

Carryover effects in free recall reveal how prior experiences influence memories of new experiences

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Abstract

We perceive, interpret, and remember ongoing experiences through the lens of our prior experiences. Inferring that we are one type of situation versus another can lead us to interpret the same physical experience differently. In turn, this can affect how we focus our attention, form expectations of what will happen next, remember what is happening now, draw on our prior related experiences, and so on. To study these phenomena, we asked participants to perform simple word list learning tasks. Across different experimental conditions, we held the set of to-be-learned words constant, but we manipulated the orders in which the words were studied. We found that these order manipulations affected not only how the participants recalled the ordered lists, but also how they recalled later randomly ordered lists. Our work shows how structure in our ongoing experiences can exert influence on how we remember unrelated subsequent experiences.

17 Introduction

18 Experience is subjective: different people who encounter identical physical experiences
19 can take away very different meanings and memories. One reason is that our subjective
20 experiences in the moment are shaped in part the idiosyncratic prior experiences, mem-
21 ories, goals, thoughts, expectations, and emotions that we bring with us into the present
22 moment. These factors collectively define a *context* for our experiences (Manning, 2020).

23 The contexts we encounter help us to construct *situation models* (Manning et al., 2015;
24 Ranganath and Ritchey, 2012) or *schemas* (Baldassano et al., 2018; Masís-Obando et al.,
25 2022) that describe how experiences are likely to unfold based on our prior experiences
26 with similar contextual cues. For example, when we enter a sit-down restaurant, we might
27 expect to be seated at a table, given a menu, and served food. Priming someone to expect a
28 particular situation or context can also influence how they resolve potential ambiguities in
29 their ongoing experiences, including ambiguous movies and narratives (Yeshurun et al.,
30 2017).

31 Our understanding of how we form situation models and schemas, and how they
32 interact with our subjective experiences and memories, is constrained in part by substantial
33 differences in how we study these processes. Situation models and schemas are most often
34 studied using “naturalistic” stimuli such as narratives and movies (Nastase et al., 2020;
35 Zwaan et al., 1995; Zwaan and Radvansky, 1998). In contrast, our understanding of how
36 we organize our memories has been most widely studied using more traditional paradigms
37 like free recall of random word lists (Kahana, 2012). In free recall, participants study lists
38 of items and are instructed to recall the items in any order they choose. The orders in
39 which words come to mind can provide insights into how participants have organized
40 their memories of the studied words. Because random word lists are unstructured by
41 design, it is not clear if or how non-trivial situation models might apply to these stimuli.

42 Nevertheless, there are *some* commonalities between memory for word lists and memory
43 for real-world experiences.

44 Like remembering real-world experiences, remembering words on a studied list re-
45 quires distinguishing the current list from the rest of one's experience. To model this
46 fundamental memory capability, cognitive scientists have posited the existence of a spe-
47 cial representation, called *context*, that is associated with each list. According to early
48 theories (e.g. Anderson and Bower, 1972; Estes, 1955) context representations are com-
49 posed of many features which fluctuate from moment to moment, slowly drifting through
50 a multidimensional feature space. During recall, this representation forms part of the
51 retrieval cue, enabling us to distinguish list items from non-list items. Understanding the
52 role of context in memory processes is particularly important in self-cued memory tasks,
53 such as *free recall*, where the retrieval cue is "context" itself.

54 Over the past half-century, context-based models have enjoyed impressive success at
55 explaining many stereotyped behaviors observed during free recall and other list-learning
56 tasks (Estes, 1955; Glenberg et al., 1983; Howard and Kahana, 2002; Kimball et al., 2007;
57 Polyn and Kahana, 2008; Polyn et al., 2009; Raaijmakers and Shiffrin, 1980; Sederberg et al.,
58 2008; Shankar and Howard, 2012; Sirotin et al., 2005; ?). These phenomena include the
59 well-known recency and primacy effects (superior recall of items from the end and, to
60 a lesser extent, from the beginning of the study list), as well as semantic and temporal
61 clustering effects (?). The contiguity effect is an example of temporal clustering, which is
62 perhaps the dominant form of organization in free recall. This effect can be seen in the
63 tendency for people to successively recall items that occupied neighboring positions in the
64 study list. For example, if a list contained the sub-sequence "ABSENCE HOLLOW PUPIL" and
65 the participant recalls the word "HOLLOW", it is far more likely that the next response will
66 be either "PUPIL" or "ABSENCE" than some other list item (Kahana, 1996). In addition, there

67 is a strong forward bias in the contiguity effect: subjects make forward transitions (i.e.,
68 “HOLLOW” followed by “PUPIL”) about twice as often as they make backward transitions,
69 despite an overall tendency to begin recall at the end of the list. There are also striking
70 effects of semantic clustering (Bousfield, 1953; Bousfield et al., 1954; Jenkins and Russell,
71 1952; Manning and Kahana, 2012; Romney et al., 1993), whereby the recall of a given item
72 is more likely to be followed by recall of a similar or related item than a dissimilar or
73 unrelated one. In general, people organize memories for words along a wide variety of
74 stimulus dimensions. As captured by models like the *Context Maintenance and Retrieval*
75 *Model* (Polyn et al., 2009), the stimulus features associated with each word (e.g. the word’s
76 meaning, font size, font color, location on the screen, size of the object the word represents,
77 etc.) are incorporated into the participant’s mental context representation (Manning, 2020;
78 Manning et al., 2015, 2011, 2012; Smith and Vela, 2001). During a memory test, any of
79 these features may serve as a memory cue, which in turn leads the participant to recall in
80 succession words that share stimulus features.

81 A key mystery is whether the sorts of situation models and schemas that people use to
82 organize their memories of real-world experiences might map onto the clustering effects
83 that reflect how people organize their memories for word lists. On one hand, situation
84 models and clustering effects both reflect statistical regularities in ongoing experience.
85 Our memory systems exploit these regularities when generating inferences about the
86 unobserved past and yet-to-be-experienced future (Bower et al., 1979; Momennejad et al.,
87 2017; Ranganath and Ritchey, 2012; Schapiro and Turk-Browne, 2015; Xu et al., 2022). On
88 the other hand, the rich structure of real-world experiences and other naturalistic stimuli
89 that enable people to form deep and meaningful situation models and schemas have no
90 obvious analog in simple word lists. Often lists in free recall studies are explicitly *designed*
91 to be devoid of exploitable temporal structure, for example by sorting the words in a

92 random order (Kahana, 2012).

93 We designed an experimental paradigm to explore how people organize their mem-
94 ories for simple stimuli (word lists) whose temporal properties change across different
95 “situations,” analogous to how the content of real-world experiences change across dif-
96 ferent real-world situations. We asked participants to study and freely recall a series
97 of word lists (Fig. 1). Across the different conditions in the experiment, we varied the
98 lists’ presentation orders in different ways across lists. The studied items (words) were
99 designed to vary along three general dimensions: semantic (word *category*, and physical
100 *size* of the referent), lexicographic (word *length* and *first letter*), and visual (font *color* and
101 the onscreen *location* of each word). In our main manipulation conditions, we asked par-
102 ticipants to study and recall eight lists whose items were sorted by a target feature (e.g.,
103 word category). Next, we asked them to study and recall an additional eight lists whose
104 items had the same features, but that were sorted in a random temporal order. We were in-
105 terested in how these order manipulations affected participants’ recall behaviors on early
106 (sorted) lists, as well as how order manipulations on early lists affected recall behaviors
107 on later (unsorted) lists. We used a series of control conditions as a baseline; in these
108 control conditions all of the lists were sorted randomly, but we manipulated the presence
109 or absence of the visual features. Finally, in an *adaptive* experimental condition we used
110 participants’ recall behaviors on early lists to manipulate, in real-time, the presentation
111 orders of subsequent lists. In this adaptive condition, we sought to identify potential
112 commonalities within and across participants in how people organized their memories
113 and how those organizational tendencies affect overall performance.

114 **Materials and methods**

115 **Participants**

116 We enrolled a total of 491 Dartmouth undergraduate students across 11 experimental
117 conditions. The conditions included two primary controls (feature rich, reduced), two
118 secondary controls (reduced (early), reduced (late)), six order manipulation conditions
119 (category, size, length, first letter, color, and location), and a final adaptive condition. Each
120 of these conditions are described in the *Experimental design* subsection below.

121 Participants received course credit for enrolling in our study. We asked each participant
122 to fill out a demographic survey that included information about their self-reported age,
123 gender, ethnicity, race, education, vision, reading impairments, medications or recent
124 injuries, coffee consumption on the day of testing, and level of alertness at the time of
125 testing. All components of the demographics survey were optional. One participant
126 elected not to fill out any part of the demographic survey, and all other participants report
127 some or all of their requested demographic information.

128 We aimed to run (to completion) at least 60 participants in each of the two primary
129 control conditions and in the adaptive condition. In all other conditions we set a target
130 enrollment of at least 30 participants. Because our data collection efforts were coordinated
131 12 researchers and multiple testing rooms and computers, it was not feasible for individ-
132 ual experimenters to know how many participants had been run in each experimental
133 condition until the relevant databases were synchronized at the end of each working day.
134 We also over-enrolled participants for each condition to help ensure that we met our min-
135 imum enrollment targets even if some participants dropped out of the study prematurely
136 or did not show up for their testing session. This led us to exceed our target enrollments
137 for several conditions.

Participants were assigned to experimental conditions based loosely on their date of participation. (This aspect of our procedure helped us to more easily synchronize the experiment databases across multiple testing computers.) Of the 490 participants who opted to fill out the demographics survey, reported ages ranged from 17 to 31 years (mean: 19.1; standard deviation: 1.356). A total of 318 participants reported their gender as female, 170 as male, and 2 participants declined to report their gender. A total of 442 participants reported their ethnicity as “not Hispanic or Latino,” 39 as “Hispanic or Latino,” and 9 declined to report their ethnicity. Participants reported their races as White (345 participants), Asian (120 participants), Black or African American (31 participants), American Indian or Alaska Native (11 participants), Native Hawaiian or Other Pacific Islander (4 participants), Mixed race (3 participants), Middle Eastern (1 participant), and Arab (1 participant). A total of 5 participants declined to report their race. We note that several participants reported more than one of racial category. Participants reported their highest degrees achieved as “Some college” (359 participants), “High school graduate” (117 participants), “College graduate” (7 participants), “Some high school” (5 participants), “Doctorate” (1 participant), and “Master’s degree” (1 participant). A total of 482 participants reported no reading impairments, and 8 reported mild reading impairments such as mild dyslexia. A total of 489 participants reported having normal color vision and 1 participant reported that they were color blind. A total of 482 participants reported taking no prescription medications and having no recent injuries; 4 participants reported having ADHD, 1 reported having dyslexia, 1 reported having allergies, 1 reported a recently torn ACL/MCL, and 1 reported a concussion from several months prior. The participants reported consuming 0 – 3 cups of coffee prior to the testing session (mean: 0.32 cups; standard deviation: 0.58 cups). Participants reported their current level of alertness, and we converted their responses to numerical scores as follows: “very sluggish” (-2), “a little

163 sluggish" (-1), "neutral" (0), "a little alert" (1), and "very alert" (2). Across all partici-
164 pants, the full range of alertness levels were reported (range: -2 – 2; mean: 0.35; standard
165 deviation: 0.89).

166 We dropped from our dataset the 1 participant who reported abnormal color vision, as
167 well as 39 participants whose data were corrupted due to technical failures while running
168 the experiment or during the daily database merges. In total, this left usable data from
169 452 participants, broken down by experimental condition as follows: feature rich (67
170 participants), reduced (61 participants), reduced (late) (41 participants), reduced (early),
171 (42 participants), category (30 participants), size (30 participants), length (30 participants),
172 first letter (30 participants), color (31 participants), location (30 participants), and adaptive
173 (60 participants). The participant who declined to fill out their demographic survey
174 participated in the location condition, and we verified verbally that they had normal color
175 vision.

176 **Experimental design**

177 Our experiment is a variant of the classic free recall paradigm that we term *feature-rich free*
178 *recall*. In feature-rich free recall, participants study 16 lists, each comprised of 16 words that
179 vary along a number of stimulus dimensions (Fig. 1). The stimulus dimensions include
180 two semantic features related to the *meanings* of the words (semantic category, referent
181 object size), two lexicographic features related to the *letters* that make up the words (word
182 length in number of letters, identity of the word's first letter), and two visual features
183 that are independent of the words themselves (text color, presentation location). Each
184 list contains four words from each of four different semantic categories and two object
185 sizes; all other stimulus features are randomized. After studying each list, the participant
186 attempts to recall as many words as they can from that list, in any order they choose.

187 Because each individual word is associated with several well-defined (and quantifiable)
188 features, and because each list incorporates a diverse mix of feature values along each
189 dimension, this allows us to evaluate participants' memory fingerprints in rich detail.

190 **Stimuli**

191 Stimuli in our paradigm were 256 English words selected in a previous study (Ziman et al.,
192 2018). The words all referred to concrete nouns, and were chosen from 15 unique semantic
193 categories: body parts, building-related, cities, clothing, countries, flowers, fruits, insects,
194 instruments, kitchen-related, mammals, (US) states, tools, trees, and vegetables. We
195 also tagged each word according to the approximate size of the object the word referred
196 to. Words were labeled as "small" if the corresponding object was likely able to "fit
197 in a standard shoebox" or "large" if the object was larger than a shoebox. Semantic
198 categories varied in how many object sizes they reflected (mean number of different sizes
199 per category: 1.33; standard deviation: 0.49). The numbers of words in each semantic
200 category also varied from 12 – 28 (mean number of words per category: 17.07; standard
201 deviation number of words: 4.65). We also identified lexicographic features for each word,
202 including the words' first letters and lengths (i.e., number of letters). Across all categories,
203 all possible first letters were represented except for 'Q' (average number of unique first
204 letters per category: 11; standard deviation: 2 letters). Word lengths ranged from 3 – 12
205 letters (average: 6.17 letters; standard deviation: 2.06 letters).

206 We assigned the categorized words into a total of 16 lists with several constraints.
207 First, we required that each list contained words from exactly 4 unique categories, each
208 with exactly 4 exemplars from each category. Second, we required that (across all words
209 on the list) at least one instance of both object sizes were represented. On average, each
210 category was represented in 4.27 lists (standard deviation: 1.16 lists). Aside from these



Figure 1: Feature-rich free recall. After studying lists comprised of words that vary along several feature dimensions, participants verbally recall words in any order (microphone icon). Each experimental condition manipulates word features and/or presentation orders within and/or across lists. The rows display representative (illustrated) examples of the first lists participants might encounter in each condition. The rectangles during the “Presentation phase” show illustrated screen captures during a series of word presentations. Each word appeared onscreen for 2 seconds, followed by 2 seconds of blank screen. The red microphone icons during the “Recall” phase denote the one minute verbal recall interval. The labels on the right (and corresponding groupings on the left) denote experimental condition labels.

211 two constraints, we assigned each word to a unique list. After random assignment, each
212 list contained words with an average of 11.13 unique starting letters (standard deviation:
213 1.15 letters) and an average word length of 6.17 letters (standard deviation: 0.34 letters).

214 The above assignments of words to lists was performed once across all participants,
215 such that every participant studied the same set of 16 lists. In every condition we random-
216 ized the study order of these lists across participants. For participants in some conditions,
217 on some lists, we also randomly varied two additional visual features to each word: the
218 presentation font color, and the word's onscreen location. These attributes were assigned
219 independently for word (and for every participant) at the times the words were displayed
220 onscreen. These visual features were varied for words in all lists and conditions except for
221 the "reduced" condition (all lists), the first eight lists of the "reduced (early)" condition,
222 and the last eight lists of the "reduced (late)" condition. In these latter cases, words were
223 all presented in black at the center of the experimental computer's display.

224 To assign a random font color to each word, we selected three integers uniformly
225 and at random between 0 and 255, corresponding to the red (r), green (g), and blue (b)
226 color channels for that word. To assign random presentation locations to each word, we
227 selected two floating point numbers uniformly at random (one for the word's horizontal
228 x coordinate and the other for its vertical y coordinate). The bounds of these coordinates
229 were selected to cover the entire visible area of the display without cutting off any part of
230 the words. The words were shown on 27 in (diagonal) Retina 5K iMac displays (resolution:
231 5120×2880 pixels).

232 Most of the experimental manipulations we carried out entailed presenting or sorting
233 the presented words differently on the first eight lists participants studied (which we call
234 *early* lists) versus on the final eight lists they studied (*late* lists). Since every participant
235 studied exactly 16 lists, using this terminology every list was either "early" or "late"

236 depending on its order in the list study sequence.

237 **Real-time speech-to-text processing**

238 Our experimental paradigm incorporates the Google Cloud Speech API speech-to-text
239 engine (Halpern et al., 2016) to automatically transcribe participants' verbal recalls into
240 text. This allows recalls to be transcribed in real time– a distinguishing feature of the
241 experiment; in typical verbal recall experiments the audio data must be parsed manually.
242 In prior work, we used a similar experimental setup (equivalent to the “reduced” condition
243 in the present study) to verify that the automatically transcribed recalls were sufficiently
244 close to human-transcribed recalls to yield reliable data (Ziman et al., 2018). This real-time
245 speech processing component of the paradigm plays an important role in the “adaptive”
246 condition of the experiment, as described below.

247 **Random conditions (Fig. 1, top four rows)**

248 We used four “control” conditions to evaluate and explore participants' baseline behaviors.
249 We also used performance on these control conditions to help interpret performance in
250 other “manipulation” conditions. Two control conditions served as “anchorpoints.” In the
251 first anchorpoint condition, which we call the *feature rich* condition, we randomly shuffled
252 the presentation order (independently for each participant) of the words on each list. In
253 the second anchorpoint condition, which we call the *reduced* condition, we randomized
254 word presentations as in the feature rich condition. However, rather than assigning each
255 word a random color and location, we instead displayed all of the words in black and at
256 the center of the screen.

257 In the *reduced (early)* condition, we followed the “reduced” procedure (presenting each
258 word in black at the center of the screen) for early lists, and followed the “feature rich”

259 procedure (presenting each word in a random color and location) for late lists. Finally, in
260 the *reduced (late)* condition, we followed the feature rich procedure for earlylists and the
261 reduced procedure for late lists.

262 **Order manipulation conditions (Fig. 1, middle six rows)**

263 Each of six *order manipulation* conditions used a different feature-based sorting procedure
264 to order words on early lists, where each sorting procedure relied on one relevant feature
265 dimension. All of the irrelevant features varied freely across words on early lists, in
266 that we did not consider irrelevant features in ordering the early lists. However, some
267 features were correlated– for example, some semantic categories of words referred to
268 objects that tended to be a particular size, which means that category and size are not
269 fully independent. On late lists, the words were always presented in a randomized order
270 (chosen anew for each participant). In all of the order manipulation conditions, we varied
271 words’ font colors and onscreen locations, as in the feature rich condition.

272 **Defining feature-based distances.** Sorting words according to a given relevant feature
273 requires first defining a distance function for quantifying the dissimilarity between each
274 pair of features. This function varied according to the type of features. Semantic features
275 (category and size) are *categorical*. For these features, we defined a binary distance function:
276 two words were considered to “match” (i.e., have a distance of 0) if their labels are the
277 same (i.e., both from the same semantic category or both of the same size). If two words’
278 labels were different for a given feature, we defined the words to have a distance of 1 for
279 that feature. Lexicographic features (length and first letter) are *discrete*. For these features
280 we defined a discrete distance function. Specifically, we defined the distance between
281 two words as either the absolute difference between their lengths, or the absolute distance
282 between their starting letters in the English alphabet, respectively. For example, two

words that started with the same letter would have a “first letter” distance of 0, and words starting with ‘J’ and ‘A’ would have a first letter distance of 9. Because words’ lengths and letters’ positions in the alphabet are always integers, these discrete distances always take on integer values. Finally, the visual features (color and location) are *continuous* and *multivariate*, in that each “feature” takes on multiple (positive) real values. We defined the “color” and “location” distances between two words as the Euclidean distances between their (r, g, b) color or (x, y) location vectors, respectively. Therefore the color and location distance measures always take on positive real values (upper bounded at 441.67 for color, or 27 in for location, reflecting the distances between the corresponding maximally different vectors).

Constructing feature-sorted lists. Given a list of words, a relevant feature, and each word’s value(s) for that feature, we developed a stochastic algorithm for (noisily) sorting the words. First, we choose a word uniformly at random from the set of candidates. Next, we compute the distances between the chosen word’s feature(s) and the corresponding feature(s) of all yet-to-be-presented words. Third, we convert these distances (between the previously presented word’s feature values, a , and the candidate word’s feature values, b) to similarity scores:

$$\text{similarity}(a, b) = \exp\{-\tau \cdot \text{distance}(a, b)\}, \quad (1)$$

where $\tau = 1$ in our implementation. We note that increasing the value of τ would amplify the influence of similarity on order, and decreasing the value of τ would diminish the influence of similarity on order. Also note that this approach requires $\tau > 0$. Finally, we computed a set of normalized similarity values by dividing the similarities by their sum:

$$\text{similarity}_{\text{normalized}}(a, b) = \frac{\text{similarity}(a, b)}{\sum_{i=1}^n \text{similarity}(a, i)}, \quad (2)$$

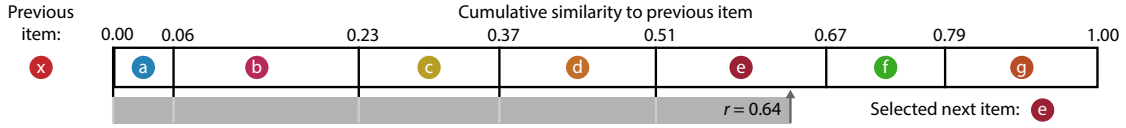


Figure 2: Generating stochastic feature-sorted lists. For a given feature dimension (e.g., color), we compute the similarity (Eqn. 1) between the feature value(s) of the previous item, x , and all yet-to-be-presented items ($a - g$). Next, we normalize these similarity scores so that they sum to one. We lay in sequence a set of “sticks,” one for each candidate item, whose lengths are equal to these normalized similarity scores. Note that the combined lengths of these sticks is one. To select the next to-be-presented item, we draw a random number, r , from the uniform distribution bounded between 0 and 1 (inclusive). The identity of the next item is given by the stick adjacent to an indicator that moves distance r (starting from 0) along the sequence of sticks. In this case, the next to-be-presented item is e . Note that each item’s chances of selection is proportional to its similarity to the previous item, along the given feature dimension.

304 where in the demoniator, i takes on each of the n feature values of the to-be-presented
 305 words. The resulting set of normalized similarity scores sums to one.

306 As illustrated in Figure 2, we use these normalized similarity scores to construct a
 307 sequence of “sticks” that we lay end to end in a line. Each of the n sticks corresponds
 308 to a single to-be-presented word, and the stick lengths are proportional to the relative
 309 similarities between each word’s feature value(s) and the feature value(s) of the just-
 310 presented word. We choose the next to-be-presented word by moving an indicator along
 311 the set of sticks, by a distance chosen uniformly at random on the interval $[0, 1]$. We
 312 select the word associated with the stick lying next to the indicator to be presented next.
 313 This process continues iteratively (re-computing the similarity scores and stochastically
 314 choosing the next to-be-presented word using the just-presented word) until all of the
 315 words have been presented. The result is an ordered list that tends to change gradually
 316 along the selected feature dimension.

317 **Adaptive condition**

318 We designed the *adaptive* experimental condition to study the effect on memory for infor-
319 mation that matched (or mismatched) the ways participants “naturally” organized their
320 memories of the lists they studied. Like the other conditions, all participants in the adap-
321 tive condition studied a total of 16 lists, in a randomized order. We varied the words’ colors
322 and locations for every word presentation, as in the feature rich and order manipulation
323 conditions.

324 All participants in the adaptive condition began the experiment by studying a set of
325 four *initialization* lists. Words and features on these lists were presented in a randomized
326 order (computed independently for each participant). These initialization lists were used
327 to estimate each participant’s “memory fingerprint,” defined below. At a high level, a
328 participant’s memory fingerprint describes how they prioritize different semantic, lexico-
329 graphic, and/or visual features when they organize their memories.

330 Next, participants studied a sequence of 12 lists in three batches of 4 lists each. These
331 batches came in three types: *random*, *stabilize*, and *destabilize*. The batch types determined
332 how words on the lists in that batch were ordered. Lists in each batch were always
333 presented consecutively (e.g., a participant might receive four random lists, followed
334 by four stabilize lists, followed by four destabilize lists). The batch orders were evenly
335 counterbalanced across participants: there are six possible orderings of the three batches,
336 and 10 participants were randomly assigned to each ordering sub-condition.

337 Lists in the random batches were sorted randomly (as on the initialization lists and in
338 the feature rich condition). Lists in the stabilize and destabilize batches were sorted in
339 ways that either matched or mismatched each participant’s memory fingerprint, respec-
340 tively. Our procedures for computing participants’ memory fingerprints and ordering the
341 stabilize and destabilize lists are described next.

342 **Feature clustering scores (uncorrected).** Feature clustering scores describe participants’
343 tendencies to recall similar presented items together in their recall sequences, where
344 “similarity” considers one given feature dimension (e.g., category, color, etc.). We base
345 our main approach to computing clustering scores on analogous temporal and semantic
346 clustering scores developed by (Polyn et al., 2009). Computing the clustering score for
347 one feature dimension starts by considering those feature values from the first word the
348 participant recalled on the list. Next, we sort all not-yet-recalled words in ascending order
349 according to their feature-based distance to the just-recalled item (see *Defining feature-based*
350 *distances*). We then compute the percentile rank of the observed next recall. We averaged
351 these percentile ranks across all of the participant’s recalls for the current list to obtain a
352 single uncorrected clustering score for the list, for the given feature dimension. We repeat
353 this process for each feature dimension in turn to obtain a single uncorrected clustering
354 score for each list, for each feature dimension.

355 **Temporal clustering score (uncorrected).** Temporal clustering describes a participant’s
356 tendency to organize their recall sequences by the learned items’ encoding positions. For
357 instance, if a participant recalled the episode events in the exact order they occurred (or
358 in exact reverse order), this would yield a score of 1. If a participant recalled the events in
359 random order, this would yield an expected score of 0.5. For each recall-event transition
360 (and separately for each participant), we sorted all not-yet-recalled events according to
361 their absolute lag (that is, distance away in the episode). We then computed the percentile
362 rank of the next event the participant recalled. We took an average of these percentile ranks
363 across all of the participant’s recalls to obtain a single (uncorrected) temporal clustering
364 score for the participant.

365 **Permutation-corrected feature clustering scores.** Suppose that two lists contain unequal
366 numbers of items of each size. For example, suppose that list *A* contains all “large” items,
367 whereas list *B* contains an equal mix of “large” and “small” items. For a participant
368 recalling list *A*, any correctly recalled item will necessarily match the size of the previous
369 correctly recalled item. In other words, successively recalling several list *A* items of the
370 same size is essentially meaningless, since *any* correctly recalled list *A* word will be large.
371 In contrast, successively recalling several list *B* items *could* be meaningful, since (early in
372 the recall sequence) the yet-to-be-recalled items come from a mix of sizes. However, once
373 all of the “small” items on list *B* have been recalled, the best possible next matching recall
374 will be a large item. And all subsequent correct recalls must also be large items– so for
375 those later recalls it becomes difficult to determine whether the participant is successively
376 recalling “large” items because they are organizing their memories according to size, or
377 (alternatively), whether they are simply recalling the yet-to-be-recalled items in a random
378 order. In general, the precise order and blend of feature values expressed in a given list,
379 the orders and numbers of correct recalls a participant makes, the number of intervening
380 presentation positions between successive recalls, and so on, can all affect the range of
381 clustering scores that are possible to observe for a given list. The uncorrected clustering
382 score therefore conflates participants’ actual memory organization with other “nuisance”
383 factors.

384 Following our prior work (Heusser et al., 2017), we used a permutation-correction
385 procedure to help isolate the behavioral aspects of clustering that we were most interested
386 in. After computing the uncorrected clustering score (for the given list and observed
387 recall sequence), we compute a “null” distribution of n additional clustering scores after
388 randomly shuffling the recall order (we use $n = 500$ in the present study). This null
389 distribution represents an approximation of the range of clustering scores one might expect

390 to observe by “chance,” given that a hypothetical participant was *not* truly clustering their
391 recalls, but where the hypothetical participant studied and recalled exactly the same items
392 (with the same features) as the true participant. We define the permutation-corrected
393 clustering score as the percentile rank of the observed uncorrected clustering score in this
394 estimated null distribution. In this way, a corrected score of 1 indicates that the observed
395 score was greater than any clustering score one might expect by chance; in other words,
396 good evidence that the participant was truly clustering their recalls along the given feature
397 dimension. We applied this correction procedure to all of the clustering scores (feature
398 and temporal) reported in this paper.

399 **Memory fingerprints.** We define each participant’s *memory fingerprint* as the set of their
400 permutation-corrected clustering scores across all dimensions we tracked in our study,
401 including their six feature-based clustering scores (category, size, length, first letter, color,
402 and location) and their temporal clustering score. Conceptually, this memory fingerprint
403 describes the participant’s tendencies to order (and, presumably, organize in memory)
404 the studied words along each dimension. To obtain stable estimates of these fingerprints
405 for each participant, we averaged clustering scores across lists. We also tracked and
406 characterized how participants’ fingerprints changed across lists (e.g., Figs. 6, S8).

407 **Online “fingerprint” analysis.** The presentation orders of some lists in the adaptive
408 condition of our experiment (see *Adaptive condition*) were sorted according to participants’
409 *current* memory fingerprint, estimated using all of the lists they had studied up to that point
410 in the experiment. Because our experiment incorporated a speech-to-text component, all
411 of the behavioral data for each participant could be analyzed just a few seconds after the
412 conclusion of the recall intervals for each list. We used the Quail Python package (Heusser
413 et al., 2017) to apply speech-to-text algorithms to the just collected data, aggregate the data

414 for the given participant, and estimate the participant’s memory fingerprint using all of
415 their available data up to that point in the experiment. Two aspects of our implementation
416 are worth noting. First, because memory fingerprints are averaged across lists, the already-
417 computed memory fingerprints for earlier lists could be cached and loaded as needed
418 in future computations. This meant that our computations pertaining to updating our
419 estimates of a participant’s memory fingerprint only needed to consider data from the
420 most recent list. Second, each element of the null distributions of uncorrected fingerprint
421 scores (see *Permutation-corrected feature clustering scores*) could be estimated independently
422 from the others. This enabled us to make use of the testing computers’ multi-core CPU
423 architectures by elements of the null distributions in batches of eight (i.e., the number
424 of CPU cores on each testing computer). Taken together, we were able to compress
425 the fingerprint computations into just a few seconds of computing time. The combined
426 processing time for the speech-to-text algorithm and fingerprint computations easily fit
427 within the inter-list intervals, where participants typically paused before moving on to the
428 next list.

429 **Ordering “stabilize” and “destabilize” lists by an estimated fingerprint.** In the adap-
430 tive condition of our experiment, the presentation orders for *stabilize* and *destabilize* lists
431 were chosen to either maximally or minimally (respectively) comport with participants’
432 memory fingerprints. Given a participant’s memory fingerprint and a to-be-presented set
433 of items, we designed a permutation-based procedure for ordering the items. First, we
434 dropped from the participant’s fingerprint the temporal clustering score. For the remain-
435 ing feature dimensions, we arranged the clustering scores in the fingerprint into a template
436 vector, f . Second, we computed $n = 2500$ random permutations of the to-be-presented
437 items. These permutations served as prospective presentation orders. We sought to select
438 the specific order that most (or least) matched f . Third, for each random permutation, we

439 computed the (permutation-corrected) “fingerprint,” treating the permutation as though
440 it were a potential “perfect” recall sequence. (We did not include temporal clustering
441 scores in these fingerprints.) This yielded a “simulated fingerprint” vector, \hat{f}_p for each per-
442 mutation p . We used these simulated fingerprints to select a specific permutation, i , that
443 either maximized (for stabilized lists) or minimized (for destabilize lists) the correlation
444 between \hat{f}_i and f .

445 **Computing low-dimensional embeddings of memory fingerprints**

446 Following some of our prior work (Heusser et al., 2018), we use low-dimensional em-
447 beddings to help visualize how participants’ memory fingerprints change across lists
448 (Figs. 6A, S8A). To compute a shared embedding space across participants and experimen-
449 tal conditions, we concatenated the full set of fingerprints (across all lists, participants,
450 and experimental conditions) to create a large matrix with number-of-lists \times number-of-
451 participants rows and seven columns (one for each word feature dimension’s clustering
452 scores, plus an additional temporal clustering score column). We used principal compo-
453 nents analysis to project the seven-dimensional observations into a two-dimensional space
454 (using the two principal components that explained the most variance in the data). For
455 two visualizations (Figs. 6B, and S8B) we computed an additional set of two-dimensional
456 embeddings for participants’ *average* fingerprints (i.e., across lists within a given group of
457 lists— early or late). For those visualizations we averaged each participant’s rows (for the
458 given group of lists) in the combined fingerprint matrix prior to projecting it into the shared
459 two-dimensional space. This yielded a single two-dimensional coordinate for each *partic-*
460 *ipant* and *list group*, rather than for each individual list. We used these embeddings solely
461 for visualization. All statistical tests were carried out in the original (seven-dimensional)
462 feature spaces.

463 **Analyses**

464 **Probability of n^{th} recall curves**

465 Probability of first recall curves (Atkinson and Shiffrin, 1968; Postman and Phillips, 1965;
466 Welch and Burnett, 1924) reflect the probability that an item will be recalled first, as a
467 function of its serial position during encoding. To carry out this analysis, we initialized
468 (for each participant) a number-of-lists (16) by number-of-words-per-list (16) matrix of
469 zeros. Then, for each list, we found the index of the word that was recalled first, and we
470 filled in that position in the matrix with a 1. Finally, we averaged over the rows of the
471 matrix to obtain a 1 by 16 array of probabilities, for each participant. We used an analogous
472 procedure to compute probability of n^{th} recall curves for each participant. Specifically,
473 we filled in the corresponding matrices according to the n^{th} recall on each list that each
474 participant made. When a given participant had made fewer than n recalls for a given
475 list, we simply excluded that list from our analysis when computing that participant's
476 curve(s).

477 **Lag-conditional response probability curve**

478 The lag-conditional probability (lag-CRP) curve (Kahana, 1996) reflects the probability of
479 recalling a given item after the just-recalled item, as a function of their relative encoding
480 positions (lag). In other words, a lag of 1 indicates that a recalled item was presented
481 immediately after the previously recalled item, and a lag of 3 indicates that a recalled item
482 came 3 items before the previously recalled item. For each recall transition (following the
483 first recall), we computed the lag between the just-recalled word's presentation position
484 and the next-recalled word's presentation position. We computed the proportions of
485 transitions (between successively recalled words) for each lag, normalizing for the total
486 numbers of possible transitions. In carrying out this analysis, we excluded all incorrect

487 recalls and successive repetitions (e.g., recalling the same word twice in a row). This
488 yielded, for each list, a 1 by number-of-lags (–15 to +15; 30 lags in total, excluding lags of
489 0) array of conditional probabilities. We averaged these probabilities across lists to obtain
490 a single lag-CRP for each participant.

491 **Serial position curve**

492 Serial position curves (Murdock, 1962) reflect the proportion of participants who remember
493 each item as a function of the item’s serial position during encoding. For each participant,
494 we initialized a number-of-lists (16) by number-of-words-per-list (16) matrix of zeros.
495 Then, for each correct recall, we identified the presentation position of the word and
496 entered a 1 into that position (row: list; column: presentation position) in the matrix.
497 This resulted in a matrix whose entries indicated whether or not the words presented at
498 each position, on each list, were recalled by the participant (depending on whether the
499 corresponding entires were set to one or zero). Finally, we averaged over the rows of the
500 matrix to yield a 1 by 16 array representing the proportion of words at each position that
501 the participant remembered.

502 **Identifying event boundaries**

503 We used the distances between feature values for successively presented words (see *Defin-*
504 *ing feature-based distances*) to estimate “event boundaries” where the feature values changed
505 more than usual (DuBrow and Davachi, 2016; Ezzyat and Davachi, 2011; Manning et al.,
506 2016; Radvansky and Copeland, 2006; Swallow et al., 2011, 2009). For each list, for each
507 feature dimension, we computed the distribution of distances between the feature values
508 for successively presented words. We defined event boundaries (e.g., Fig. 3B) as occurring
509 between any successive pair of words whose distances along the given feature dimension

were greater than one standard deviation above the mean for that list. Note that, because event boundaries are defined for each feature dimension, each individual list may contain several sets of event boundaries, each at different moments in the presentation sequence (depending on the feature dimension of interest).

Results

We sought to manipulate two aspects of how participants memorized sequences of word lists. First, we added two additional sources of visual variation to the individual word presentations: font color and onscreen location. Importantly, these visual features were independent of the meaning or semantic content of the words (e.g., word category, size of the referent) and of the lexicographic properties of the word (e.g., word length, first letter). We wondered whether this additional word-independent information might facilitate recall (e.g., by providing new potential ways of organizing or retrieving memories of the studied words) or impair recall (e.g., by distracting participants). Second, our primary experimental manipulations entailed manipulating the orders in which words were studied (and how those orderings changed over time). We wondered whether presenting the same list of words in different orders (e.g., sorted along one feature dimension versus another) might serve to influence how participants organized their memories of the words. We also wondered whether some order manipulations might be temporally “sticky” by influencing how *future* lists were remembered.

To obtain a clean preliminary estimate of the consequences on memory of randomly varying the font colors and locations of presented words (versus holding the font color fixed at black, and holding the display locations fixed at the center of the display) we compared participants’ performance on the *feature rich* and *reduced* experimental conditions (see *Random conditions*, Fig. S1). In the feature rich condition the words’ colors and

locations varied randomly across words, and in the reduced condition words were always presented in black, at the center of the display. Aggregating across all lists for each participant, we found no difference in recall accuracy for feature rich versus reduced lists ($t(126) = -0.290, p = 0.772$). However, participants in the feature rich condition clustered their recalls substantially more along every dimension we examined (temporal clustering: $t(126) = 10.624, p < 0.001$; category clustering: $t(126) = 10.077, p < 0.001$; size clustering: $t(126) = 11.829, p < 0.001$; word length clustering: $t(126) = 10.639, p < 0.001$; first letter clustering: $t(126) = 7.775, p = 0.000$; see *Permutation-corrected feature clustering scores* for more information about how we quantified each participant’s clustering tendencies.) Taken together, these comparisons suggest that adding new features changes how participants organize their memories of studied words, even when those new features are independent of the words themselves and even when the new features vary randomly across words. We found no evidence that those additional uninformative features were distracting (in terms of their impact on memory performance), but they did affect participants’ recall dynamics (measured via their clustering scores).

We also wondered whether adding these irrelevant visual features to later lists (after the participants had already studied impoverished lists), or removing the visual features from later lists (after the participants had already studied visually diverse lists) might affect memory performance. In other words, we sought to test for potential effects of changing the “richness” of participants’ experiences over time. All participants studied and recalled a total of 16 lists; we defined *early* lists as the first eight lists and *late* lists as the last eight lists each participant encountered. To help interpret our results, we compared participants’ memories on early versus late lists in the above feature rich and reduced conditions. Participants in both conditions remembered more words on early versus late lists (feature rich: $t(66) = 4.553, p < 0.001$; reduced: $t(60) = 2.434, p = 0.018$). Participants in the feature

rich (but not reduced) conditions exhibited more temporal clustering on early versus late lists (feature rich: $t(66) = 2.318, p = 0.024$; reduced: $t(60) = 0.929, p = 0.357$). And participants in both conditions exhibited more semantic (category and size) clustering on early versus late lists (feature rich, category: $t(66) = 3.805, p < 0.001$; feature rich, size: $t(66) = 2.190, p = 0.032$; reduced, category: $t(60) = 2.856, p = 0.006$; reduced, size: $t(60) = 2.947, p = 0.005$). Participants in the reduced (but not feature rich) conditions exhibited more lexicographic clustering on early versus late lists (feature rich, word length: $t(66) = 0.161, p = 0.872$; feature rich, first letter: $t(66) = 0.410, p = 0.683$; reduced, word length: $t(60) = 3.528, p = 0.001$; reduced, first letter: $t(60) = 2.275, p = 0.026$). Taken together, these comparisons suggest that even when the presence or absence of irrelevant visual features is stable across lists, participants still exhibit some differences in their performance and memory organization tendencies for early versus late lists.

With these differences in mind, we next compared participants' memories on early versus late lists for two additional experimental conditions (see *Random conditions*, Fig. S1). In a *reduced (early)* condition, we held the irrelevant visual features constant on early lists, but allowed them to vary randomly on late lists. In a *reduced (late)* condition, we allowed the irrelevant visual features to vary randomly on early lists, but held them constant on late lists. Given our above findings that (a) participants tended to remember more words and exhibit stronger clustering effects on feature rich (versus reduced) lists, and (b) participants tended to remember more words and exhibit stronger clustering effects on early (versus late) lists, we expected these early versus late differences to be enhanced in the reduced (early) condition and diminished in the reduced (late) condition. However, to our surprise, participants in *neither* condition exhibited reliable early versus late differences in accuracy (reduced (early): $t(41) = 1.499, p = 0.141$; reduced (late): $t(40) = 1.462, p = 0.152$), temporal clustering (reduced (early): $t(41) = 0.998, p = 0.324$; reduced (late):

584 $t(40) = 1.099, p = 0.278$), nor feature based clustering (reduced (early), category: $t(41) =$
585 $0.753, p = 0.456$; reduced (early), size: $t(41) = 0.721, p = 0.475$; reduced (early), length:
586 $t(41) = 0.493, p = 0.625$; reduced (early), first letter: $t(41) = 0.780, p = 0.440$; reduced (late),
587 category: $t(40) = -0.086, p = 0.932$; reduced (late), size: $t(40) = 0.746, p = 0.460$; reduced
588 (late), length: $t(40) = 1.476, p = 0.148$; reduced (late), first letter: $t(40) = 0.966, p = 0.340$).

589 We hypothesized that adding or removing the irrelevant features was acting as a sort
590 of “event boundary” between early and late lists. In prior work, we (and others) have
591 found that memories formed just after event boundaries can be enhanced (e.g., due to less
592 contextual interference between pre- and post-boundary items; Manning et al., 2016).

593 We found that *adding* irrelevant visual features on later lists that had not been present
594 on early lists (as in the reduced (early) condition) served to enhance recall performance
595 relative to conditions where all lists had the same blends of features (accuracy for feature
596 rich versus reduced (early): $t(107) = -2.230, p = 0.028$; reduced versus reduced (early):
597 $t(101) = -2.045, p = 0.043$; also see Fig. S3A). However, *subtracting* irrelevant visual fea-
598 tures on later lists that *had* been present on early lists (as in the reduced (late) condition) did
599 not appear to impact recall performance (accuracy for feature rich versus reduced (late):
600 $t(106) = -0.638, p = 0.525$; reduced versus reduced (late): $t(100) = -0.407, p = 0.685$).
601 These comparisons suggest that recall accuracy has a directional component (i.e., accu-
602 racy is affected differently by removing features later that had been present earlier versus
603 adding features later that had *not* been present earlier). In contrast, we found that partic-
604 ipants exhibited more temporal and feature-based clustering when we added irrelevant
605 visual features to *any* lists (comparisons of clustering on feature rich and reduced lists
606 are reported above; temporal clustering in reduced versus reduced (early) and reduced
607 versus reduced (late) conditions: $t_s \leq -9.780, p_s < 0.001$; feature based clustering in re-
608 duced versus reduced (early) and reduced versus reduced (late) conditions: $t_s \leq -5.443, p_s$

609 < 0.001). Temporal and feature-based clustering were not reliably different in the feature
610 rich, reduced (early), and reduced (late) conditions (temporal clustering in feature rich
611 versus reduced (early) and feature rich versus reduced (late) conditions: $t_s \geq -1.434$, p_s
612 ≥ 0.154 ; feature based clustering in feature rich versus reduced (early) and feature rich
613 versus reduced (late) conditions: $t_s \geq -1.359$, $p_s > 0.177$).

614 Taken together, our findings thus far suggest that adding item features that change
615 over time, even when they vary randomly and independently of the items, can enhance
616 participants' overall memory performance and can also enhance temporal and feature-
617 based clustering. To the extent that the number of item features that vary from moment
618 to moment approximates the "richness" of participants' experiences, our findings sug-
619 gest that participants remember "richer" stimuli better and organize richer stimuli more
620 reliably in their memories. Next, we turn to examine the memory effects of varying the
621 temporal ordering of different stimulus features while holding the features themselves
622 constant. We hypothesized that changing the order in which participants were exposed
623 to the words on a given list might enhance (or diminish) the relative influence of different
624 features. For example, presenting a set of words alphabetically might enhance partici-
625 pants' attention to the studied items' first letters, whereas sorting the same list of words by
626 semantic category might instead enhance participants' attention to the words' semantic
627 attributes. Importantly, we expected these order manipulations to hold even when the
628 variation in the total set of features (across words) was held constant across lists (e.g.,
629 unlike in the reduced (early) and reduced (late) conditions, where visual features were
630 added or removed from a subset of the lists participants studied).

631 Across six order manipulation conditions, we sorted early lists by each feature dimen-
632 sion but randomly ordered the items on late lists (see *Order manipulation conditions*; features:
633 category, size, length, first letter, color, and location). Participants in the category-ordered

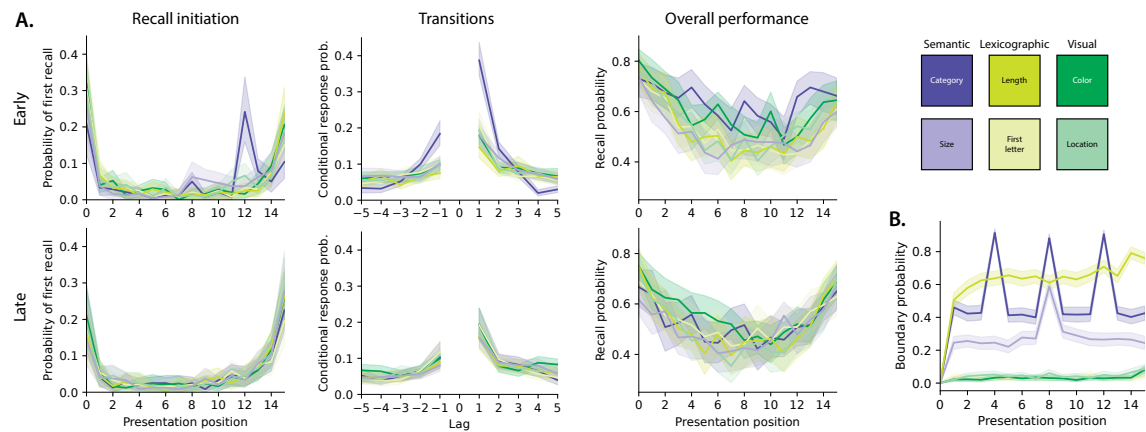


Figure 3: Recall dynamics in feature rich free recall (order manipulation conditions). **A.** Behavioral plots. **Left panels.** The probabilities of initiating recall with each word are plotted as a function of presentation position. **Middle panels.** The conditional probabilities of recalling each word are plotted as a function of the relative position (Lag) to the words recalled just-prior. **Right panels.** The overall probabilities of recalling each word are plotted as a function of presentation position. **All panels.** Error ribbons denote bootstrap-estimated 95% confidence intervals (calculated across participants). Top panels display the recall dynamics for early (order manipulation) lists in each condition (color). Bottom panels display the recall dynamics for late (randomly ordered) lists. See Figures S1 and S2 for analogous plots for the random (control) and adaptive conditions. **B.** Proportion of event boundaries (see *Identifying event boundaries*) for each condition's feature of focus, plotted as a function of presentation position.

condition showed an increase in memory performance on early lists (accuracy, relative to
 early feature rich lists; $t(95) = 3.034, p = 0.003$). Participants in the color-ordered condition
 also showed a trending increase in memory performance on early lists (again, relative to
 early feature rich lists: $t(96) = 1.850, p = 0.067$). Participants' performance on early lists
 in all of the other order manipulation conditions was indistinguishable from performance
 on the early feature rich lists ($|t|s < 1.013, ps > 0.314$). Participants in both of the se-
 mantically ordered conditions exhibited stronger temporal clustering on early lists (versus
 early feature rich lists; category: $t(95) = 8.508, p < 0.001$; size: $t(95) = 2.429, p = 0.017$).
 Participants in the length-ordered condition tended to exhibit *less* temporal clustering
 on early lists relative to early feature rich lists ($t(95) = -1.666, p = 0.099$), whereas par-
 ticipants in the first letter-ordered condition exhibited stronger temporal clustering on
 early lists ($t(95) = 2.587, p = 0.011$). Participants in the visually ordered conditions ex-
 hibited more similar performance on early lists, relative to early feature rich lists (color:
 $t(96) = -1.064, p = 0.290$; we found a trending enhancement for participants in the location-
 ordered condition: $t(95) = 1.682, p = 0.096$). We also compared feature-based clustering
 on early lists across the order manipulation and feature rich conditions. Since results were
 similar across both semantic conditions (category and size), both lexicographic conditions
 (length and first letter), and both visual conditions (color and location), here we aggre-
 gate data from conditions that manipulated each of these three feature groupings in our
 comparisons to simplify the presentation. On early lists, participants in the semantically
 ordered conditions exhibited stronger semantic clustering relative to participants in the
 feature rich condition (category: $t(125) = 2.524, p = 0.013$; size: $t(125) = 3.510, p = 0.001$),
 but showed no reliable differences in lexicographic (length: $t(125) = 0.539, p = 0.591$; first
 letter: $t(125) = -0.587, p = 0.558$) or visual (color: $t(125) = -0.579, p = 0.564$; location:
 $t(125) = -0.346, p = 0.730$) clustering. Similarly, participants in the lexicographically or-

659 dered conditions exhibited stronger (relative to feature rich participants) lexicographic
 660 clustering (length: $t(125) = 3.426, p = 0.001$; first letter: $t(125) = 3.236, p = 0.002$) on early
 661 lists, but showed no reliable differences in semantic (category: $t(125) = -1.078, p = 0.283$;
 662 size: $t(125) = -0.310, p = 0.757$) or visual (color: $t(125) = -0.209, p = 0.835$; location:
 663 $t(125) = -0.004, p = 0.997$) clustering. And participants in the visually ordered condi-
 664 tions exhibited stronger visual clustering (again, relative to feature rich participants, and
 665 on early lists; color: $t(126) = 2.099, p = 0.038$; location: $t(126) = 4.392, p = 0.000$), but
 666 showed now reliable differences in semantic (category: $t(126) = 0.204, p = 0.839$; size:
 667 $t(126) = -0.093, p = 0.926$) or lexicographic (length: $t(126) = 0.714, p = 0.476$; first letter:
 668 $t(126) = 0.820, p = 0.414$) clustering. Taken together, these order manipulation results sug-
 669 gest several broad patterns (Figs. 3A, 4). First, most of the order manipulations we carried
 670 out did *not* reliably affect overall recall performance. Second, most of the order manipula-
 671 tions increased participants' tendencies to temporally cluster their recalls. Third, all of the
 672 order manipulations enhanced participants' clustering of each condition's target feature
 673 (i.e., semantic manipulations enhanced semantic clustering, lexicographic manipulations
 674 enhanced lexicographic clustering, and visual manipulations enhanced visual clustering)
 675 while leaving clustering along other feature dimensions roughly unchanged (i.e., semantic
 676 manipulations did not affect lexicographic or color clustering, and so on).

677 When we closely examined the sequences of words participants recalled in early order
 678 manipulated lists (Fig. 3A, top panel), we noticed several differences from the dynamics of
 679 participants' recalls of randomly ordered lists (Figs. S1, S7). One striking difference is that
 680 participants in the category condition (dark purple curves, Fig. 3) most often initiated recall
 681 with the fourth-from-last item (*Recall initiation*, top left panel), whereas participants who
 682 recalled randomly ordered lists tended to initiate recall with either the first or last list items
 683 (Fig. S1, top left panel). We hypothesized that the participants might be "clumping" their

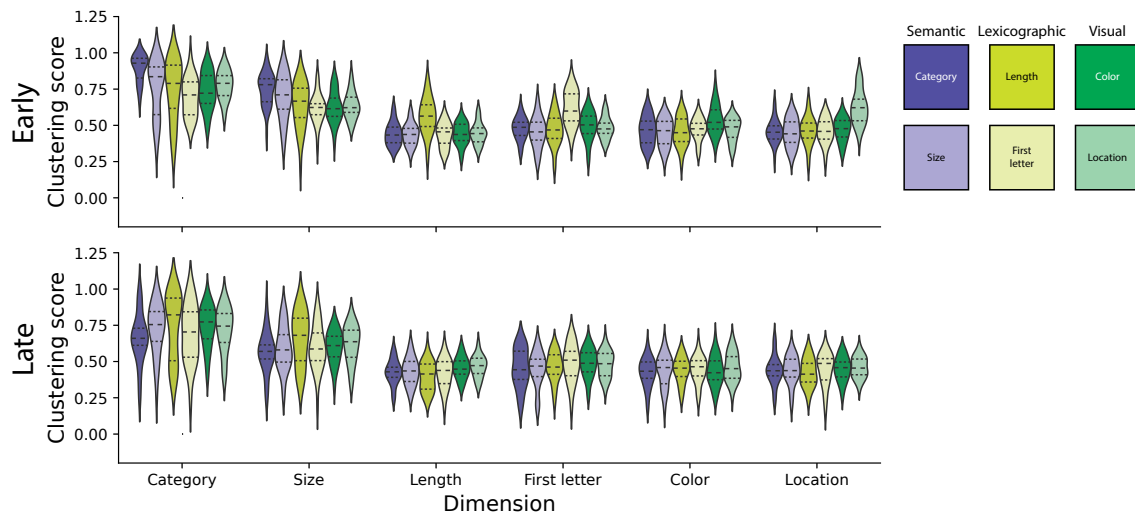


Figure 4: Memory “fingerprints” (order manipulation conditions). The across-participant distributions of clustering scores for each feature type (x -coordinate) are displayed for each experimental condition (color), separately for order manipulation (early, top) and randomly ordered (late, bottom) lists. See Figures S5 and S6 for analogous plots for the random (control) and adaptive conditions.

684 recalls into groups of items that shared category labels. Indeed, when we compared the
 685 positions of feature changes in the study sequence (Fig. 3B; see *Identifying event boundaries*)
 686 with the positions of items participants recalled first, we noticed a striking correspondence
 687 in both semantic conditions. Specifically, on category-ordered lists, the category labels
 688 changed every four items on average (dark purple peaks in Fig. 3B), and participants
 689 also seemed to display an increased tendency (relative to other order manipulation and
 690 random conditions) to initiate recall of category-ordered lists with items whose study
 691 positions were integer multiples of four. Similarly, for size-ordered lists, the size labels
 692 changed every eight items on average (light purple peaks in Fig. 3B), and participants
 693 also seemed to display an icnreased tendancy to initiate recall of size-ordered lists with
 694 items whose study positions were integer multiples of eight. A second striking difference
 695 is that participants in the category condition exhibited a much steeper lag-CRP (Fig. 3A,

top middle panel) than participants in other conditions. (This is another expression of participants' increased tendencies to temporally cluster their recalls on category-ordered lists, as we reported above.) Taken together, these order-specific idiosyncracies suggest a hierarchical set of influences on participants' memories. At longer timescales, "event boundaries" (to use the term loosely) can be induced across lists by adding or removing irrelevant visual features. At shorter timescales, "event boundaries" can be induced across items (within a single list) by adjusting how item features change throughout the list.

The above comparisons between memory performance on early lists in the order manipulation versus feature rich conditions highlight how sorted lists are remembered differently from random lists. We also wondered how sorting lists along each feature dimension influenced memory relative to sorting lists along the other feature dimensions. Participants trended towards remembering early lists that were sorted semantically better than lexicographically sorted lists ($t(118) = 1.936, p = 0.055$). Participants also remembered visually sorted lists better than lexicographically sorted lists ($t(119) = 2.145, p = 0.034$). However, participants showed no reliable differences in recall performance on semantically versus visually sorted lists ($t(119) = 0.113, p = 0.910$). Participants temporally clustered semantically sorted lists more strongly than either lexicographically ($t(118) = 5.572, p < 0.001$) or visually ($t(119) = 6.215, p < 0.001$) sorted lists, but did not show reliable differences in temporal clustering on lexicographically versus visually sorted lists ($t(119) = 0.189, p = 0.850$). Participants also showed reliably more semantic clustering on semantically sorted lists than lexicographically (category: $t(118) = 3.492, p = 0.001$, size: $t(118) = 3.972, p < 0.001$) or visually (category: $t(119) = 2.702, p = 0.008$, size: $t(119) = 4.230, p < 0.001$) sorted lists; more lexicographic clustering on lexicographically sorted lists than semantically (length: $t(118) = 3.112, p = 0.002$; first letter: $t(118) = 3.686, p = 0.000$) or visually (length: $t(119) = 3.024, p = 0.003$; first letter: $t(119) = 2.644, p = 0.009$) sorted lists; and more visual

721 clustering on visually sorted lists than semantically (color: $t(119) = -2.659, p = 0.009$;
722 location: $t(119) = -4.604, p = 0.000$) or lexicographically (color: $t(119) = -2.366, p = 0.020$;
723 location: $t(119) = -4.265, p < 0.001$) sorted lists. In summary, sorting lists by different
724 features appeared to have slightly different effects on overall memory performance and
725 temporal clustering, and people tended to cluster their recalls along a given feature di-
726 mension more when the studied lists were (versus were not) sorted along that dimension.

727 Beyond affecting how we process and remember *ongoing* experiences, what is happen-
728 ing to us now can also affect how we process and remember *future* experiences. Within
729 the framework of our study, we wondered: if early lists are sorted along different feature
730 dimensions, might this affect how people remember later (random) lists? In exploring this
731 question, we considered both group-level effects (i.e., effects that tended to be common
732 across individuals) and participant-level effects (i.e., effect that were idiosyncratic across
733 individuals).

734 At the group level, there seemed to be almost no lingering impact of sorting early
735 lists on memory for later lists. To simplify the presentation, we report these null results
736 in aggregate across the three feature groupings. Relative to memory performance on
737 late feature rich lists, participants' memory performance in all six order manipulation
738 conditions showed no reliable differences (semantic: $t(125) = 0.487, p = 0.627$; lexico-
739 graphic: $t(125) = 0.878, p = 0.382$; visual: $t(126) = 1.437, p = 0.153$). Nor did we observe
740 any reliable differences in temporal clustering on late lists (relative to late feature rich
741 lists; semantic: $t(125) = 0.146, p = 0.884$; lexicographic: $t(125) = 0.923, p = 0.358$; visual:
742 $t(126) = 0.525, p = 0.601$). Aside from a slightly increased tendency for participants to
743 cluster words by their length on late visual order manipulation lists (more than late fea-
744 ture rich lists; $t(126) = 2.199, p = 0.030$), we observed no reliable differences in any type of
745 feature clustering on late order manipulation condition lists versus late feature rich lists

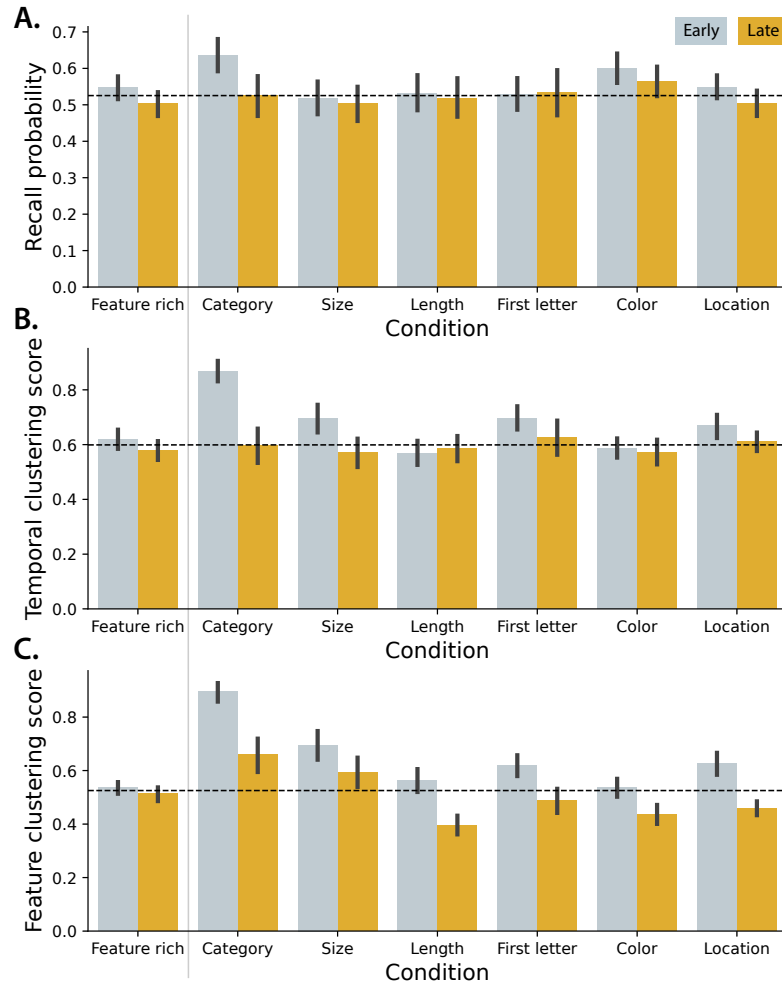


Figure 5: Recall probability and clustering scores on early and late lists. The bar heights display the average (across participants) recall probabilities (A.), temporal clustering scores (B.), and feature clustering scores (C.) for early (gray) and late (gold) lists. For the feature rich bars (left), the feature clustering scores are averaged across features. For the order manipulation conditions, feature clustering scores are displayed for the focused-on feature for each condition (e.g., category clustering scores are displayed for the category condition, and so on). All panels: error bars denote bootstrap-estimated 95% confidence intervals. The horizontal dotted lines denote the average values (across all lists and participants) for the feature rich condition.

746 ($\|t\|_s \leq 1.234, p_s \geq 0.220$).

747 We also looked for more subtle group-level patterns. For example, perhaps sorting
748 early lists by one feature dimension could affect how participants cluster *other* features (on
749 early and/or late lists) as well. We defined participants' *memory fingerprints* as the set of
750 temporal and feature clustering scores. A participant's memory fingerprint describes how
751 they tend to retrieve memories of the studied items, perhaps searching through several
752 feature spaces (or along several representational dimensions). To gain insights into the
753 dynamics of how participants' clustering scores tended to change over time, we computed
754 the average (across participants) fingerprint from each list, from each order manipulation
755 condition (Fig. 6). We projected these fingerprints into a two-dimensional space to help
756 visualize the dynamics (top panels; see *Computing low-dimensional embeddings of memory*
757 *fingerprints*). We found that participants' average fingerprints tended to remain relatively
758 stable on early lists, and exhibited a "jump" to another stable state on later lists. The
759 sizes of these jumps varied somewhat across conditions (the Euclidean distances between
760 fingerprints in their original high dimensional spaces are displayed in the bottom panels).
761 We also averaged the fingerprints across early and late lists, respectively, for each condition
762 (Fig. 6B). We found that participants' fingerprints on early lists seem to be influenced by
763 the order manipulations on those lists (see the locations of the circles in Fig. 6B). There
764 also seemed to be some consistency across different features within a broader type. For
765 example, both semantic feature conditions (category and size; purple markers) diverge in
766 a similar direction from the group; both lexicographic feature conditions (length and first
767 letter; yellow markers) diverge in a similar direction; and both visual conditions (color
768 and location; green) also diverge in a similar direction. But on late lists, participants'
769 fingerprints seem to return to a common state that is roughly shared across conditions
770 (i.e., the stars in that panel are clumped together).



Figure 6: Memory fingerprint dynamics (order manipulation conditions). **A.** Each column (and color) reflects an experimental condition. In the top panels, each marker displays a 2D projection of the (across-participant) average memory fingerprint for one list. Order manipulation (early) lists are denoted by circles and randomly ordered (late) lists are denoted by stars. All of the fingerprints (across all conditions and lists) are projected into a common space. The bar plots in the bottom panels display the Euclidean distances of the per-list memory fingerprints to the list 0 fingerprint, for each condition. Error bars denote bootstrap-estimated 95% confidence intervals. The dotted vertical lines denote the boundaries between early and late lists. **B.** In this panel, the fingerprints for early (circle) and late (star) lists are averaged across lists and participants before projecting the fingerprints into a (new) 2D space. See Figure S8 for analogous plots for the random (control) conditions.

When we examined the data at the level of individual participants (Figs. 7 and 8), a clearer story emerged. Within each order manipulation condition, participants exhibited a range of feature clustering scores, on both early and late lists (Fig. 7A, B). Across every order manipulation condition, participants who exhibited stronger feature clustering (for their condition's manipulated feature) recalled more words. This trend held overall across conditions and participants (early: $r(179) = 0.537, p < 0.001$; late: $r(179) = 0.492, p = 0.000$) as well as for each condition individually for early ($r_s \geq 0.386$, all $p_s \leq 0.035$) and late ($r_s \geq 0.462$, all $p_s \leq 0.010$) lists. We found no evidence of a condition-level trend; for example the conditions where participants tended to show stronger clustering scores were not correlated with the conditions where participants remembered more words (early: $r(4) = 0.526, p = 0.284$; late: $r(4) = -0.257, p = 0.623$; see insets of panels A and B). We observed carryover associations between feature clustering and recall performance

(Fig. 7C, D). Participants who showed stronger feature clustering on early lists tended to recall more items on late lists (across conditions: $r(179) = 0.492, p < 0.001$; all conditions individually: $r_s \geq 0.462$, all $p_s \leq 0.010$). Participants who recalled more items on early lists also tended to show stronger feature clustering on late lists (across conditions: $r(179) = 0.280, p < 0.001$; all non-visual conditions: $r_s \geq 0.445$, all $p_s \leq 0.014$; color: $r(29) = 0.298, p = 0.103$; location: $r(28) = 0.354, p = 0.055$). Neither of these effects showed condition-level trends (early feature clustering versus late recall probability: $r(4) = -0.299, p = 0.565$; early recall probability versus late feature clustering: $r(4) = 0.400, p = 0.432$). We also looked for associations between feature clustering and temporal clustering. Across every order manipulation condition, participants who exhibited stronger feature clustering also exhibited stronger temporal clustering. For early lists (Fig. ??E), this trend held overall ($r(179) = 0.924, p < 0.001$), for each condition individually (all $r_s \geq 0.822$, all $p_s < 0.001$), and across conditions ($r(4) = 0.964, p = 0.002$). For late lists (Fig. ??F), the results were more variable (overall: $r(179) = 0.348, p = 0.000$; all non-visual conditions: $r_s \geq 0.382$, all $p_s \leq 0.037$; color: $r(29) = 0.453, p = 0.011$; location: $r(28) = 0.190, p = 0.314$; across-conditions: $r(4) = -0.036, p = 0.945$). While less robust than the carryover associations between feature clustering and recall performance, we also observed some carryover associations between feature clustering and temporal clustering (Fig. 7G, H). Participants who showed stronger feature clustering on early lists trended towards showing stronger temporal clustering on later lists (overall: $r(179) = 0.301, p < 0.001$; for individual conditions: all $r_s \geq 0.297$, all $p_s \leq 0.111$; across conditions: $r(4) = 0.107, p = 0.840$). And participants who showed stronger temporal clustering on early lists trended towards showing stronger feature clustering on later lists (overall: $r(179) = 0.579, p < 0.001$; all non-visual conditions: $r_s \geq 0.323$, all $p_s \leq 0.082$; visual conditions: $r_s \geq 0.089$, all $p_s \leq 0.632$; across conditions: $r(4) = 0.916, p = 0.010$). Taken together, the results displayed in Figure 7 show that

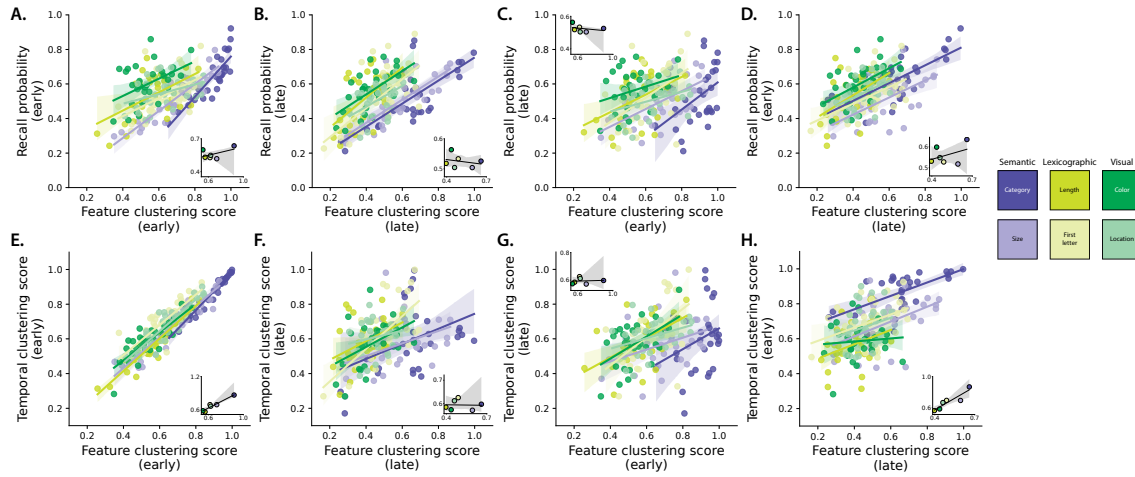


Figure 7: Interactions between feature clustering, recall probability, and contiguity. **A.** Recall probability versus feature clustering scores for order manipulation (early) lists. **B.** Recall probability versus feature clustering for randomly ordered (late) lists. **C.** Recall probability on late lists versus feature clustering on early lists. **D.** Recall probability on early lists versus feature clustering on late lists. **E.** Temporal clustering scores (contiguity) versus feature clustering scores on early lists. **F.** Temporal clustering scores versus feature clustering scores on late lists. **G.** Temporal clustering scores on late lists versus feature clustering scores on early lists. **H.** Temporal clustering scores on early lists versus feature clustering scores on late lists. **All panels.** Each dot in the main scatterplots denotes the average scores for one participant. The colored regression lines are computed across participants. The inset displays condition-averaged results, where each dot reflects a single condition and the regression line is computed across experimental conditions. All error ribbons denote bootstrap-estimated 95% confidence intervals.

participants who were more sensitive to the order manipulations (i.e., participants who showed stronger feature clustering for their condition’s feature on early lists) remembered more words and showed stronger temporal clustering. These associations also appeared to carry over across lists, even when the items on later lists were presented in a random order.

If participants show different sensitivities to order manipulations, how do their behaviors carry over to later lists? We found that participants who showed strong feature clustering on early lists often tended to show strong feature clustering on late lists (Fig. 8A; overall across participants and conditions: $r(179) = 0.592, p < 0.001$; non-visual feature

817 conditions: all $r_s \geq 0.350$, all $p_s \leq 0.058$; color: $r(29) = -0.071, p = 0.704$; location:
 818 $r(28) = 0.032, p = 0.868$; across conditions: $r(4) = 0.934, p = 0.006$). Although participants
 819 tended to show weaker feature clustering on late lists (Fig. 6) on *average*, the associations
 820 between early and late lists for individual participants suggests that some influence of
 821 early order manipulations may linger on late lists. We found that participants who exhib-
 822 ited larger carryover in feature clustering (i.e., continued to show strong feature clustering
 823 on late lists) for the semantic order manipulations (but not other manipulations) also
 824 tended to show a larger improvement in recall (Fig. 8B; overall: $r(179) = 0.378, p < 0.001$;
 825 category: $r(28) = 0.419, p = 0.021$; size: $r(28) = 0.737, p < 0.001$; non-semantic condi-
 826 tions: all $r_s \leq 0.252$, all $p_s \geq 0.179$; across conditions: $r(4) = 0.773, p = 0.072$) on late
 827 lists, relative to early lists. Participants who exhibited larger carryover in feature cluster-
 828 ing also tended to show stronger temporal clustering on late lists (relative to early lists)
 829 for all but the category condition (Fig. 8C; overall: $r(179) = 0.434, p < 0.001$; category:
 830 $r(28) = 0.229, p = 0.223$; all non-category conditions: all $r_s \geq 0.448$, all $p_s \leq 0.012$; across
 831 conditions: $r(4) = 0.598, p = 0.210$).

832 We suggest two potential interpretations of these findings. First, it is possible that
 833 some participants are more “malleable” or “adaptable” with respect to how they organize
 834 incoming information. When presented with list of items sorted along *any* feature dimen-
 835 sion, they will simply adopt that feature as a dominant dimension for organizing those
 836 items and subsequent (randomly ordered) items. This flexibility in memory organization
 837 might afford such participants a memory advantage, explaining their strong recall perfor-
 838 mance. An alternative interpretation is that each participant comes into our study with
 839 a “preferred” way of organizing incoming information. If they happen to be assigned to
 840 an order manipulation condition that matches their preferences, then they will appear to
 841 be “sensitive” to the order manipulation and also exhibit a high degree of carryover in

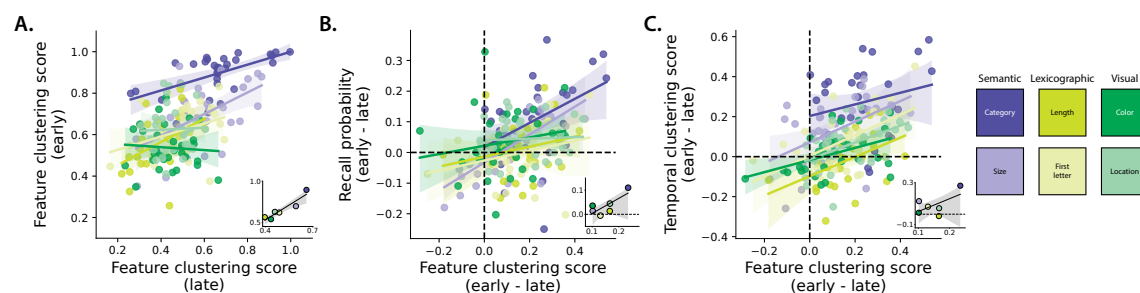


Figure 8: Feature clustering carryover effects. **A.** Feature clustering scores for ordder manipulation (early) versus randomly ordered (late) lists. **B.** Accuracy differences (on early versus late lists) versus feature clustering “carryover” (defined as the differences between the average clustering scores on early and late lists). **C.** Temporal clustering differences (on early versus late lists) versus feature clustering carryover. **All panels.** Each dot in the main scatterplots denotes the average scores for one participant. The colored regression lines are computed across participants. The inset displays condition-averaged results, where each dot reflects a single condition and the regression line is computed across experimental conditions. All error ribbons denote bootstrap-estimated 95% confidence intervals.

feature clustering from early to late lists. These participants might demonstrate strong recall performance not because of their inherently superior memory abilities, but rather because the specific condition they were assigned to happened to be especially easy for them, given their pre-experimental tendencies. To help distinguish between these interpretations, we designed an *adaptive* experimental condition (see *Adaptive condition*). The primary manipulation in the adaptive condition is that participants each experience three key types of lists. On *random* lists, words are ordered randomly (as in the feature rich condition). On *stabilize* lists, the presentation order is adjusted to be maximally similar to the current estimate of the participant’s memory fingerprint (see *Online “fingerprint” analysis*). Third, on *destabilize* lists, the presentation is adjusted to be *minimally* similar to the current estimate of the participant’s memory fingerprint (see *Ordering “stabilize” and “destabilize” lists by an estimated fingerprint*). The orders in which participants experienced each type of list were counterbalanced across participants to help reduce the influence of potential list order effects. Because the presentation orders on stabilize and destabilize lists

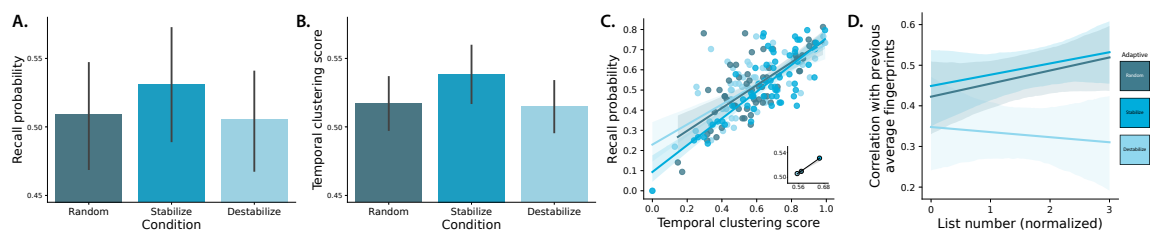


Figure 9: Adaptive free recall. **A.** Average probability of recall (taken across words, lists, and participants) for lists from each adaptive condition. **B.** Average temporal clustering scores for lists from each adaptive condition. **C.** Recall probability versus temporal clustering scores by participant (main panel; each participant contributes one dot per condition) and averaged within condition (inset; each dot represents a single condition). **D.** Per-list correlations between the current list’s fingerprint and the average fingerprint computed from all previous lists. The normalized list numbers (x -axis) denote the number of lists of the same type that the participant had experienced at the time of the current list. All panels: Colors denote the sorting type (condition) for each list. Error bars and ribbons denote bootstrap-estimated 95% confidence intervals. For additional details about participants’ behavior and performance during the adaptive conditions, see Figure S2.

are adjusted to best match each participant’s (potentially unique) memory fingerprint, the adaptive condition removes uncertainty about whether participants’ assigned conditions might just “happen” to match their preferred ways or organizing their memories.

Participants’ fingerprints on stabilize and random lists tended to become (numerically) slightly more similar to their average fingerprints computed from the previous lists they had experienced, and their fingerprints on destabilize lists tended to become numerically less similar (Fig. 9D). Overall, we found that participants tended to be better at remembering words on stabilize lists relative to words on random ($t(59) = 1.740, p = 0.087$) or destabilize ($t(59) = 1.714, p = 0.092$) lists (Fig. 9A). Participants showed no reliable differences in their memory performance on destabilize versus random lists ($t(59) = -0.249, p = 0.804$). Participants also exhibited stronger temporal clustering on stabilize lists, relative to random ($t(59) = 3.554, p = 0.001$) and destabilize ($t(59) = 4.045, p < 0.001$) lists (Fig. 9B). We found no reliable differences in temporal clustering for items on random versus destabilize lists ($t(59) = -0.781, p = 0.438$).

As in the other experimental manipulations, participants in the adaptive condition

exhibited substantial variability with respect to their overall memory performance and their clustering tendencies (Fig. 9C). We found that individual participants who exhibited strong temporal clustering scores also tended to recall more items. This held across subjects, aggregating across all list types ($r(178) = 0.721, p < 0.001$), and for each list type individually (all r s ≥ 0.683 , all p s ≤ 0.001). Taken together, the results from the adaptive condition suggest that each participant comes into the experiment with their own unique memory organization tendencies, as characterized by their memory fingerprint. When participants study lists whose items come pre-sorted according to their unique preferences, they tend to remember more and show stronger temporal clustering.

Discussion

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