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# Spatial Clustering During Memory Search

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In recalling a list of previously experienced items, participants are known to organize their responses on the basis of the items' semantic and temporal similarities. Here, we examine how spatial information influences the organization of responses in free recall. In Experiment 1, participants studied and subsequently recalled lists of landmarks. In Experiment 2, participants played a game in which they delivered objects to landmarks in a virtual environment and later recalled the delivered objects. Participants in both experiments were simply asked to recall as many items as they could remember in any order. By analyzing the conditional probabilities of recall transitions, we demonstrate strong spatial and temporal organization of studied items in both experiments.

*Keywords:* free recall, spatial clustering, spatial memory



Research on free recall has been instrumental in characterizing the organizational structure of human memory. This organization can be seen in the way participants cluster their responses according to different attributes of the studied items, such as their meaning (semantic clustering) or their temporal/ordinal position on the studied list (temporal clustering). Semantic clustering may be seen in participants' tendency to successively recall semantically related items, and temporal clustering may be seen in participants' tendency to successively recall neighboring list items (Bousfield & Sedgewick, 1944; Kahana, 2012). In addition to demonstrating temporal and semantic clustering effects, researchers have also shown that recalls can be clustered by attributes attached to items by the way in which the items were encoded (Frost, 1971; Hintzman, Block, & Inskeep, 1972). Thus, for example, in a list where some items were encoded using a size task and other items were encoded using an animacy task, participants will organize their recalls according to the encoding task, as well as according to temporal and semantic proximity (Polyn, Norman, & Kahana, 2009).

Here we extend the organizational analysis of free recall to the domain of spatial memory. In particular, we seek to determine whether and how episodic memories become organized according to their spatial attributes. Although many of our everyday experiences occur in distinct spatial contexts, most studies of memory have participants studying semantically varying material within a single spatial context—the memory lab. As such, the influence of spatial information on the organization of memories is not well understood.

Our work builds on prior studies that have examined the dual contributions of temporal and spatial information in how maps are learned and how map locations are later recalled or recognized (e.g., Clayton & Chattin, 1989; Curiel & Radvansky, 1998; McNamara, Halpin, & Hardy, 1992; McNamara, Ratcliff, & McKoon, 1984; Shelton & Yamamoto, 2009). For example, McNamara et al. (1992) asked participants to learn a list of object–name location pairings on a two-dimensional array. Once participants could correctly recall the object name associated with each location, they were given a recognition test in which they were asked to distinguish between studied and novel objects names presented without any spatial information. They found that participants were faster at correctly recognizing studied (target) items when they were preceded by a test item that was studied in both temporal and spatial proximity. Curiel and Radvansky (1998) used a similar paradigm to examine the spatial organization of remembered items. During the learning of object–location pairs, one group of participants named the objects when cued by the locations, and the other group pointed to the location of a named object. On a subsequent free recall task, the researchers found strong evidence for spatial clustering in the pointing task but not in the naming task. In each of these experiments participants were instructed to learn the location of each of the presented items within a two-dimensional array, either by retrieving the name associated with a location or retrieving the location associated with a name.

Most theories of memory search assume that the just-recalled item, and its associated semantic and contextual information, forms part of the retrieval cue for the next response. Temporal

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clustering effects should be observed to the extent that recalling an item retrieves its associated temporal context, as this information will be similar to the contexts associated with neighboring list items (Howard & Kahana, 2002; Polyn et al., 2009; Sederberg, Howard, & Kahana, 2008). Similarly, spatial clustering effects should be observed to the extent that recalling an item retrieves its associated spatial features, as this information will be similar to the spatial features associated with spatially proximate items. Assuming that spatial attributes form an integral part of the item representations encoded in memory, one would expect to see spatial clustering even in tasks where participants are not instructed to encode the spatial context of the to-be-learned items and where retrieval makes no explicit reference to the spatial characteristics of the items.

Two complementary free recall experiments were performed to test these ideas. In Experiment 1, we had participants study and subsequently recall lists of landmarks. In Experiment 2, we had participants play a game in which they delivered objects to landmarks in a virtual environment and later recalled the delivered objects. We then analyzed the conditional probabilities of recall transitions to examine the spatial and temporal organization of the studied items. In both cases, the participants' goal was to freely recall as many items as they could remember.

## Experiment 1

### Method

**Participants.** Participants were 43 young adults (24 male, age 18–30 years) recruited from the University of Pennsylvania student community. Participants were compensated monetarily for their participation and were given a bonus based on their responses to the orienting task (see below).

**Procedure.** Each participant took part in four experimental sessions, each on a separate day. The first session was intended to familiarize participants with the items being studied and freely recalled in the subsequent three sessions. These items were drawn from a pool consisting of 256 names of well-known landmarks (e.g., Eiffel Tower, Golden Gate Bridge), 256 names of celebrities, and 256 common objects. Images corresponding to these items were obtained from free sources on the Internet and were chosen to be distinctive and memorable. The images were presented with the name written in text above them.

In the familiarization session, participants viewed each item from each of the three categories for 3,500 ms during which time they rated its familiarity on a 4-point scale. Each stimulus was followed by a blank interstimulus interval (ISI) of 1,000 ± 200 ms. This provided participants with a base level of familiarity with each item and provided us with norms on the familiarities of the items.

Across the subsequent three sessions, participants took part in 48 study-test trials involving immediate free recall of 24 item lists. There were two types of lists: mixed-category lists that contained eight items from each of the three categories and same-category lists that were composed of items all drawn from the same category. In the mixed-category lists, items were presented in trains of same-category items, with each train containing two to six items. The order of category trains was randomized, with the constraints that all categories appeared in each set of three trains and that adjacent trains did not contain the same category. Each session contained 10 mixed-category lists and six same-category lists. The order of mixed-category and same-category lists within each session was randomized. Items did not appear more than once within a session and were chosen so that items from the same subcategory (e.g., stadiums, presidents) did not appear in the same list.

Each item was presented for 3,500 ms, during which the participant was instructed to make a category-specific 4-point semantic judgment (celebrities: "How much do you love or hate this person?"; locations: "How much would you like to visit this place?"; objects: "How often do you come across this object in your daily life?"). If participants did not respond while the stimulus was on the screen, a message appeared asking them to respond more quickly. Each stimulus was followed by a blank ISI of 1,000 ± 200 ms. Each list was followed by immediate free recall of items from the list. After presentation of the last stimulus, the screen was blank for 1,300 ± 100 ms, followed by presentation of a row of asterisks and a 300-ms tone signaling the start of the recall period.

Participants were given 90 s to recall the names of stimuli from the list in any order, without regard to stimulus category. Verbal responses were recorded with a microphone; following each session, digital recordings were scored using custom software (Solway, Geller, Sederberg, & Kahana, 2010). At the end of each session, there was a final free recall period where participants were given 360 s to recall names of stimuli from any of the lists presented during the session. Additionally, scalp electroencephalography (EEG) data were collected during all sessions, with the intent of examining whether category-related EEG signals become reinstated in the moments prior to recall of an item. Information regarding the EEG methods and results, as well as more specific behavioral analyses concerning differences in clustering for different categories, can be found in Morton et al. (in press).

Because final free recall is a test of the same items that were previously tested in immediate free recall, items recalled on an immediate test will have an advantage in final free recall due to output encoding. As such, clustering effects that are observed in immediate free recall will tend to be observed in final free recall simply as a result of the output encoding process. However, because recent items have a large advantage in immediate free recall but a disadvantage in final free recall (the negative recency effect; Craik, 1970), the consistency of clustering effects across both immediate and final free recall suggests that these effects are not entirely a result of recency-sensitive retrieval processes.

**Spatial clustering analysis.** To quantify the influence of spatial information on recall, we first calculated the great circle, or "as-the-crow-flies," distances between all pairwise locations. Given two locations with longitude and latitude in radians, we obtained the great-circle distances between the two points using the equations that compose the haversine formula (Sinnott, 1984). We then normalized our data set by assigning a spatial factor of 1 to pairwise transitions between the two closest locations in the entire word pool, whereas all other transitions between locations received correspondingly smaller spatial factor values with 0 as a lower bound. For each participant, on a trial-by-trial basis, we assigned a percentile ranking to each recall transition based on the spatial factor for that transition compared to all the available transitions.

The overall spatial clustering percentile ranking (henceforth, spatial cluster score or SCS) was calculated for each trial by averaging the percentile rankings for that trial, and each participant's SCS for a data set was the averaged value of that participant's trial SCSs. Finally, the overall SCS was calculated as the mean of the participant SCSs. We calculated these SCS values for both the trials in which only locations were presented and the multicategory trials.

As illustrated in Figure 1, to obtain an overall SCS of 1, recall transitions across the entire data set would have had to occur always between the two closest presented locations that had not already been recalled. Likewise, if the SCS were calculated as 0, transitions would have always occurred between the two farthest possible locations. To verify that the chance level was .5, we used a bootstrapping procedure; we took the mean of the SCSs calculated using a permutation test with 1,000 iterations, in which the order of the recalled items on each trial was randomly permuted. This procedure gives us a more reliable estimate of the baseline value of the SCS, especially given that we are shuffling the items that were actually recalled. This allows the bootstrap to preserve any spatial clustering effects that may arise by chance within a particular recall sequence. Further, we need not assume any distributional form in testing whether our observed SCS is significantly different from the chance value when using this bootstrap procedure; rather than using Student's $t$ distribution to test whether the observed SCS is significantly different from 0.5, we take the percentage of SCSs obtained from our randomly permuted sample that are greater than our observed SCS as our $p$ value. This removes all distributional assumptions in such a test.

## Results

Our primary question was whether participants would exhibit significant spatial clustering in a free recall task that does not require explicit retrieval of spatial information. To address this question, we separately considered recall of location-only lists, recall of multicategory lists, and final free recall of all list types. Our analyses of the multicategory lists and the final free recall periods considered only recall transitions between locations. Consistent with the hypothesis that spatial information serves as part of the retrieval cue in free recall, we found significant spatial clustering in free recall of both location-only lists ($SCS = 0.56$, $p < .01$, by a permutation test) and multicategory lists ($SCS = 0.54$, $p < .01$). The spatial clustering effect was especially evident in final free recall ($SCS = 0.69$, $p < .01$). The effect in final free recall was significantly greater than in both the location-only and multicategory lists, as shown by paired-samples $t$ tests, $t(42) = 14.27$, $p < .001$, for location-only lists, and $t(42) = 13.41$, $p < .001$, for multicategory lists. The finding of significantly higher spatial clustering in the final free recall condition is likely attributable to the fact that recency and temporal clustering effects are attenuated in final free recall (Klein, Addis, & Kahana, 2005), and it is consistent with the finding of overall higher levels of category clustering in final free recall than in immediate free recall for this data set (see Morton et al., 2012). The use of geographical association thus becomes stronger due to the fact that geographical proximity is time consistent and thus able to take the place of the fading temporal associations.

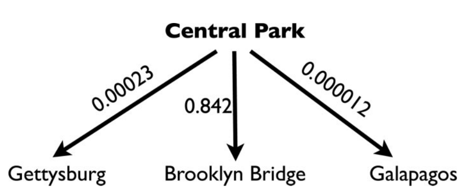


*Figure 1.* In this theoretical example, the participant has just recalled the location Central Park, and there are only three possible locations that have not been recalled to which the participant can transition. Each possible transition has the corresponding pairwise similarity value shown. If the participant next recalls the farthest possible location (Galapagos), the transition will receive a percentile rank of 0; if Gettysburg is next recalled, the obtained value will be .5; and if Brooklyn Bridge is recalled, the percentile rank will be 1.

Figure 2 shows the conditional-response probability (CRP) as a function of spatial distance for location-only lists, multicategory lists, and for final free recall. For this analysis, we first binned the spatial distances among all of the landmarks into quintiles. Then, for each pair of successively recalled landmarks, we estimated the probability of making a transition to a landmark of a given spatial distance bin by dividing the frequency of actual transitions by the frequency of possible transitions. These curves show that in all three recall conditions, participants exhibit a strong tendency to successively recall landmarks from proximate geographical locations.

Along with the spatial clustering described above, participants also exhibited strong temporal clustering of the list items. Specifically, participants exhibited the usual temporal contiguity effect as seen in their tendency to successively recall items studied in neighboring list positions. This can be seen in Figure 3, which shows the conditional response probability as a function of lag for the immediate free recall periods (both location-only and mixed lists) and the final free recall periods, revealing that, in spite of the strong spatial clustering effects observed, we still observe strong temporal contiguity effects. For the immediate free recall periods, the temporal clustering score (TCS) was .58 ($p = .001$) for the location-only condition and .64 ($p = .001$) for the mixed list condition. For the final free recall periods, the TCS was .63 ($p = .001$).

In a large meta-analysis of nine delayed free recall studies, Sederberg, Miller, Howard, and Kahana (2010) found a significant positive correlation between temporal clustering and overall recall performance. Thus, those people who exhibit stronger temporal contiguity effects also tend to recall more items. Consistent with this meta-analysis, we observed a significant positive correlation between temporal clustering and recall performance both for mixed category lists ($r = .36$, $p < .05$) and in final free recall ($r = .36$, $p < .05$). This effect was not reliably observed, however, in the pure location lists ($r = -.10$, $p > .1$).

Extending Sederberg et al.'s (2010) analysis of temporal clustering to the case of spatial clustering, we wondered whether participants who exhibit stronger spatial clustering also tend to recall more list items. For the pure location lists, which did not exhibit a significant correlation in the temporal contiguity analysis, we observed a robust positive correlation between spatial clustering and overall recall ($r = .44$, $p < .01$). This effect was not reliably observed, however, in either the mixed category lists ($r = -.16$, $p > .1$) or in final free recall ($r = -.008$, $p > .1$).

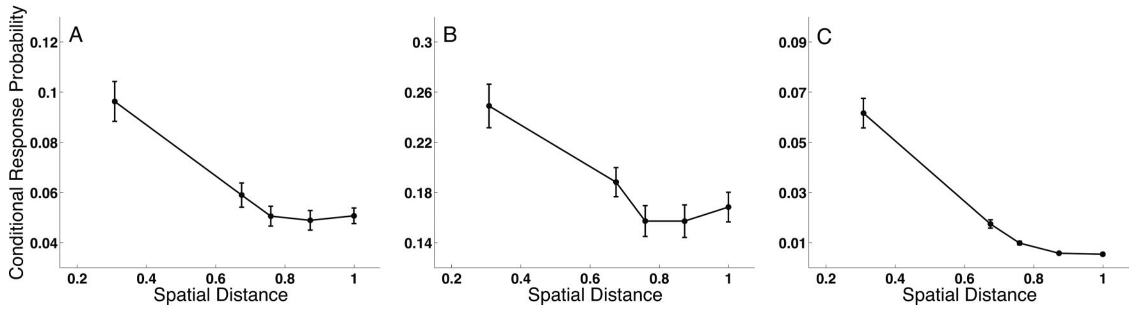


*Figure 2.* Conditional response probability (CRP) as a function of spatial distance for Experiment 1. The $x$ value for each point represents the mean of that bin's spatial distance values (i.e., 1-spatial similarity value), while the $y$ value represents the mean CRP across that entire bin of pairwise values. The probability of recalling a given location immediately subsequent to the previously recalled location decreased as the distance between those two locations increased (and thus as their spatial similarity decreased). The $x$ values represent all possible spatial distances, binned into quintiles. Error bars are ± standard error of the mean. A: The spatial-CRP for location-only immediate free recall periods. B: The spatial-CRP for mixed-list immediate free recall periods. We observe higher conditional probabilities because there are fewer locations on mixed lists and thus fewer possible location-to-location transitions. C: The spatial-CRP for the final free recall periods.

## Experiment 2

In this experiment we use a virtual navigation task to achieve full experimental control over the assignment of landmarks (stores) to locations within the environment. As such, this experiment overcomes any potential concerns about a confounding between distance and other similarity attributes.

### Method

**Participants.** Participants were 14 college-age individuals (nine male), recruited from the University of Pennsylvania student community. Each participant completed four sessions. Participants were compensated monetarily for their participation, with a performance-based bonus as incentive.

**Environment design.** The virtual town consisted of 19 stores and 37 nonstore buildings (see Figure 4A, for an overhead map of the town). The town also contained a park, as well as smaller props such as trees, benches, trash cans, and mailboxes. All the stores were visually distinct, with various unique features such as large banners displaying the stores' names, allowing for the stores to be identifiable from a distance (see Figures 4B and 4C for an example street view and store). The layout of the town was identical for every participant, though the 19 stores that were placed in the town were chosen randomly from a pool of 23 stores. For a given participant, the stores remained consistent across all sessions. The 3-D models used in the virtual environment were created using Autodesk Maya software. The environment was displayed to participants using the Panda Experiment Programming Library, which is an in-house Python based wrapper around Panda3d, an open source game engine.

**Procedure.** We conducted a free recall experiment in which participants were presented with items at various locations within a virtual town. Participants began the first session with no prior knowledge of the layout of the environment. Movement in the virtual environment was controlled with a gamepad, with the left thumb used to moderate forward and reverse speed, as well as direction. The experimental session began with a practice period, during which participants were instructed to locate a specific store via a text overlay at the top of the screen (e.g., "Please find the Music Store"). Upon arriving at the target store, participants were

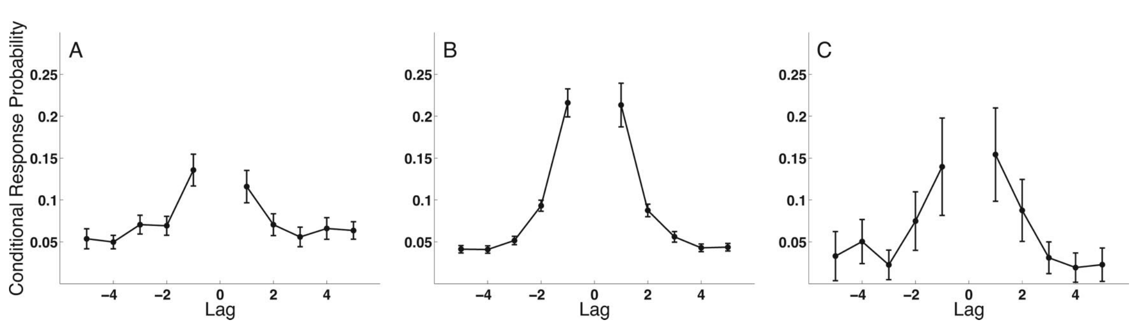


*Figure 3.* Conditional response probability (CRP) as a function of temporal lag for Experiment 1. The CRP as a function of lag (or lag-CRP) shows the probability of recalling an item from serial position $i$ + lag immediately following an item from serial position $i$. A: The lag-CRP for location-only immediate free recall periods. B: The lag-CRP for mixed-list immediate free recall periods. C: The lag-CRP for the final free recall periods. Only within-list transitions were included in this analysis.

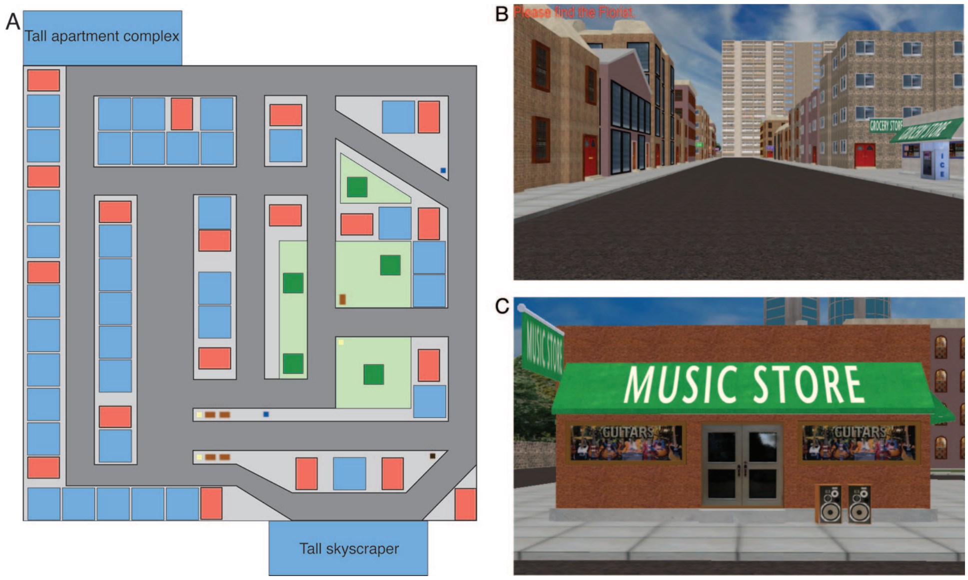


*Figure 4.* A: An overhead map of the layout of the virtual town. Shaded blue areas represent locations of nonstore buildings. Shaded red areas represent locations of stores. Shaded green areas represent grass, and the small dark blue, brown, and yellow boxes represent mailboxes, benches, and street lights, respectively. B: A view down one of the streets in the town. C: An example store.

then instructed to locate another store. The practice session continued until each store had been found twice (in the three subsequent sessions, participants needed to find each store only once to advance beyond the practice, as the town remained the same). After completing the practice period, participants began a series of "delivery days," during which they were instructed to locate a particular store, and, upon arrival at the store, were presented with the name of a common item. Items were presented auditorily and were thematically related to the target store (one might deliver a guitar to the music store, for example). Each delivery can be thought of as an item presentation in a free recall list. Participants travelled to 17 of the 19 stores in the town, randomly selected. Items were presented at the first 16 stores, and upon arrival at the 17th store, the screen went blank, a row of asterisks appeared on the screen, and a tone sounded, which signaled the start of the recall period. Participants were given 90 s to attempt to recall any of the just-delivered items, in any order. A delivery day can be thought of as one list in a free recall task. Participants completed five lists of 16 items in the first session, and eight lists of 16 items in the three later sessions. After the final list in the session, participants were asked to freely recall the stores in the town (termed the "store recall period"), and finally, after the store recall period, participants were asked to freely recall any of the delivered items presented in the current session (the "final free recall period"). As noted in Experiment 1, any observation of clustering in final free recall will to some extent be confounded by clustering observed in immediate free recall due to output encoding. Nonetheless, the stability of results across both immediate and final free recall suggests that they are not entirely a consequence of recency sensitive retrieval processes.

**Spatial clustering analysis.** To determine whether the spatial proximity between delivered items had an effect on the order in which items were recalled, we calculated a spatial clustering score as in Experiment 1. Here, instead of using great-circle distance, we used the shortest possible traversable path a participant could travel between stores as our distance metric (rather than a measure such as Euclidean distance).

## Results

The store recall phase of this experiment was most analogous to Experiment 1 in that participants were asked to recall landmarks defined, at least in part, by their locations within a spatial environment. As expected, we observed a high level of spatial clustering in recall of stores ($SCS = 0.72$, $p = .001$, by a permutation test). This spatial clustering effect can also be seen in the spatial-CRP shown in Figure 5A.

Our main interest in this experiment was in whether participants would exhibit spatial clustering for recall of objects that were delivered to stores. Although each object was revealed when the participant navigated to a particular store, there was no requirement for participants to know where the objects were learned (this is in contrast to learning the store locations, which benefitted the participants by allowing them to navigate efficiently and complete the task in a reasonable period of time). Given that participants were asked to recall the delivered objects without regard to the stores or any other locational information, the navigation task could reasonably be considered as a distractor task between deliveries. Spatial clustering in recall of objects would be expected only insofar as the spatial information used during virtual navigation becomes part of the representation of the object revealed after navigating to a particular location and if that spatial information in turn served as a cue during recall.

In immediate and final free recall we observed significant spatial clustering. For final free recall the spatial clustering score was .61 ($p = .001$ by a permutation test), and in immediate free recall

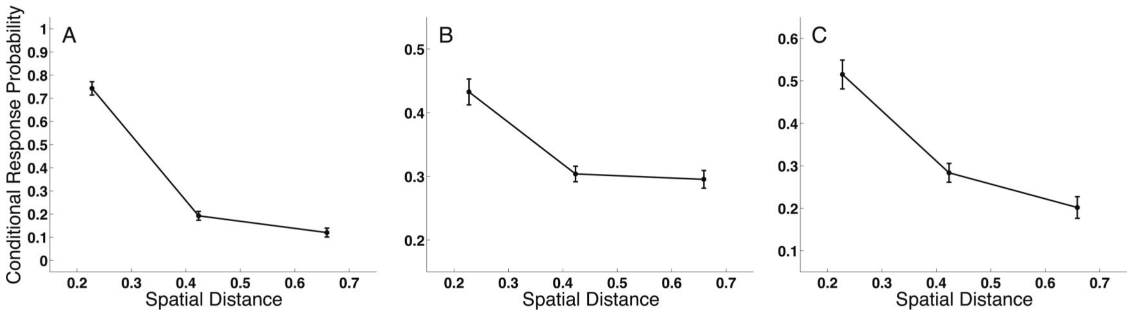


*Figure 5.* Conditional response probability (CRP) as a function of spatial distance for Experiment 2. The CRP as a function of spatial distance (or spatial-CRP) shows the probability of recalling an item presented at a given store location immediately following recall of an item presented at a different store location. The $x$ values represent all possible spatial distances between stores, binned into thirds. Error bars are $\pm$ standard error of the mean. A: The spatial-CRP for the store recall periods. B: The spatial-CRP for the immediate free recall periods. C: The spatial-CRP for the final free recall periods.

the spatial clustering score was .53 ($p = .001$). As in Experiment 1, these two distributions significantly differed, $t(13) = 3.42$, $p < .01$, with a higher spatial clustering effect exhibited in final free recall than in immediate free recall.

Figures 5B and 5C show the spatial CRPs for these conditions, which further demonstrate the robust spatial clustering effect. As spatial distance increases between recalled values (and thus as the spatial clustering value decreases), the conditional response probability decreases significantly across all recall period types. This indicates that participants were significantly more likely to recall two items or locations sequentially if they were relatively close in the virtual town.

As in Experiment 1, and in spite of the strong spatial clustering effects observed, we still observed a robust temporal contiguity effect. Figure 6 shows the conditional response probability as a function of serial lag for the immediate free recall periods and the final free recall periods. For immediate free recall the temporal clustering score was .65 ($p = .001$ by a permutation test) and in final free recall the temporal clustering score was .62 ($p < .01$).

Although randomization of delivery locations on each trial mitigates against any confounding between spatial proximity and serial position lag, this does not completely rule out a confounding between spatial proximity and temporal lag (i.e., the elapsed time between when successively recalled items were initially presented to the participant). To test for such a potential confound in our study, we calculated both the mean temporal lag and the spatial distance between the presentations of sequentially recalled items. We then asked whether items experienced at nearby spatial locations were also experienced closer in time than items experienced at more distant spatial locations. Using the same binning of spatial distance as in our spatial CRP analysis (Figure 5), we compared the temporal lag for sequentially recalled items studied in each of the spatial distance bins. The mean temporal lags were 71.8 $\pm$ 10 s (SEM) for the shortest distances, 70.5 $\pm$ 6.5 s for the middle distances, and 78.3 $\pm$ 10 s for the farthest distances. An analysis of variance (ANOVA) failed to reject the hypothesis that these three conditions come from the same distribution, $F(2, 39) < 1$, *ns*. In addition, paired-samples $t$ tests failed to detect any reliable differences between the individual conditions ($p > .1$ for all comparisons).

We performed a further check for any possible confounding between temporal and spatial distance using our spatial clustering score (SCS). For every trial, we calculated both its spatial clustering score and the mean temporal lag for successively recalled

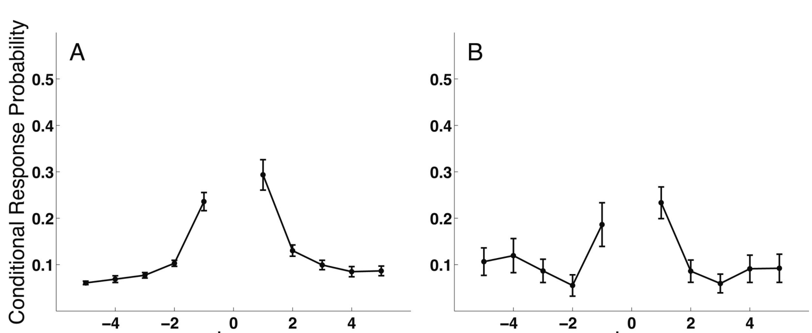


*Figure 6.* Conditional response probability (CRP) as a function of temporal lag for Experiment 2. The CRP as a function of lag (or lag-CRP) shows the probability of recalling an item from serial position $i$ + lag immediately following an item from serial position $i$. A: The lag-CRP for the immediate free recall periods. B: The lag-CRP for the final free recall periods. Only within-list transitions were included in the analysis.

items. If temporal information is, in fact, driving the spatial clustering effect, then we would expect a correlation between trial spatial clustering scores and average temporal lag, with high spatial clustering trials associated with smaller time intervals. The observed correlation ($r = -.06$) was not reliably different from zero ($p > .1$).

We next asked whether the degree of either spatial or temporal clustering predicted overall recall performance in the present task. In results consistent with Sederberg et al.'s (2010) meta-analysis, we found that participants who exhibited higher levels of temporal clustering also recalled more words, with a significant positive correlation in final free recall ($r = .63$, $p = .01$) and a positive but not statistically significant correlation in immediate free recall ($r = .44$, $p = .11$). In the case of spatial clustering, we observed strong and reliable positive correlations with overall recall performance in both immediate ($r = .59$, $p = .02$) and final free recall ($r = .62$, $p = .01$).

## General Discussion

The *law of contiguity* has long held its place as the primary law of association. As formulated by Hume (1739-1740/1896), this law states that ideas enter into association with one another when they are contiguous in space and time. Whereas a massive body of experimental work has demonstrated the potent influence of temporal contiguity on the association of ideas, we know surprisingly little about how spatial contiguity influences the association of ideas. In the present article we report two experiments that examine how spatial information influenced the order of recalling items in episodic memory. We hypothesized that spatial information, like other item and context attributes, would influence the dynamics of free recall.

In Experiment 1, participants studied and then freely recalled lists that included multiple well-known landmarks. When recalling these lists, participants exhibited significant spatial clustering of landmarks based on their geographical proximity. This clustering was reliably observed both for pure lists comprised of just landmark items and in mixed lists in which landmarks, objects, and celebrity names were randomly mixed. The spatial clustering effect appeared alongside the well-characterized temporal clustering (contiguity) effect and the general tendency to recall items by category.

Although it is tempting to interpret these results as reflecting participants' use of spatial features to guide recall, the naturalistic nature of the stimuli (real-world landmarks) leaves open the possibility that participants were clustering on the basis of other dimensions of stimulus similarity that are correlated with geographical proximity (more castles in Europe; ancient structures in Asia and the Mediterranean countries, etc.).

In Experiment 2, we addressed this potential confound by having participants learn landmarks (stores) and objects within a visually rich virtual environment. Because we used a computer to control the assignment of stores and objects to virtual locations, we were able to overcome any potential confounding between distance and other similarity attributes. Consistent with our findings of geographical clustering in Experiment 1, we observed substantial spatial clustering in recall of stores in a task where the assignment of stores to locations was fully randomized and where participants had no preexperimental associations between the landmarks and the novel virtual town.

Our primary goal in Experiment 2, however, was to assess a more subtle potential influence of spatial information on memory retrieval. Specifically, we hypothesized that the spatial location in which an item is experienced would form a type of context for the item, even if the item itself had no spatial information associated with it prior to the experiment. This was done by having participants deliver common objects as part of a video game in which they navigated from store to store in a virtual town. By delivering a guitar to the music store, we hypothesized that the guitar would become flavored by the spatial context of the music store. Later, when recalling the delivered objects outside of the spatial context of the virtual town, remembering "guitar" was hypothesized to evoke its spatial context and thus help to cue retrieval of unrelated items studied in nearby spatial locations. Our findings from Experiment 2 supported this hypothesis by demonstrating significant spatial clustering of delivered items. As expected, these spatial clustering effects were far weaker than the clustering observed during recall of the stores.

Unlike a regular immediate free recall task, our "delivery person" task included a significant amount of distracting activity between exposures to the to-be-remembered objects. This duration between experienced items (16.5 $\pm$ 9 s) for our participants in Experiment 2 made this task more like continual distractor free recall than standard immediate free recall. This makes it all the more impressive that one observes strong temporal and spatial clustering, as these effects must be quite extended in clock time, and thus not representing the coactivation of immediately contiguous items or positions.

The present studies provide empirical support for the hypothesis that the human memory system associates each new experience within a spatiotemporal context and that this context becomes reactivated when the experience is recalled (Howard, Fotedar, Datey, & Hasselmo, 2005; Howard, Kahana, & Wingfield, 2006; Polyn et al., 2009; Sederberg et al., 2008). More specifically, the class of retrieved spatiotemporal context models assumes a multiattribute (vector) representation of context that includes temporal, spatial, and semantic information. This vector representation of context follows an autoregressive process, integrating the information associated with each experienced and/or recalled item. Integration of item representations can produce a noisy representation of temporal information, whereas integration of velocity information can produce a noisy representation of spatial location. Temporal co-occurrence of representationally similar items will result in retrieved contexts being more similar for semantically similar items. These models assume that the vector representing spatiotemporal context becomes associated with each experienced item and that items in turn retrieve their associated contexts. Although this class of models has been applied to temporal and semantic clustering effects in free recall, and to spatial coding in rodents, a fully specified model of temporal, semantic, and spatial coding in humans has yet to be developed.

That people can encode and retrieve spatial information when instructed to do so has been well known almost since the start of our field (e.g., Warren, 1919). And the finding that recall dynamics is guided by item and context similarity is also well documented (Kahana, 2012). As such, one would expect to find strong spatial clustering in a task where participants were instructed to encode each object in a specific location, as observed in a study of two-dimensional spatial clustering by Curiel and Radvansky

(1998). It is perhaps less obvious that remembering an item whose locational information was incidentally encoded would prime memories of unrelated items experienced at neighboring locations, as we have shown in this article.

The spatial clustering effects we observed can be masked, however, by the very strong temporal and semantic organization one normally observes in free recall. In Experiment 2 we found that although such effects were robust, they are not very large in magnitude. That we could observe these effects in a modest sample was perhaps a result of our collecting four experimental sessions' worth of data from each participant. Nonetheless, we see the present findings as a very natural, and not altogether surprising, extension of prior work demonstrating contextual retrieval and contextual cuing based on other incidental features of an item, such as its temporal context and its encoding task (Polyn et al., 2009).

Although the present study does not speak to the neural substrates of these temporal and spatial clustering effects, it is striking that the hippocampus, which is known to play a critical role in free recall, appears to have neurons that are specialized for encoding both spatial and temporal information. Hippocampal place cells fire at specific locations within an environment (see Moser, Kropff, & Moser, 2008; O'Keefe & Nadel, 1978, for reviews), and recently documented hippocampal time cells fire at specific temporal intervals between distinct events (MacDonald, Lepage, Eden, & Eichenbaum, 2011). According to retrieved context theories of episodic and spatial memory (Byrne, Becker, & Burgess, 2007; Howard et al., 2005; Polyn & Kahana, 2008; Rolls, 2010), one would predict that recalling an item would reinstate its spatiotemporal context, and as such the pattern of brain activity just prior to recalling a word should bear resemblance to words studied at proximate times and in proximate spatial locations. Two recent articles report neurobiological evidence for reinstatement of temporal context (Howard, Viskontas, Shankar, & Fried, 2012; Manning, Polyn, Baltuch, Litt, & Kahana, 2011). Manning et al. (2011) analyzed electrocorticographic (ECoG) activity recorded from indwelling electrodes as neurosurgical patients studied and recalled lists of common nouns. They found that the pattern of activity just prior to recall of a given item was not only similar to the ECoG activity present when the item was studied but was also similar to the ECoG activity recorded during study of neighboring items. The neural similarity decreased in a graded manner with the lag between the item and its neighbors, exactly as would be predicted by a temporal context reinstatement account. Howard et al. (2012) analyzed the firing rates of ensembles of individual neurons as neurosurgical patients implanted with hippocampal depth electrodes performed a continuous recognition memory task. They found that the ensemble similarity of neural activity when a photograph was repeated was similar to the neural activity recorded during the encoding of neighboring photos. We would predict, on the basis of the spatial clustering results reported here, that spatial context should exhibit a similar neural reinstatement effect. Specifically, these psychological findings would suggest that place cell representations active in a given region of the environment should reinstate when participants recall an item that was delivered to that location, as in Experiment 2. Such findings would also be consistent with computational models of spatial and episodic memory in which recalling or reexperiencing an item is assumed to reinstate its previously associated temporal and spatial context (Howard et al., 2006).

Although there is still much that can be learned from traditional list learning methods, we believe that there is great promise in the use of virtual reality software to create more realistic synthetic experiences that can be kept under tight experimental control. At the very least, the conservation of memory phenomena across these two types of paradigms blunts the oft-mentioned criticism of verbal learning research as lacking in ecological validity.



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