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

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Abstract

We perceive, interpet, 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.

Introduction

Experience is subjective: different people who encounter identical physical experiences can take away very different meanings and memories. One reason is that our subjective experiences in the moment are shaped in part the idiosyncratic prior experiences, memories, goals, thoughts, expectations, and emotions that we bring with us into the present moment. These factors collectively define a *context* for our experiences[13]. situation models: forming expectations, predicting ambiguous future experiences The contexts we encounter help us to construct *situation models*[15,24] or *schemas*[2,18] that describe how experiences are likely to unfold based on our prior experiences with similar contextual cues. For example, when we enter a sit-down restaurant, we might expect to be seated at a table, given a menu, and served food. Priming someone to expect a particular situation or context can also influence how they resolve potentail ambiguities in their ongoing experiences, including ambiguous movies and narratives[32].

Our understanding of how we form situation models and schemas, and how they interact with our subjective experiences and memories, is constrained in part by substantial differences in how we study these processes. Situation models and schemas are most often studied using "naturalistic" stimuli such as narratives and movies[20,33,34]. In contrast, our understanding of how we organize our memories has been most widely studied using more traditional paradigms like free recall of random word lists[11]. In free recall, participants study lists of items and are instructed to recall the items in any order they choose. The orders in which words come to mind can provide insights into how participants have organized their memories of the studied words. Because random word lists are unstructured by design, it is not clear if or how non-trivial situation models might apply to these stimuli. Nevertheless, there are *some* commonalities between memory for word lists and memory for real-world experiences.

Like remembering real-world experiences, remembering words on a studied list requires distinguishing the current list from the rest of one's experience. To model this fundamental memory capability, cognitive scientists have posited the existence of a special representation, called *context*, that is associated with each list. According to early theories e.g.[1,6] context representations are composed of many features which fluctuate from moment to moment, slowly drifting through a multidimensional feature space. During recall, this representation forms part of the retrieval cue, enabling us to distinguish list items from non-list items. Understanding the role of context in memory processes is particularly important in self-cued memory tasks, such as *free recall*, where the retrieval cue is "context" itself.

Over the past half-century, context-based models have enjoyed impressive success at explaining many stereotyped behaviors observed during free recall and other list-learning tasks[6–8,12,21–23,27? –29]. These phenomena include the well-known recency and primacy effects (superior recall of items from the end and, to a lesser extent, from the beginning of the study list), as well as semantic and temporal clustering effects[?] . The contiguity effect is an example of temporal clustering, which is perhaps the dominant form of organization in free recall. This effect can be seen in the tendency for people to successively recall items that occupied neighboring positions in the study list. For example, if a list contained the sub-sequence "absence hollow pupil" and the participant recalls the word "hollow", it is far more likely that the next response will be either "pupil" or "absence" than some other list item[10]. In addition, there is a strong forward bias in the contiguity effect: subjects make forward transitions (i.e., "hollow" followed by "pupil") about twice as often as they make backward transitions, despite an overall tendency to begin recall at the end of the list. There are also striking effects of semantic clustering[3,4,9,14,25], whereby the recall of a given item is more likely to be followed by recall of a similar or related item than a dissimilar or unrelated one. In general, people organize memories for words along a wide variety of stimulus dimensions. As captured by models like the *Context Maintenance and Retrieval Model*[22], the stimulus features associated with each word (e.g. the word's meaning, font size, font color, location on the screen, size of the object the word represents, etc.) are incorporated into the participant's mental context representation[13,15–17,30]. During a memory test, any of these features may serve as a memory cue, which in turn leads the participant to recall in succession words that share stimulus features.

A key mystery is whether the sorts of situation models and schemas that people use to organize their memories of real-world experiences might map onto the clustering effects that reflect how people organize their memories for word lists. On one hand, situation models and clustering effects both reflect statistical regularities in ongoing experience. Our memory systems exploit these regularities when generating inferences about the unobserved past and yet-to-be-experienced future[5,19,24,26,31]. On the other hand, the rich structure of real-world experiences and other naturalistic stimuli that enable people to form deep and meaningful situation models and schemas have no obvious analog in simple word lists. Often lists in free recall studies are explicitly *designed* to be devoid of exploitable temporal structure, for example by sorting the words in a random order[11].

We designed an experimental paradigm to explore how people organize their memories for simple stimuli (word lists) whose temporal properties change across different "situations," analogous to how the content of real-world experiences change across different real-world situations. We asked participants to study and freely recall a series of word lists (Fig. 1). Across the different conditions in the experiment, we varied the lists' presentation orders in different ways across lists. The studied items (words) were designed to vary along three general dimensions: semantic (word *category*, and physical *size* of the referent), lexicographic (word *length* and *first letter*), and visual (font *color* and

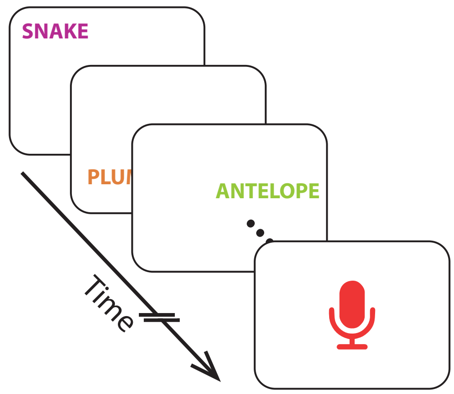

Figure 1: Feature-rich free recall. After studying lists comprised of words that vary along several feature dimensions, participants verbally recall words in any order (microphone icon).

the onscreen *location* of each word). In our main manipulation conditions, we asked participants to study and recall eight lists whose items were sorted by a target feature (e.g., word category). Next, we asked them to study and recall an additional eight lists whose items had the same features, but that were sorted in a random temporal order. We were interested in how these order manipulations affected participants' recall behaviors on early (sorted) lists, as well as how order manipulations on early lists affected recall behaviors on later (unsorted) lists. We used a series of control conditions as a baseline; in these control conditions all of the lists were sorted randomly, but we manipulated the presence or absence of the visual features. Finally, in an *adaptive* experimental condition we used participants' recall behaviors on early lists to manipulate, in real-time, the presentation orders of subsequent lists. In this adaptive condition, we sought to identify potential commonalities within and across participants in how people organized their memories and how those organizational tendancies affect overall performance.

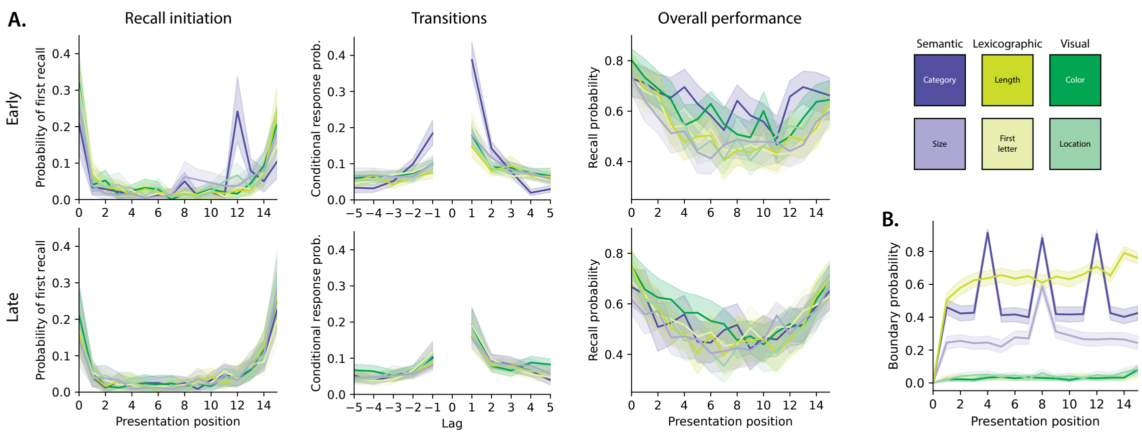

Figure 2: Recall dynamics in feature rich free recall (order manipulation conditions). A. Behavioral plots. **Left panels.** The probabilities of initiating recall with each word are plotted as a function of presentation position. **Middle panels.** The conditional probabilities of recalling each word 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 *Methods*) for each condition's feature of focus, plotted as a function of presentation position.

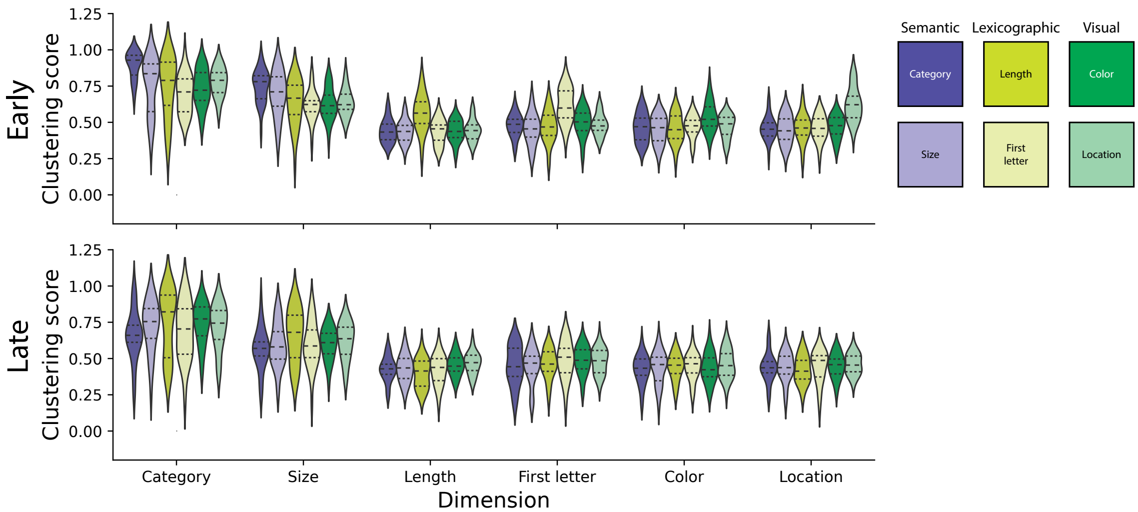

Figure 3: Memory "fingerprints" (order manipulation conditions). The across-participant distributions of clustering scores for each feature type (x-coordinate) are displayed for each experimental condition (color), separately for order manipulation (early, top) and randomly ordered (late, bottom) lists. See Figures S5 and S6 for analogous plots for the random (control) and adaptive conditions.

Results

Figure S3.

Figure S7.

Figure S4.

Discussion

Materials and methods

Participants

We enrolled a total of 491 Dartmouth undergraduate students across 11 experimental conditions. The conditions included two primary controls (feature rich, reduced), two

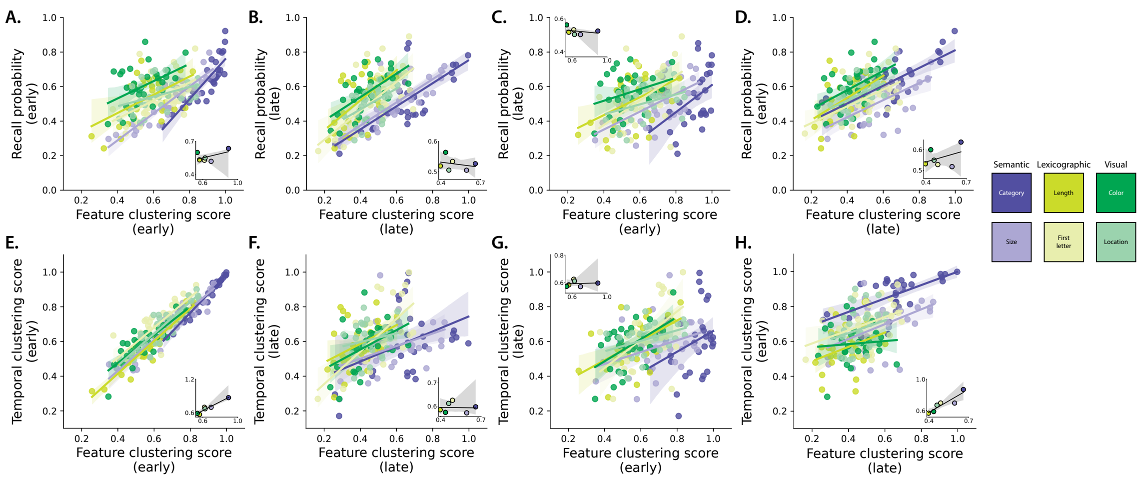

Figure 4: Interactions between feature clustering, recall probability, and contiguity. A. Recall probability versus feature clustering scores for order manipulation (early) lists. **B.** Recall probability versus feature clustering for randomly ordered (late) lists. **C.** Recall probability on late 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.

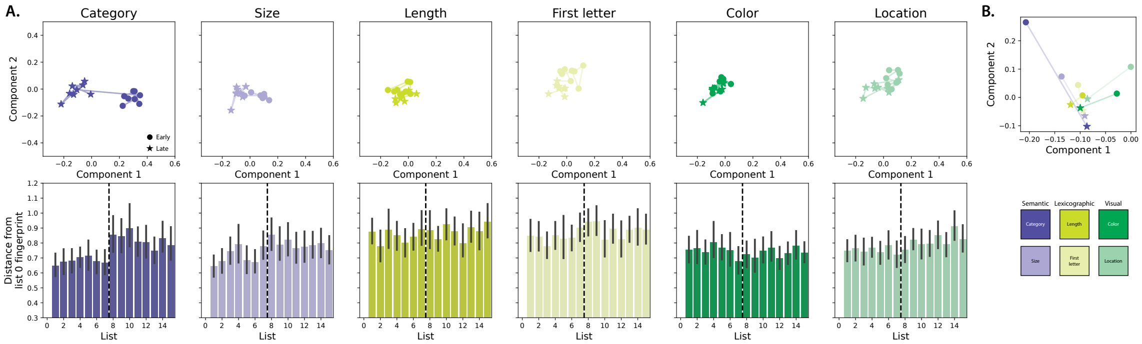

Figure 5: Memory fingerprint dynamics (order manipulation conditions). A. Each column (and color) reflects an experimental condition. In the top panels, each marker displays a 2D projection of the (across-participant) average memory fingerprint for one list. Order manipulation (early) lists are denoted 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.

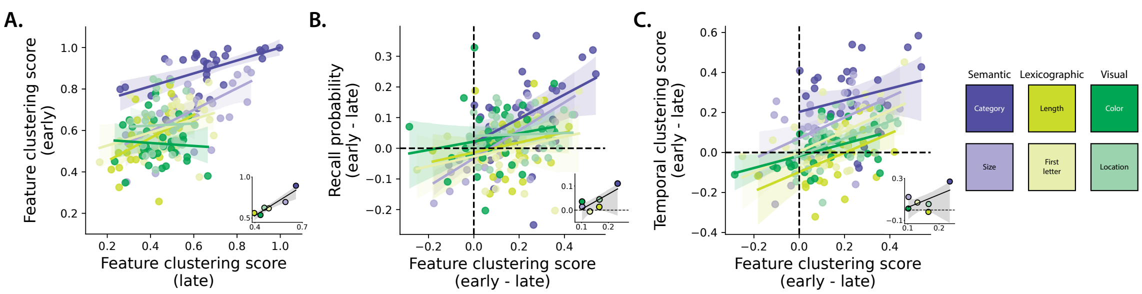

Figure 6: Feature clustering carryover effects. A. Feature clustering scores for ordder manipulation (early) versus randomly ordered (late) lists. **B.** Accuracy differences (on early versus late lists) versus feature clustering "carryover" (defined as the differences between the average clustering 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.

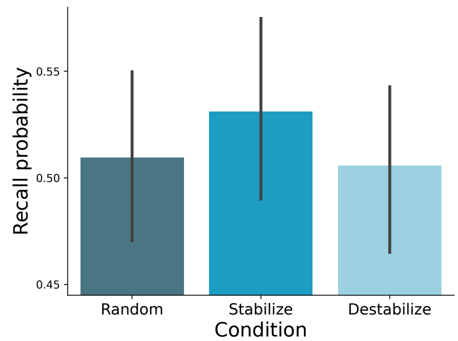

Figure 7: Recall performance (adaptive conditons). The bars display the average probability of recall (taken across words, lists, and participants) for lists from each adaptive condition. Error bars denote bootstrap-estimated 95% confidence intervals. For additional details about participants' behavior and performance during the adaptive conditions, see Figure S2.

secondary controls (reduced (early), reduced (late)), six order manipulation conditions (category, size, length, first letter, color, and locaiton), and a final adaptive condition. Each of these conditions are described in the *Experimental design* subsection below.

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

We aimed to run (to completion) at least 60 participants in each of the two primary control conditions and in the adaptive condition. In all other conditions we set a target enrollment of at least 30 participants. Because our data collection efforts were coordinated 12 researchers and multiple testing rooms and computers, it was not feasible for individual experimenters to know how many participants had been run in each experimental condition until the relevant databases were synchronized at the end of each working day.

We also over-enrolled participants for each condition to help ensure that we met our minimum enrollment targets even if some participants dropped out of the study prematurely or did not show up for their testing session. This led us to exceed our target enrollments 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.) A complete report...

Experimental design

Our experiment is a variant of the classic free recall paradigm that we term *feature-rich free recall*. In feature-rich free recall, participants study 16 lists, each comprised of 16 words that vary along a number of stimulus dimensions: semantic category, object size, text color, text location, word length, and starting letter (Fig. **??**). Each list contains four words from each of four different semantic categories; all other stimulus features are randomized. After studying each list, the participant attempts to recall as many words as they can from that list, in any order they choose. Because each individual word is associated with several well-defined (and quantifiable) features, and because each list incorporates a diverse mix of feature values along each dimension, this allows us to evaluate participants' memory fingerprints in rich detail.

Our experimental paradigm incorporates the Annyang and Google Cloud Speech API speech-to-text engines to automatically transcribe participants' verbal recalls into text. This allows recalls to be transcribed in real time– a distinguishing feature of the experiment; in typical verbal recall experiments the audio data must be parsed manually. (We have run a pilot experiment to verify that the automatically transcribed recalls are sufficiently close to human-transcribed recalls to yield reliable data.) This real-time speech processing component of the paradigm plays an important role in Experiments 3–5.

Stimuli

Real-time speech-to-text processing

Order manipulation conditions

Feature dimensions.

Constructing feature-sorted lists.

Random conditions

Adaptive conditions

Online "fingerprint" analysis.

Ordering "stabilize" lists by an estimated fingerprint.

Ordering "destabilize" lists by an estimated fingerprint.

Analysis

Probability of first recall and probability of n^{th} recall

Lag conditional response probability

Computing clustering scores and memory fingerprints

Identifying event boundaries

Serial position curves and recall accuracy

Computing low-dimensional embeddings of memory fingerprints

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