lag of 1 indicates that a recalled item was presented
674 immediately after the previously recalled item, and a lag of -3 indicates that a recalled item came
675 3 items before the previously recalled item. For each recall transition (following the first recall),
676 we computed the lag between the current recall event and the next recall event, normalizing by
677 the total number of possible transitions. This yielded a number-of-participants (17) by number-

678 of-lags (-29 to +29; 61 lags total) matrix. We averaged over the rows of this matrix to obtain a
679 group-averaged lag-CRP curve (Fig. 3B).

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

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

699 **Semantic clustering scores.** Semantic clustering describes a participant's tendency to recall se-
700 mantically similar presented items together in their recall sequences. Here, we used the topic
701 vectors for each event as a proxy for its semantic content. Thus, the similarity between the seman-
702 tic content for two events can be computed by correlating their respective topic vectors. For each
703 recall event transition, we sorted all not-yet-recalled events according to how correlated the topic

704 vector of the closest-matching video event was to the topic vector of the closest-matching video event
705 to the just-recalled event. We then computed the percentile rank of the observed next recall. We
706 averaged these percentile ranks across all of the participant's recalls to obtain a single semantic
707 clustering score for the participant.

708 **Novel naturalistic memory metrics**

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

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

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

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

726 Note: in all instances where we performed statistical tests involving precision or distinctiveness

727 scores, we used Fisher’s z -transformation (Fisher, 1925) to stabilize the variance across the dis-
728 tribution of correlation values prior to performing the test. Similarly, when averaging precision
729 or distinctiveness scores, we z -transformed the scores prior to computing the mean, and inverse
730 z -transformed the result.

731 **Visualizing the video and recall topic trajectories**

732 We used the UMAP algorithm (McInnes et al., 2018) to project the 100-dimensional topic space
733 onto a two-dimensional space for visualization (Figs. 7, 8). Importantly, to ensure that all of
734 the trajectories were projected onto the *same* lower dimensional space, we computed the low-
735 dimensional embedding on a “stacked” matrix created by vertically concatenating the events-
736 by-topics topic proportions matrices for the video, across-participants average recalls and all 17
737 individual participants’ recalls. We then divided the rows of the result (a total-number-of-events
738 by two matrix) back into separate matrices for the video topic trajectory and the trajectories for
739 each participant’s recalls (Fig. 7). This general approach for discovering a shared low-dimensional
740 embedding for a collections of high-dimensional observations follows Heusser et al. (2018b). Note:
741 for further details on how we created this low-dimensional embedding space, see *Supporting
742 Information*.

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

744 In Figure 7B, we present an analysis aimed at characterizing locations in topic space that dif-
745 ferent participants move through in a consistent way (via their recall topic trajectories). The
746 two-dimensional topic space used in our visualizations (Fig. 7) comprised a 60×60 (arbitrary
747 units) square. We tiled this space with a 50×50 grid of evenly spaced vertices, and defined a
748 circular area centered on each vertex whose radius was two times the distance between adjacent
749 vertices (i.e., 2.4 units). For each vertex, we examined the set of line segments formed by connecting
750 each pair successively recalled events, across all participants, that passed through this circle. We
751 computed the distribution of angles formed by those segments and the x -axis, and used a Rayleigh
752 test to determine whether the distribution of angles was reliably “peaked” (i.e., consistent across

753 all transitions that passed through that local portion of topic space). To create Figure 7B we drew
754 an arrow originating from each grid vertex, pointing in the direction of the average angle formed
755 by line segments that passed within its circular radius. We set the arrow lengths to be inversely
756 proportional to the p -values of the Rayleigh tests at each vertex. Specifically, for each vertex we
757 converted all of the angles of segments that passed within 2.4 units to unit vectors, and we set
758 the arrow lengths at each vertex proportional to the length of the (circular) mean vector. We also
759 indicated any significant results ($p < 0.05$, corrected using the Benjamani-Hochberg procedure) by
760 coloring the arrows in blue (darker blue denotes a lower p -value, i.e., a longer mean vector); all
761 tests with $p \geq 0.05$ are displayed in gray and given a lower opacity value.

762 **Searchlight fMRI analyses**

763 In Figure 9, we present two analyses aimed at identifying brain regions whose responses (as par-
764 ticipants viewed the video) exhibited a particular temporal structure. We developed a searchlight
765 analysis wherein we constructed a cube centered on each voxel (radius: 5 voxels) and for each
766 of these cubes, computed the temporal correlation matrix of the voxel responses during video
767 viewing. Specifically, for each of the 1976 volumes collected during video viewing, we correlated
768 the activity patterns in the given cube with the activity patterns (in the same cube) collected during
769 every other timepoint. This yielded a 1976 by 1976 correlation matrix for each cube.

770 Next, we constructed a series of “template” matrices: the first reflecting the timecourse of
771 video’s topic trajectory, and the others reflecting that of each participant’s recall topic trajectory.
772 To construct the video template, we computed the correlations between the topic proportions
773 estimated for every pair of TRs (prior to segmenting the trajectory into discrete events; i.e., the
774 correlation matrix shown in Figs. 2B and 9A). We constructed similar temporal correlation matrices
775 for each participant’s recall topic trajectory (Figs. 2D, S4). However, to correct for length differences
776 and potential non-linear transformations between viewing time and recall time, we first used
777 dynamic time warping (Berndt and Clifford, 1994) to temporally align participants’ recall topic
778 trajectories with the video topic trajectory. An example correlation matrix before and after warping
779 is shown in Fig. 9B. This yielded a 1976 by 1976 correlation matrix for the video template and for

780 each participant's recall template.

781 To determine which (cubes of) voxel responses matched the video template, we correlated
782 the upper triangle of the voxel correlation matrix for each cube with the upper triangle of the
783 video template matrix (Kriegeskorte et al., 2008). This yielded, for each participant, a voxelwise
784 map of correlation values. We then performed a one-sample *t*-test on the distribution of (Fisher
785 *z*-transformed) correlations at each voxel, across participants. This resulted in a value for each
786 voxel (cube), describing how reliably its timescourse mirrored that of the video.

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

798 We used an analogous procedure to identify which voxels' responses reflected the recall tem-
799 plates. For each participant, we correlated the upper triangle of the correlation matrix for each cube
800 of voxels with their (time warped) recall correlation matrix. As in the video template analysis this
801 yielded a voxelwise map of correlation coefficients per participant. However, whereas the video
802 analysis compared every participant's responses to the same template, here the recall templates
803 were unique for each participant. As in the analysis described above, we *t*-scored the (Fisher
804 *z*-transformed) voxelwise correlations, and used the same permutation procedure we developed
805 for the video responses to ensure specificity to the recall timeseries and assign significance values.
806 To create the map in Figure 9B we again thresholded out any voxels whose correspondence values
807 fell below the 95th percentile of the permutation-derived null distribution.

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964 Supporting information

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972 Author contributions

973 Conceptualization: A.C.H. and J.R.M.; Methodology: A.C.H., P.C.F. and J.R.M.; Software: A.C.H.,
974 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.,

⁹⁷⁵ P.C.F. and J.R.M.; Supervision: J.R.M.

⁹⁷⁶ **Author information**

⁹⁷⁷ The authors declare no competing financial interests. Correspondence and requests for materials
⁹⁷⁸ should be addressed to J.R.M. (jeremy.r.manning@dartmouth.edu).