Recall Initiation Instructions Influence How Space and Time Interact in Memory

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Abstract

Recent work has examined the interaction between space and time in memory search, but there is still limited understanding of this relationship. Here, we test the hypothesis that individuals can exert control over how time and space interact in response to subtle differences in task instructions. To test this hypothesis, we analyzed two experiments where participants completed two immediate free recall tasks, a verbal task involving words presented at a central location and a spatial task involving squares presented at different locations. Some participants were free to recall the words or locations spontaneously in any order they preferred. In contrast, another group was subtly biased toward temporal information by instructions to begin recall from the last presented item before recalling the remaining items in any order they wished. Replicating recent work, all conditions showed clear evidence that recall was organized along both the temporal and the spatial dimensions. Extending this work, we found that the subtle change in recall instructions increased the reliance on temporal information in the spatial recall task. Correlational analyses suggest that spatial and temporal information do not compete when participants search memory spontaneously. However, they do compete when instructions favor temporal information. These findings highlight that individuals can exert some cognitive control over how associative dimensions interact during memory search and emphasize the importance of incorporating such processes into theoretical models.

Recalling one event often triggers the recall of another event that is similar to the first along some associative dimension. For example, in recall tasks, participants often recall two words that share a strong semantic association successively (Bousfield, 1953; Healey & Kahana, 2014). Another influential dimension is time, as evidenced by the strong tendency for participants to successively recall items that were presented near to each other in time (see Healey et al., 2019, for a review). This temporal influence is evident in the Temporal Contiguity Effect: when subjects study a list of items and then recall them in whatever order they come to mind (i.e., free recall), successfully recalling one item tends to be followed by recalling another item that was studied nearby in time. This effect can be measured by calculating the probability of recalling item $i + lag$ after recalling item i. These probabilities are computed for different lags by dividing the number of times a transition of a particular lag was made by the number of times it could have been made. The resulting lag conditional response probabilities (lag-CRP) typically peak for short lags, indicating a preference for successively recalling items studies nearby in time (see Healey et al., 2019, and Kahana, 1996, for more detailed discussion). Lag-C

RPs show a temporal contiguity effect in a wide variety of recall tasks, including both immediate and delayed free recall (e.g., Howard & Kahana, 1999).

Recent evidence suggests that spatial similarity also serves as an associative dimension in memory search (Clark & Bruno, in press; Gibson, Healey, Schor, & Gondoli, 2021; Miller et al., 2013). In Gibson et al. (2021), we adapted the temporal lag-CRP analysis to measure the probability of successively recalling items that were presented nearby in *space* in a free recall task where the items were a sequence of spatial locations. As described in detail below, we found that both temporal and spatial relations played crucial roles in determining recall order. Here, we aim to replicate key findings from the small but growing literature on spatial recall and extend them by asking how temporal and spatial information interact in memory and whether that interaction is influenced by the recall initiation strategies participants are asked to employ.

The Role of Space in Free Recall

Although many previous studies have suggested that spatial context may be encoded during study and used to cue retrieval during recall (Bonanni et al., 2007; Dent & Smyth, 2006; Gmeindl et al., 2011; Guérard & Tremblay, 2008; Hurlstone, 2019; Hurlstone et al., 2014; Nairne & Dutta, 1992), these studies did not examine the extent to which spatial similarity can cue sequential dependencies between successive recalls. The few attempts to measure such dependencies used materials that leave open the possibility that spatial similarity may be confounded with semantic similarity (Miller et al., 2013). For example, when recalling landmarks, it might appear that recalling "Brooklyn Bridge" followed by "Central Park" is evidence of one memory cueing recall of another memory via spatial proximity. However, it's essential to consider possible confounds between space and other associative dimensions. Landmarks may share semantic associations (e.g., both are classic examples of American urban architecture) and likely also share temporal associations (e.g., if you recently saw both when watching a movie set in New York). In Gibson et al. (2021), we filled this gap in the literature by using stimuli that could only be distinguished spatially within the context of a delayed free recall task.

In each trial of this spatial recall task, participants viewed sequences of 10 red squares that appeared in a 6 × 10 matrix of 60 locations, each of which was marked by a white rectangle. Following a brief spatial distraction task, participants attempted to recall these locations by clicking on the white rectangles in any order. To measure the role of spatial proximity in driving recall in this task, Gibson et al. (2021) developed a spatial analog of the temporal lag-CRP, a common measure for temporal contiguity (Healey et al., 2019). The lag-CRP reflects the probability of recalling item *lag* + *i* after recalling item *i*. It is calculated by dividing the number of times a transition of a particular lag was *actually* made by the number of times it *could* have been made (Healey et al., 2019; Kahana, 1996). In the context of temporal contiguity, lag simply represents the number of serial positions separating two successively recalled words. When considering spatial contiguity, we calculated lag as the spatial distance separating two items in the 6 × 10 matrix (see Methods for full details). Gibson et al. (2021) found that spatially contiguous items were more likely to be sequentially recalled than more distant items, suggesting that spatial similarity is one of the associative dimensions that underlie memory search.

Time and Space Interact

A central question of the current work is whether the temporal and spatial associative dimensions interact during memory search, possibly trading off with each other. It has long been known that memories are associated along many dimensions, such as time, space, and meaning (Cortis Mack et al., 2018; Miller et al., 2013; Pantelis et al., 2008; Polyn et al., 2009). However, relatively little is known about how the memory system combines information from different dimensions during memory search (Healey & Uitvlugt 2019). Time and space are particularly important dimensions because, outside the lab, they are all but ubiquitous insofar as all of our experiences happen at a particular time and place. Thus, in principle information about time and information about space could be combined to improve memory search: knowing both when and where an event happened helps uniquely identify it. But there is also the possibility for interference: a given location may be paired with many different events across time. Therefore, understanding how information about time and information about space interact during memory search is of great theoretical importance.

There is evidence that temporal contiguity interacts with the *semantic* associative dimension (Polyn et al., 2011, Howard & Kahana, 2002, Healey et al., 2019). For example, encouraging participants to focus on temporal order considerably reduces the amount of semantic clustering in participants' recall, even for lists with strong semantic associations (Healey & Uitvlugt, 2019). Little is known, however, about whether time and space interact. Earlier studies found a temporal contiguity effect even when spatial stimuli serve as the memoranda (Cortis Mack et al., 2018; Mundorf et al., 2022); however, these studies did not measure spatial lag-CRPs and were therefore unable to directly compare spatial and temporal lag-CRPs. Leveraging their measure of spatial contiguity, Gibson et al. took a first step in exploring how spatial and temporal associative dimensions might interact. They showed the spatial contiguity effect was significantly larger than the temporal contiguity effect when both contiguity effects were obtained from the same spatial recall task, suggesting that spatial context may dominate temporal context in spatial tasks. They also showed that the magnitude of the temporal contiguity effect in a spatial recall task was smaller than the magnitude of the temporal contiguity effect obtained in a verbal recall task. These group-level contiguity effects provide some evidence that the spatial and temporal associative dimensions interact. Here, we seek more direct evidence of interactions by examining how these contiguity effects trade off within individuals.

This apparent tradeoff between the spatial and temporal associative dimensions is important for a variety of reasons. First, the apparent dominance of space over time draws attention to the fact that many previous studies of spatial memory have required participants to recall in serial order (Hurlstone, 2019; Hurlstone et al., 2014), which strongly emphasizes the temporal associative dimension. In fact, Gmeindl et al. (2011) explicitly showed that spatial memory scores obtained on a spatial matrix task are significantly lower when participants are required to recall in serial order as opposed to any order, though they did not report sequential dependencies. Thus, although there is theoretical interest in the relationship between serial order tasks and free recall tasks (Hurlstone et al., 2014, Ward, Tan, & Grenfell-Essam, 2010, Farrell, 2012), the use of serial order instructions may not be appropriate in spatial memory tasks unless one is solely interested in the temporal associative dimension. Second, the apparent dominance of space over time in spatial tasks raises questions about whether contiguity effects are automatic (Healey, 2018; Mundorf et al., 2021; Healey & Uitvlugt, 2019) or rather are contingent on explicit retrieval strategies (Hintzman, 2016).

The Present Study

To address specific hypotheses about how time and space interact in memory we present analyses of three archival datasets in which samples of adolescents completed verbal and spatial free recall tasks[1]. Of particular interest in the present study was the extent to which the use of the temporal associative dimension over the spatial associative dimension is malleable and under the control of the individual. Presumably, participants could ignore the spatial associative dimension entirely when given the mandate to preserve the serial (temporal) order of the items in a spatial memory task. However, such extreme instructions would likely preclude any measurement of the spatial contiguity effect. Instead, all the participants in the present study were given standard free recall instructions, but some were allowed to initiate recall in an unconstrained, or spontaneous,

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[1] Whereas Gibson et al. (2021) examined delayed recall, the present analyses are based on immediate recall. The use of immediate instead of delayed free recall was largely for practical reasons. Elimination of the delay allows more trials to be completed in an experimental session, and participants also tend to recall more items which provides more recall transitions for the contiguity analyses that are our focus here. Moreover, apart from the recency effect, recall dynamics are generally quite similar between immediate and delayed free recall (see Howard & Kahana, 1999, for a comparison of different types of free recall tasks).

fashion whereas others were given an additional instruction intended to draw attention away from the spatial associative dimension and toward the temporal associative dimension.

We manipulated the emphasis on the temporal versus spatial dimension by encouraging subjects to use a recency “recall initiation strategy”. Initiation strategies refer to the extent to which an individual tends to begin recall from the end or the beginning of the memory list, reflecting either a “recency” or “primacy” strategy, respectively (Healey & Kahana, 2014, Healey, Crutchley, & Kahana, 2014, Madigan, 1971; Gibson et al., 2010). In immediate free recall with words presented at a central location in the absence of any specific initiation instructions, most participants spontaneously adopt a recency strategy, initiating recall from recency items, especially for longer lists (Healey et al., 2014, Ward et al., 2010, Grenfell-Essam & Ward, 2012). In the present study, some participants were allowed to spontaneously use any recall initiation strategy—the spontaneous recall condition—whereas others were explicitly instructed to use this recency strategy—the instructed recall condition.

The recency strategy as opposed to the primacy strategy was chosen in the present study because it represents a more subtle manipulation. Specifically, because most participants naturally adopt the recency strategy in the absence of instruction, explicitly encouraging them to adopt this strategy represents a minor deviation from their natural tendency. That is, the instruction to begin recall from the final items is not expected to dramatically change subjects’ initiation behavior but does introduce a subtle emphasis on time as opposed to space. This allows us to test whether a shift in emphasis changes the order in which items come to mind *after* recall has been initiated and the initiation instruction is, ostensibly, no longer relevant.

The central question is the extent to which the explicit instruction to begin recall toward the end of the list would diminish the magnitude of the spatial contiguity effect obtained in the spatial recall task and boost the magnitudes of the temporal contiguity effects obtained in both the spatial and verbal recall tasks. We expected the spatial contiguity effect to be larger than the temporal contiguity effect in the spatial recall task when recall was spontaneous. This finding would replicate what Gibson et al. (2021) found in a spatial recall task. However, we also expected that the spatial associative dimension would become less dominant in the spatial recall task when attention was shifted to the temporal dimension in the instructed recall condition, resulting in a smaller spatial contiguity effect. Moreover, based on Gibson et al.'s findings, we expected that the temporal contiguity effect would be smaller in the spatial recall task than in the verbal recall task when recall was spontaneous. But, once again, we expected that the spatial associative dimension would become less dominant in the spatial recall task when recall was instructed, resulting in a larger temporal contiguity effect.

In addition to these group-level predictions, we also examined individual differences in four sets of correlational analyses. To examine these correlations, we computed contiguity factor scores which provide a single number summary of the magnitudes of the spatial and temporal contiguity effects (Sederberg, Miller, Howard, & Kahana, 2010). The predicted pattern of correlations depends on how instruction conditions influence recall strategies.

First, we examined the extent to which the magnitudes of spatial and temporal contiguity effects reflected a trade-off of attention within individuals. For instance, one interpretation of Gibson et al.'s (2021) finding that the spatial associative dimension dominated the temporal associative dimension in their spatial recall task is that individuals focused more attention on the spatial information than temporal information during recall, such that individuals who exhibited large spatial contiguity factor scores would be more likely to exhibit small temporal contiguity factor scores, and vice-versa. If, as expected, the spatial associative dimension is found to dominate the temporal associative dimension at the group level in the spatial recall task when recall is spontaneous, then we may observe a negative correlation between the two corresponding contiguity factor scores. Likewise, if, as expected, the temporal associative dimension is found to dominate the spatial associative dimension at the group level in the spatial recall task when recall is instructed, then it is also possible that we will observe a negative correlation between the two corresponding contiguity factor scores. However, it is also possible that the magnitudes of these two contiguity factor scores would only trade off in the instructed recall condition when individuals were explicitly instructed to focus attention on the temporal dimension. In this scenario, the spatial and temporal contiguity factor scores would be expected to be uncorrelated in the spontaneous recall condition, indicating that the two associative dimensions exerted their influence more or less independently. This latter finding would be important because it would suggest that individuals can divide attention across both dimensions simultaneously during memory search.

Second, we examined the correlations between each of the temporal and spatial contiguity factor scores and overall recall accuracy in the spatial recall task to determine the extent to which one or both associative dimensions drive differences in recall. There is evidence that temporal, but not semantic, contiguity factor scores predicted overall recall accuracy across a variety of verbal free recall tasks (Healey, Crutchley, & Kahana, 2014, Sederberg et al., 2010). Thus, it will be important to determine the extent to which either or both dimensions predict recall performance in the present study, as well as the extent to which the observed pattern is modulated by recall instruction. Similarly, a third analysis examined the correlation between temporal contiguity factor scores and overall recall accuracy in the verbal recall task when there was variation in time but not space.

Finally, we also examined the correlations between the temporal contiguity factor scores obtained across the spatial and verbal recall tasks to determine the extent to which individuals consistently use the same retrieval strategies across different tasks. For instance, will the individuals who exhibit strong temporal contiguity effects on a verbal recall task be more likely to exhibit strong temporal contiguity effects on a spatial recall task? And, does the magnitude of this positive correlation depend on whether recall is spontaneous or instructed? At the very least, we would expect to observe a positive correlation between the temporal contiguity factor scores obtained from different tasks in the instructed recall condition, given that individuals were explicitly (and consistently) instructed to focus attention on the temporal dimension across both tasks.

In summary, the present study sought to clarify the role of both spatial and temporal associative dimensions in episodic memory and clarify how explicit recall strategies leave their signature on the modulation of these dimensions.

Experiment 1

In Experiment 1 we analyze archival data from Gibson et al. (2010) and Gibson et al. (2018). Both studies investigated differences in memory ability between adolescents with and without diagnoses of ADHD. Here, our analyses focus exclusively on the 75 total participants from non-ADHD control groups in these two studies (N = 30 from Gibson et al., 2010; N = 45 from Gibson et al., 2018).

Method

Participants. Across the two studies combined (Gibson et al., 2010; Gibson et al., 2018) the control groups consisted of 75 adolescents (10-14 years old), recruited from three public middle schools (grades 6-8) in a district serving 2,500 students from suburban and rural neighborhoods. Although these participants were younger than those typically recruited in studies of young adults, our previous research has suggested that the memory performance of this age group is quite similar to that of young adults (Gibson et al., 2019). Due to technical issues, data files from two participants from the spontaneous recall group were corrupted. Therefore, the analyses reported here are based on 73 participants. Due to the use of archival data, this sample size was not determined with the current analyses in mind, which limits power, especially for the examination of correlations. Therefore, our approach will be to run a parallel set of analyses on a second, never before published, dataset in Experiment 2.

Procedure and tasks. Testing began with a brief meeting with caregivers and adolescents to obtain consent and assent, respectively, in the Attention, Memory, and Perception Laboratory at the University of Notre Dame. Adolescents were then assessed on a battery of neuropsychological measures, and parents completed a structured interview to determine the diagnostic status of their child as well as a battery of other questionnaires (for a complete list, see Table S1).

The present study focuses on the verbal and spatial recall tasks. In the verbal recall task, participants were presented with 15 lists of 12 unrelated words. The words ranged in length from 4 to 6 letters and were high-frequency based on the Zipf scale (Van Heuven, Mandera, Keuleers, & Brysbaert, 2014). The words were printed in 20-point font; and, all words appeared white against the black background of a standard CRT monitor. Each word was presented consecutively for 1 s in the middle of the screen, with a 1 s delay before the next word. The lists were presented in the same random order to all participants. Trials began when the participant indicated readiness. Following the presentation of a single list, question marks appeared in the center of the screen to prompt recall. Participants reported answers verbally by speaking into a microphone. Responses were scored as correct for exact matches or if the response was a different form (i.e., singular/plural, verb tense) of the correct response.

In the spatial recall task, participants were presented with 15 trials of 12 different spatial locations. Locations were cued by temporarily changing the color of the square from white to red. Each of the 12 locations in a trial was cued in consecutive order for one second with a 1 s delay before the next cue appeared. Squares appeared at any one of 15 × 12 = 180 unique locations. Each location was cued only once across the 15 lists. To make the task manageable, only 36 of the possible 180 squares appeared at any one time. These 36 squares were selected randomly from the 180 possible locations and remained visible for three consecutive trials (3 trials × 12 cued locations = 36 locations). At test, the 36 possible squares for that trial were displayed, and participants clicked the relevant locations. No restriction was placed on the number of squares they clicked. At the conclusion of the third trial in each set, a new set of 36 locations was randomly selected from the 180 possible locations without replacement. This sequence of three trials was repeated five times for a total of 15 trials. The five sets of 36 randomly-selected squares were determined separately for each participant. Each trial was initiated after the participant signaled readiness.

Of critical interest, the participants in the two Gibson et al. (2010; 2018) studies were given different instructions about how to initiate recall at the conclusion of each list in the verbal and spatial recall tasks. The 30 participants in Gibson et al.'s (2010) study were told that they could recall the items in any order; whereas, the 45 participants in Gibson et al.'s (2018) study were told that they should begin recalling items from the end of the list first (though in no particular order). These two recall initiation instruction conditions will be referred to as the "spontaneous recall group" and the "instructed recall group," respectively. All participants were required to attempt recall for 30 s before proceeding.

Three practice trials preceded the experimental trials in each of the verbal and spatial recall tasks. The order of the verbal and spatial recall tasks was counterbalanced across participants in both recall groups.

Outcome measures. Five outcome measures were obtained from the verbal and spatial recall tasks. First, the *probability of first recall* reflects the first recall response on each trial as a function of study list position. Second, the *serial position curve* reflects the overall proportion of items correctly recalled as a function of study list position. Third, the *temporal lag-CRP* reflects the probability of recalling an item as a function of its temporal direction (before vs. after) and temporal distance (or lag) relative to the just-recalled item.

A fourth measure—the *spatial lag-CRP*—was analyzed solely within the spatial recall task because the spatial location of the list items did not vary in the verbal recall task. The spatial lag-CRP reflects the probability of recalling an item as a function of its spatial distance (or lag) relative to the just-recalled item. Figure 1 shows 120 possible spatial locations arrayed around the just-recalled item and the defined spatial lags for each of these positions. This Figure can be interpreted in terms of a two-dimensional coordinate system whose axes are centered on the just-recalled item and whose coordinates are denoted as (0, 0). Spatial direction along the vertical axis (columns) was labeled "above-below" and spatial direction along the horizontal axis (rows) was labeled "left-right." Spatial distance (spatial lag) increased from 0 to 5 cell widths in both directions across the vertical and horizontal axes.

Analyses of temporal lag-CRP have typically been restricted to temporal lag values between +5 and -5 to avoid the large number of missing values that tend to be associated with larger absolute values of temporal lag. However, there were still a large number of missing values in the spatial modality, even when spatial lag values were restricted between +5 and – 5. Thus, a comprehensive analysis of spatial distance and direction was not possible in this study because repeated measures analyses entail the deletion of cases in a list-wise manner whenever data is missing from individual conditions, and none of the participants encountered all spatial lag conditions. To circumvent this limitation, five spatial lag conditions were created by ignoring spatial direction and averaging spatial lag-CRPs across the cells that fell within five square bands around the center location. This average spatial lag-CRP measure allowed examination of the spatial contiguity effect, but not directional asymmetries.

For instance, as shown in Figure 1, on one extreme, the “spatial lag 1” condition was created by averaging spatial lag-CRPs across cells with coordinates: (L1, B1), (L1, 0), (L1, A1), (0, A1), (R1,), (R1, 0), (R1, B1), and (0, B1); whereas, on the other extreme, the “spatial lag 5” condition was created by averaging spatial Lag-CRPs across cells with coordinates: (L5, B5), (L5, B4), (L5, B3), (L5, B2), (L5, B1), (L5, 0), (L5, A1), (L5, A2), (L5, A3), (L5, A4), (L5, A5), (L4, A5), (L3, A5), (L2, A5), (L1, A5), (0, A5), (R1, A5), (R2, A5), (R3, A5), (R4, A5), (R5, A5), (R5, A4), (R5, A3), (R5, A2), (R5, A1), (R5, 0), (R5, B1), (R5, B2), (R5, B3), (R5, B4), (R5, B5), (R4, B5), (R3, B5), (R2, B5), (R1, B5), (0, B5), (L1, B5), (L2, B5), (L3, B5), (L4, B5). Notice that there were five times as many cells in the spatial lag 5 condition as in the spatial lag 1 condition because the number of cells within each band increased by 8 cells each time the spatial lag condition increased from one band to the next. Such expansion was necessary to offset the increasing number of missing cases in the more distant bands.

Finally, *contiguity factor scores*, a fifth measure, provide a single-number summary of the level of temporal or spatial contiguity, which is useful in comparing conditions and exploring correlations. Contiguity factor scores are calculated for each list by taking the |lag| of each transition made by a participant, finding its percentile within the distribution of all possible |lags| for that transition (Polyn, Norman, & Kahana, 2009; Sederberg et al., 2010), and then averaging across transitions. Higher contiguity factor scores indicate more contiguity.

To establish the statistical reliability of the contiguity factor scores in the present study, we performed a split-half reliability analysis following the methodology of Sederberg et al. (2010). For each participant, we randomly split their lists into two sets. When there was an odd number of lists, we randomly selected which set would have an additional list. We then calculated contiguity factor scores for each set and correlated the first set scores with the second using a Pearson's correlation corrected for the reduction in the number of lists using the Spearman-Brown prediction formula ($2\rho/[1+\rho]$). Lastly, we iterated this procedure 2,000 times and averaged the scores. The resulting reliability values are shown in Table 1 for all experiments. The reliabilities, which range from low to modest are in the range reported by Sederberg et al. (2010) for other verbal, free recall tasks.

Results

We follow the common practice in the temporal contiguity literature (e.g., Kahana, 1996) and rely primarily on confidence intervals when reporting the results in the main text but also provide detailed ANOVAs in the Supplemental Materials. In all cases, our conclusions are supported by both the confidence interval approach and the ANOVAs. For planned comparisons of the conditions on the main outcome measures, we use $\alpha = 0.05$. Because our analyses of individual differences in the verbal and spatial tasks are more exploratory than our analyses of average condition differences, we opted to be more conservative and use $\alpha = 0.01$ to correct for the multiple correlations.

Probability of first recall. As shown in Figure 2A, when participants were free to initiate recall however they wished (i.e., the spontaneous recall group) they were approximately equally likely to initiate from the beginning or the end of the list, with relatively small differences between the verbal and spatial task modalities. By contrast, when instructed to initiate recall from the final item (i.e., the instructed recall group; Figure 2C), participants tended to do so and seldom itiated from the first item. Again, there was little difference between the two modalities.

Serial position curve. Figures 2B and 2D reveal in all conditions the pattern typically associated with immediate free recall: a strong recency effect and modest primacy effect. There are important differences among the conditions, however. Comparing instruction groups, we see that the recency effect was more prominent in the instructed recall group than in the spontaneous recall group, suggesting that the instruction to begin recall from the end of the list operated as intended.

Total errors. In the verbal task, errors consisted of extra-list intrusions, prior-list intrusions, and repetitions. In the spatial task, errors consisted of clicking on one of the 36 visible squares that had not been presented on the current trial or that had already been selected. These data are analyzed more extensively in the Supplemental Materials, but here we note that participants committed more errors, on average, in the spatial modality ($M = 2.59$, $SE = 0.20$) than in the verbal modality ($M = 0.63$, $SE = 0.09$), $F(1,71) = 139.45$, $p < .001$, $\eta_p^2 = 0.66$.This higher error rate raises the possibility that participants were more likely to guess in the spatial modality than in the verbal modality, which could account for the higher recall on the spatial task. If so, one would expect participants who made more errors to also make more correct recalls. This was not, however, the case: the correlation between total average errors and overall proportion correct was small and non-significant in both the spatial IFR task ($r(71) = 0.078$, $p =$

.513), and in the verbal IFR task ($r(71) = -0.111$, $p = .348$), suggesting there is no systematic relation between total average errors and overall proportion correct.

Temporal lag-CRP. Figures 3A and 3C show a temporal contiguity effect in all conditions. The lag-CRP is higher for short lags (≤ 2) than for longer lags (> 2). This effect is quantified in Figures 3B and 3D using temporal contiguity factor scores. Here, we see that in the spontaneous recall group, the contiguity effect is stronger in the verbal condition than in the spatial condition as demonstrated by a higher temporal contiguity factor score. However, in the spontaneous recall group, the temporal contiguity factor scores are more similar.

One of the most striking features of the data is that the asymmetry of the contiguity effect varies considerably between conditions. Past work on immediate free recall of words has found the effect is almost always asymmetric in the forward direction (Healey et al., 2019). Here, this clear forward asymmetry was found only in the verbal task under spontaneous instructions. In the spatial task under spontaneous instructions, the forward asymmetry was still present but more modest. Under instructed recall in the verbal task, there was no asymmetry, and in the spatial task, the asymmetry was reversed with higher conditional-response probabilities for negative lags. The finding that forward asymmetry was reduced for spatial material and when instructed to initiate from the last item is consistent with the suggestion that when participants are free to choose their own strategies, they tend to employ ones that promote forward serial order (e.g., rote rehearsal, the method of loci; Mundorf et al., 2021; Hintzman, 2016), particularly with verbal material. By contrast, encouraging subjects to begin by recalling the last item first almost guarantees they will make more backward transitions than they otherwise would (i.e., only backward transitions are possible after having recalled the last item), thus reducing the asymmetry of the lag-CRP.

Spatial lag-CRP. The spatial lag-CRP (Figures 4A and 4D) could only be calculated for the spatial recall task. Across both recall groups, we see the conditional-response probability increases monotonically as lag decreases, demonstrating a spatial contiguity effect. That is, the recall of one item triggered the recall of other items studied nearby spatially. This effect is stronger, as witnessed by a steeper spatial lag-CRP (compare Figures 4A vs. 4C) and higher spatial contiguity factor scores (compare Figures 4B vs. 4D), in the spontaneous recall group than in the instructed recall group.

By taking the absolute value of the temporal lags, we can make direct comparisons between the magnitude of the spatial and temporal contiguity effects. As seen in Figure 4A, there was a steeper effect of lag in the spatial dimension than in the temporal dimension when participants were allowed to initiate recall spontaneously. Similarly, as seen in Figure 4B, spatial contiguity factor scores were also higher than temporal contiguity factor scores in the spontaneous recall group. In contrast, as seen in Figure 4C, there was a steeper effect of lag in the temporal dimension than in the spatial dimension when participants were instructed to recall from the end of the list. Similarly, as seen in Figure 4D, temporal contiguity factor scores were also higher than spatial contiguity factor scores in the instructed recall group.

Although there are clear differences in spatial contiguity between participants who were allowed to initiate recall spontaneously and those who were instructed to initiate from the last item, it is possible that these differences are not due to the instructions per se altering how they search memory but are simply due to changes in recall initiation patterns---the shape of the PFR curve. That is, it is possible that similar reductions in spatial contiguity are observed among participants in the spontaneous recall condition who adopt a recency initiation pattern even in the absence of instructions to do so. We tested this possibility in a set of analyses reported in the

Supplemental Materials and found that PFR shape alone cannot account for the reduction in spatial contiguity.

Correlations. Figures 5A-F show the relationships among temporal contiguity factor scores, spatial contiguity factor scores, and overall recall in the spatial recall task. The first issue we addressed concerned the extent to which the two associative dimensions traded-off within each individual. As expected, the group-level findings suggested that the spatial associative dimension dominated the temporal associative dimension in the spontaneous recall condition and that the temporal associative dimension dominated the spatial associative dimension in the instructed recall condition. However, the corresponding pattern of correlations did not support the notion that these group-level findings consistently reflected the attentional priority to one associative dimension or the other during memory search. In particular, the correlation observed between the spatial and temporal contiguity factor scores in the spontaneous recall condition was close to zero and non-significant, $r(26) = -.038$, $p = .849$ (Figure 5A). In contrast, there was a significant negative correlation observed in the instructed recall condition, $r(43) = -.396$, $p = .007$ (Figure 5D). Thus, the two associative dimensions only appeared to trade off within individuals when attention to the temporal dimension was explicitly emphasized in the instructed recall condition.

The second issue we addressed concerned the relation between each of the two contiguity factor scores and overall recall achieved in the spatial recall task for each of the two recall conditions. The results suggested that spatial contiguity was positively correlated with overall recall in the spontaneous recall condition, $r(26) = .528$, $p = .004$ (Figure 5C); this correlation also trended in the positive direction in the instructed recall condition, $r(43) = .290$, $p = .053$ (Figure 5F), but did not achieve the more conservative significance level ($\alpha = 0.01$) that was established for the correlational analyses. In contrast, temporal contiguity had no relationship with overall recall in either recall group: $r(26) = -.293$, $p = .131$ for the spontaneous recall condition (Figure 5B), and $r(43) = -.091$, $p = .553$ for the instructed recall condition (Figure 5E). To evaluate the relative magnitude of these correlations as a function of associative dimension within each recall condition, tests of the difference between two dependent correlations were conducted (Steiger, 1980). As expected, in the spontaneous recall condition, the positive correlation between spatial contiguity factor scores and overall recall ($r = .528$) was significantly different from the negative correlation between temporal contiguity factor scores and overall recall ($r = -.293$), $z = 3.14$, $p = .002$. However, in the instructed recall condition, the positive correlation between spatial contiguity factor scores ($r = .290$) and overall recall was not significantly different from the negative correlation between temporal contiguity factor scores and overall recall ($r = -.091$), $z = 1.52$, $p = .13$. This pattern of findings is consistent with the notion that the spatial dimension became less dominant in the instructed recall condition.

Note, however, that the third issue we addressed concerned the relation between temporal contiguity factor scores and overall recall in the verbal recall task for each of the two recall conditions. As can be seen in Figures 6A and 6B, none of these correlations reached significance. Thus, the temporal contiguity factor scores did not predict overall recall even when time was the only associative dimension that was available to guide memory search.

Lastly, the fourth issue we addressed concerned the relation between the temporal contiguity effects in each of the spatial and verbal recall tasks. As can be seen in Figure 7A, this correlation was found to be non-significant in the spontaneous recall condition, $r(26) = .277$, $p = .153$. However, as can be seen in Figure 7B, this correlation was significant in the instructed recall condition, $r(43) = .510$, $p < .001$. Altogether, these findings suggest that the extent to which individuals consistently utilized the one (temporal) associative dimension that was common across the two recall tasks was dependent on task instructions.

To summarize, Experiment 1 yielded two key findings. First, we found that instructions to begin recall from the last presented item increased temporal contiguity and decreased spatial contiguity. This suggests that even a relatively small change in how participants are instructed to *initiate* can bias them to make more use of temporal information as they continue to search memory *after* initiation. Second, we found that when subjects were allowed to adopt their own recall initiation strategies, there was no apparent competition between the use of temporal and spatial information (i.e., the correlation between temporal and spatial contiguity was near zero), but when instructed to begin recalling at the end, the two types of information came into conflict (i.e., there was a negative correlation between temporal and spatial contiguity). This suggests that the subjects can dynamically alter how the two sources of information interact during memory search, sometimes allowing them to make independent contributions and sometimes increasing the reliance on one at the expense of the other.

Experiment 2

Experiment 1 showed that recall instructions can change the balance between the uses of temporal versus spatial associative dimensions during memory search. Experiment 1 also provided preliminary evidence of a theoretically important pattern of correlations between temporal contiguity factor scores, spatial contiguity factor scores, and overall recall success that varied both as a function of recall task modality and recall instructions. In Experiment 2, we attempt to replicate some of these correlational findings with greater statistical power. We do so using data from the “Teen Learn Study” which has a larger sample size (168 adolescents). In Gibson et al. (2021) we analyzed data from the delayed free recall task of that study. The Teen

Learn Study also included an immediate free recall task with recency initiation instructions. Here we report those data for the first time.

Method

Participants. Participants in the Teen Learn Study were 168 adolescents (10-13 years old), recruited from the same population as those in Experiment 1. The participants were recruited into a larger study that examined the effect of different types of working memory training on learning and reasoning. Although the original study involved three assessment periods—pretest, immediate posttest, and six-month follow-up—the present analyses focused exclusively on the pretest period, before any working memory training had been initiated. Two cohorts of adolescents participated in the study. Cohort 1 was assessed and trained between August 2015 and April 2016 and ohort 2 between August 2016 and April 2017ed. Two cohorts of adolescents participated in the study. Cohort 1 was assessed and trained between August 2015 and April 2016 and cohort 2 between August 2016 and April 2017

Sample size for the Teen Learn Study was determined by an a priori power analysis to achieve 80% power for a 3 × 2 split-plot analysis of covariance including three between-subjects factors (training conditions), two within-subjects factors (immediate post-test vs. 6-month follow-up), and with pretest as the covariate. Because the present analyses involved only within-participant factors, we assumed power was ≥ 80.

Procedure and tasks. The first assessment period included a brief meeting with caregivers and adolescents to obtain consent and assent, respectively, in the Attention, Memory, and Perception Laboratory at the University of Notre Dame. Adolescents were assessed on a battery of neuropsychological and academic outcome measures. Additionally, parents completed a battery of questionnaires providing basic personal information about the student, a brief educational and mental health history including a list of current medications, as well as ratings of ADHD symptoms and executive functioning. The full battery of assessments is listed in Table S2. All participants received the same order of tasks.

The verbal recall task was similar to the verbal task used in Experiment 1 except that it only included six lists of 10 unique, high-frequency words (one- and two-syllable nouns) presented in random order. All participants saw the same word lists presented on a standard CRT monitor in 20-point white font on a black background. Each word was presented in the middle of the screen for 1 s with no interstimulus interval. After presentation of the entire word list, question marks appeared in the center of the screen signifying the recall period.

Likewise, the spatial recall task was also similar to the verbal task used in Experiment 1, except that it only included six lists of 10 different spatial locations marked by white squares on a black background presented on a standard CRT monitor. Each of the 10 locations per list was cued by temporarily changing color from white to red for one second with no interstimulus interval. Squares appeared at any one of 60 (6 × 10) unique locations on the computer screen and each location was cued only once across the six different lists. To simplify the task for the participant, 30 of the possible 60 squares were randomly selected and appeared in three consecutive trials. After the first three trials, 30 new locations were randomly selected from the possible 60 without replacement and appeared in the last three trials.

Experiment 2 included only the instructed recall condition of Experiment 1. Thus, all participants were told that they should begin recalling items from the end of the list first (though in no particular order). Participants were given 30 s to recall the lists and were required to wait the full 30 seconds before proceeding to the next trial. In the verbal recall task, participants reported their answers verbally into a microphone. In the spatial recall task, participants used the mouse to click on the relevant spatial locations. The order and number of correct and incorrect recall responses were recorded for each participant. In the verbal recall task, responses were scored as correct for exact matches or if the response was a different form (i.e., singular/plural, verb tense) of the correct response. Two practice trials preceded the experimental trials in each of the verbal and spatial recall tasks.

Outcome measures. The same five outcome measures used in Experiment 1 were also used in Experiment 2.

Results

Again, for our results, we rely primarily on confidence intervals to support our conclusions. However, these conclusions are consistent with detailed ANOVAs presented in the Supplemental Materials.

Probability of first recall. As shown in Figure 2E, consistent with the results of Experiment 1, when instructed to initiate recall from the final item, participants tended to do so and rarely initiated from the first item. There were a few differences between the task modalities.

Serial position curve. As shown in Figure 2F and consistent with the results of Experiment 1, we see the standard pattern for an immediate free recall task: a strong recency effect and a modest primacy effect. Further, comparing the two task modalities, we see that overall recall in the spatial modality was higher than the verbal modality, again mirroring the results of Experiment 1. Figure 2F also shows that accuracy was more bow-shaped in the verbal than in the spatial task, with lower accuracy for items that were presented in the middle portion of the list.

Total Errors. As in Experiment 1, participants committed more errors, on average, in the spatial task (M = 0.71, SE = 0.03) than in the verbal task (M = 0.25, SE = 0.02), F(1,167) =

214.54, $p < .0001$, $\eta_p^2 = 0.56$. However, again replicating Experiment 1, the correlation between total average errors and overall proportion correct was small and non-significant in both the spatial IFR task ($r(167) = -0.059$, $p = .45$), and in the verbal IFR task ($r(167) = -0.147$, $p = .06$). Thus, there is no evidence that guessing inflated accurate recalls in the spatial task; indeed, to the extent that there was any relationship, the overall proportion correct *decreased* as total average errors increased.

Temporal lag-CRP. Figure 3E shows a temporal contiguity effect in both task modalities for Experiment 2. Further, the temporal contiguity factor scores shown in Figure 3F corroborate the lag-CRPs. The inconsistent asymmetry of the contiguity effect observed in the instructed recall condition of Experiment 1 is also seen here. There is a very modest forward asymmetry in the verbal recall. In the spatial recall task, however, there was a backward asymmetry.

Spatial lag-CRP. The spatial lag-CRP outcome was obtained solely within the spatial recall task and is shown in Figure 4E. The instructed recall group of Experiment 2 continues to replicate the corresponding condition in Experiment 1. Here, we see a spatial contiguity effect, such that the conditional-response probability increases as lag decreases. Further, the spatial contiguity factor scores shown in Figure 4F corroborate the lag-CRPs. Recall for one item triggered recall for another item studied nearby in space.

Also consistent with Experiment 1, we see that the temporal contiguity is stronger than the spatial contiguity in Experiment 2, as witnessed by a steeper curve. The contiguity factors scores corroborate this effect with higher values in the temporal associative dimension than in the spatial associative dimension.

Correlations. Figures 5G-I present correlations of interest in the spatial recall task of Experiment 2. First, as seen in Figure 5G, there was a significant negative correlation between the spatial and temporal contiguity factor scores, $r(166) = -.355$, $p < .001$. Thus, the results of Experiment 2 provided further support for the notion that the two associative dimensions trade off when individuals are explicitly instructed to attend to the temporal associative dimension during recall.

Second, there was a significant positive correlation between spatial contiguity factor scores and overall recall in the spatial recall task, $r(166) = .285$, $p < .001$ (Figure 5I), but not between temporal contiguity factor scores and overall recall in the spatial recall task, $r(166) = -.060$, $p = .436$ (Figure 5H). However, unlike the instructed recall condition of Experiment 1, the positive correlation between spatial contiguity factor scores and overall recall was significantly different from the negative correlation between temporal contiguity factor scores and overall recall, $z = 2.76$, $p = .006$. The weak relation between temporal contiguity factor scores and overall recall was also observed in the verbal recall task, as this correlation was non-significant, $r(166) = -.018$, $p = .816$ (Figure 6C). These findings suggest that the spatial associative dimension was more predictive of overall recall accuracy than the temporal associative dimension even though individuals prioritized the temporal dimension.

Finally, as can be seen in Figure 7C, the correlation observed between the temporal contiguity effects in the spatial and verbal recall tasks was positive and significant in the instructed recall group of Experiment 2, $r(166) = .252$, $p < .001$. These findings suggest that individuals consistently utilized the temporal associative dimension across the two recall tasks when they were instructed to do so.

Correlation analyses of Gibson et al.'s (2021) results.

The above analyses focus on the *immediate* free recall data from the Teen Learn Study dataset. The Teen Learn Study also collected *delayed* free recall data and Gibson et al. (2021)

reported group-level analyses of that data but did not examine correlations. Therefore, as a final check on the replicability of the correlations reported above in Experiments 1 and 2, here we report correlational analyses of the Teen Learn Study's *delayed* recall verbal and spatial tasks. As can be seen in Table S2, the administration of the verbal and spatial delayed recall tasks always followed the administration of the verbal and spatial immediate recall tasks in their study. Furthermore, although participants were instructed to use a recency recall strategy in the two immediate recall tasks, they were not given any recall initiation instructions in the two delayed recall tasks. Thus, the delayed tasks can be considered spontaneous recall conditions. Consistent with this interpretation, an inspection of the probability of first recall, serial position curves, and temporal lag-CRP outcomes from their study (see Figure 2 from Gibson et al, 2021) were more consistent with the spontaneous recall condition than with the instructed recall condition of Experiment 1.

First, with respect to the possibility that the spatial and temporal associative dimensions might trade off in the spatial delayed recall task, recall that Gibson et al.'s (2021) group-level findings suggested that the spatial associative dimension dominated the temporal associative dimension. However, consistent with the spontaneous recall condition of Experiment 1, there was only a small negative correlation between spatial and temporal contiguity factor scores in Gibson et al.'s study, $r(166) = -.158$, $p = .041$ (Figure 5J), that did not achieve the more conservative significance level ($\alpha = 0.01$) that was established for the correlational analyses. Thus, although we cannot rule out the possibility of a small effect, the two dimensions appear to trade off less in the spontaneous recall condition than in the instructed recall condition.

Second, once again, the spatial associative dimension was found to be more predictive of overall recall success in the spatial delayed recall task than the temporal associative dimension in that the correlation between spatial contiguity factor scores and overall recall was positive and significant, $r(166) = .364$, $p < .001$ (Figure 5L); whereas, the correlation between temporal contiguity factor scores and overall recall was actually negative and did not achieve the more conservative significance level, $r(166) = -.171$, $p = .027$ (Figure 5K). Consistent with the spontaneous recall condition of Experiment 1, the positive correlation between spatial contiguity factor scores and overall recall was significantly different from the negative correlation between temporal contiguity factor scores and overall recall, $z = 4.74$, $p < .001$. The weak relation between temporal contiguity factor scores and overall recall was also corroborated in the third analysis in which the correlation between temporal contiguity factor scores and overall recall accuracy in the verbal delayed recall task was found to be non-significant, $r(165) = .079$, $p = .311$ (Figure 6D).

Finally, as can be seen in Figure 7D, the correlation between the temporal contiguity effects in the spatial and verbal delayed recall tasks shows no relationship between the two variables in the spontaneous recall condition of Gibson et al.'s (2021) study, $r(165) = .053$, $p = .495$. These findings suggest that participants do not consistently emphasize temporal dimension across tasks under spontaneous recall instructions.

General Discussion

Recent work shows that spatial information plays an important role in episodic memory search (Clark & Bruno, in press; Gibson et al. 2021; Miller et al., 2013). Here, we addressed a critical open question in this emerging literature: how spatial information interacts with other associative dimensions, especially time. We began by replicating Gibson et al.'s (2021) key finding that participants rely on both the temporal and spatial associative dimensions, even when the task is spatial in nature, but that the spatial dimension has a more powerful influence on recall order. The present study's results extended these findings by showing that the balance between the use of spatial and temporal information is sensitive to recall initiation instructions—it is under the control of the participant. Specifically, instructing participants to begin recall at the end of the list reduced the amount of forward asymmetry in the temporal contiguity effect and reduced the overall magnitude of the spatial contiguity effect. The present findings are therefore consistent with previous studies that have examined how instructional emphasis on the temporal associative dimension can diminish the accuracy of spatial memory (e.g., Gmeindl et al., 2011) and call into question the use of serial order tasks to measure spatial memory (see e.g., Hurlstone, 2019).

The study also yielded several novel findings about the correlations among spatial contiguity and temporal contiguity. Although the reliabilities of the contiguity factor scores were not as high as one would like (Table 1), suggesting the magnitude of some of the correlations may be underestimated, a consistent pattern emerges when examining correlations across the experiments. In the spatial recall task when participants were allowed to recall spontaneously, the degree of spatial clustering was uncorrelated with the degree of temporal clustering, suggesting that the two types of information were not simply trading off. Moreover, the degree to which temporal clustering was used in the spatial recall task was found to be uncorrelated with the degree to which temporal clustering was used in the verbal recall task when recall was spontaneous. A reanalysis of data from Gibson et al. (2021) replicated this pattern of non-significant correlations. These findings suggest that both temporal and spatial retrieval strategies could co-exist. Somewhat more speculatively, the lack of correlation between the degree of spatial and temporal clustering may suggest that the mental code for space can be orthogonal to the mental code for time. Maintaining independent codes might be facilitated in the current task by the fact that in our study, the spatial and temporal aspects of our stimuli were randomly combined. By contrast, in the physical world, spatial and temporal information tend to be confounded (i.e., things that are close together in space tend to be experienced close together in time), which has led some to suggest that a single neural code could capture both dimensions (Qasim, Fried, & Jacobs, 2021; see also, Howard, 2017; Howard & Eichenbaum, 2015; Howard et al., 2005; Howard et al., 2014). Our results suggest that independent codes might also be possible under the proper conditions and that individuals can divide their attention across both dimensions during memory search.

Compared with the pattern of correlations observed in the spontaneous recall group, when participants were instructed to begin recalling from the last item, the pattern of correlations was quite different. Perhaps most striking, under the begin-at-the-end initiation instructions, spatial and temporal clustering were negatively correlated, suggesting that participants who adopted the order-based strategy encouraged by the instructions, tended to reduce their reliance on spatial information. Moreover, the degree to which temporal clustering was used in the spatial recall task was now found to be positively correlated with the degree to which temporal clustering was used in the verbal recall task when recall was instructed. Taken together with the spontaneous recall condition, these findings suggest that participants encode information about both the temporal and the spatial relationships among list items but that they have considerable cognitive control over how they are used to search memory both within the same task and across different tasks.

An ability to dynamically change which dimensions are used to search memory may also influence the extent to which those dimensions are related to overall recall accuracy. Several past studies have found positive correlations between overall recall levels and temporal contiguity factor scores (or related measures of temporal contiguity; Healey, 2018; Healey et al., 2014; Sederberg et al., 2010; Spillers & Unsworth, 2011). More importantly, recent findings have suggested that the magnitude of this relation can be modulated by instruction and task context. For example, Healey & Uitvlugt (2019) found that the correlation between temporal contiguity factor scores and recall was reduced when word lists contained strong semantic associations, and this relationship was even reversed when participants were instructed to use the semantic associations to guide memory search. Supporting this interpretation, Mundorf et al. (2021) found a significant correlation between temporal contiguity factor scores and recall levels when participants deliberately studied words for a test, but no correlation was found when encoding was incidental. Taken together, these previous findings suggest that correlations between contiguity and recall reflect participants' ability to deploy whichever study/retrieval strategies are most effective given the nature of the stimuli and task demands.

Based on these previous findings, it would be reasonable to expect that the magnitude of the correlations between each of the two contiguity factor scores and recall would be modulated by recall condition in the spatial recall task. However, the evidence for this form of modulation was weaker in the present study. Although this modulation was observed in Experiment 1, it was not observed in Experiment 2, when a larger sample was obtained. Rather, the findings suggest that spatial clustering ability benefitted recall accuracy more than temporal clustering ability, regardless of instruction condition in the spatial recall task. Of course, one reason the expected pattern of modulation was not observed in the spatial recall task may concern the unexpected finding that the temporal dimension never appeared to benefit recall accuracy in the present study, even when it was the only available dimension (as in the verbal recall task), and despite the fact that we consistently found significant temporal contiguity effects at the group level in this task.

It is important to note that while we have interpreted the present results as reflecting processes that occur during recall as opposed to during study, the present study was not designed to differentiate encoding versus retrieval strategies. Thus, we cannot rule out the possibility that the results might reflect encoding. However, the notion that participants can control the influence of different associative dimensions during search is consistent with memory models that emphasize the importance of control processes. For example, the Search of Associative Memory framework (Raaijmakers & Shiffrin, 1980, 1981) holds that an attempt to search memory begins with the creation of a retrieval plan that specifies the relative weighting of different types of information in constructing a retrieval cue. It is also possible that control processes determine not just which information is used during memory search but which types of information are encoded during study (Malmberg & Shiffrin, 2005; Lehman & Malmberg, 2013). This raises the question of whether instructions to recall items in a particular way, when repeated across trials, change only the balance of which types of information are used or which types of information are encoded.

Participants' ability to dynamically change how they search memory sits slightly less comfortably with models that emphasize the automatic encoding and retrieval of temporal information. Retrieved context models (RCMs) assume new events are automatically associated with the current state of a drifting mental context representation and that when an event is recalled, it reinstates its associated mental context (Healey & Kahana, 2016; Howard & Kahana, 2002b; Lohnas et al., 2015; Polyn et al., 2009; Sederberg et al., 2008; Mundorf et al., 2021). These models have historically focused more on the automatic mechanisms of context drift and reinstatement, and they have focused less on deliberate control processes. To account for the current findings that task instructions change how memory is searched, these models would need to include a mechanism that allows instructions to effectively increase the gain on one type of information and/or inhibit the other dimensions (for recent work exploring these ideas, see Healey & Wahlheim, 2023).

In conclusion, participants can dynamically search memory along both temporal and spatial dimensions, adapting to the demands of the task. The new but growing literature on temporal/spatial interactions presents exciting challenges for models of episodic memory which must be updated to account for not only the interaction of different associate dimensions but also the cognitive control processes that allow participants to flexibly search memory.

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Open Practices Statement

The data for these experiments are available at:
https://osf.io/8wg4z/?view_only=29d12670ebc543cd8cf176adff0147e8

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Table 1. Reliability scores for all experiments broken down by condition, where a higher value indicates a more stable measure as calculated by the methodology from Sederberg et al. (2010).

Experiment	**Condition**	**Temporal Contiguity Factor Reliability Score**	**Spatial Contiguity Factor Reliability Score**
Experiment 1 - Instructed			
	Spatial IFR	.703	.596
	Verbal IFR	.753	—
Experiment 1 - Spontaneous			
	Spatial IFR	.632	.627
	Verbal IFR	.666	—
Experiment 2			
	Spatial IFR	.642	.520
	Verbal IFR	.400	—
Gibson et al. (2021)			
	Spatial DFR	.302	.289
	Verbal DFR	.129	—

Note: IFR = immediate free recall; DFR = delayed free recall

Figure 1

The 120 possible spatial locations that lie within 5 squares of the just-recalled item.

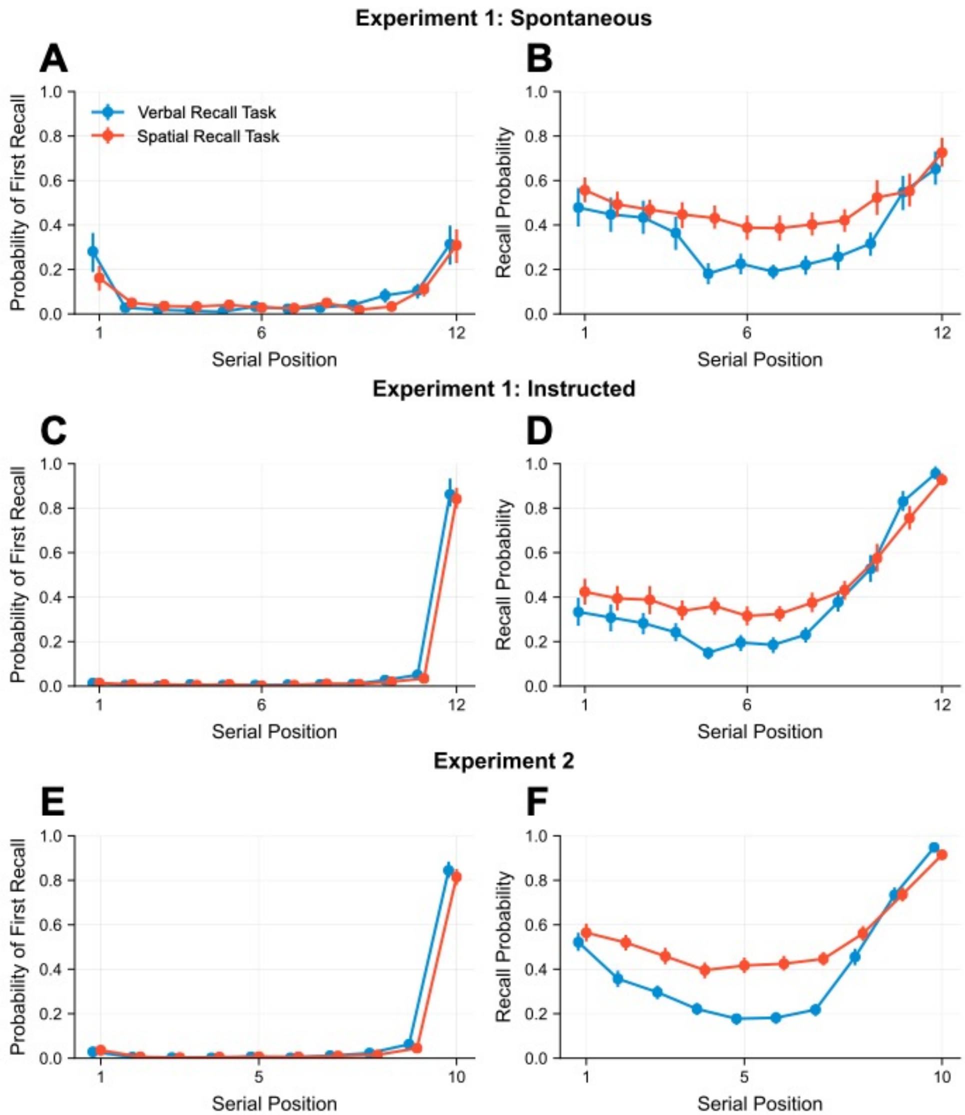
Above-Below lag / Left-Right lag

	L 5	L 4	L 3	L 2	L 1	0	R 1	R 2	R 3	R 4	R 5
A 5	5	5	5	5	5	5	5	5	5	5	5
A 4	5	4	4	4	4	4	4	4	4	4	5
A 3	5	4	3	3	3	3	3	3	3	4	5
A 2	5	4	3	2	2	2	2	2	3	4	5
A 1	5	4	3	2	1	1	1	2	3	4	5
0	5	4	3	2	1	*i*	1	2	3	4	5
B 1	5	4	3	2	1	1	1	2	3	4	5
B 2	5	4	3	2	2	2	2	2	3	4	5
B 3	5	4	3	3	3	3	3	3	3	4	5
B 4	5	4	4	4	4	4	4	4	4	4	5
B 5	5	5	5	5	5	5	5	5	5	5	5

Note: As described in the text, we limit our analysis to 5 spatial lags, and thus the figure shows only a subset of the 180 actual locations in the display. Five spatial lag conditions were created by ignoring spatial direction and averaging across the cells that fell within five square bands around the center location (numbered 1 to 5 in this figure). This averaging was required to offset the large number of missing values that tend to accrue to large lag values (see text for further discussion).

Figure 2

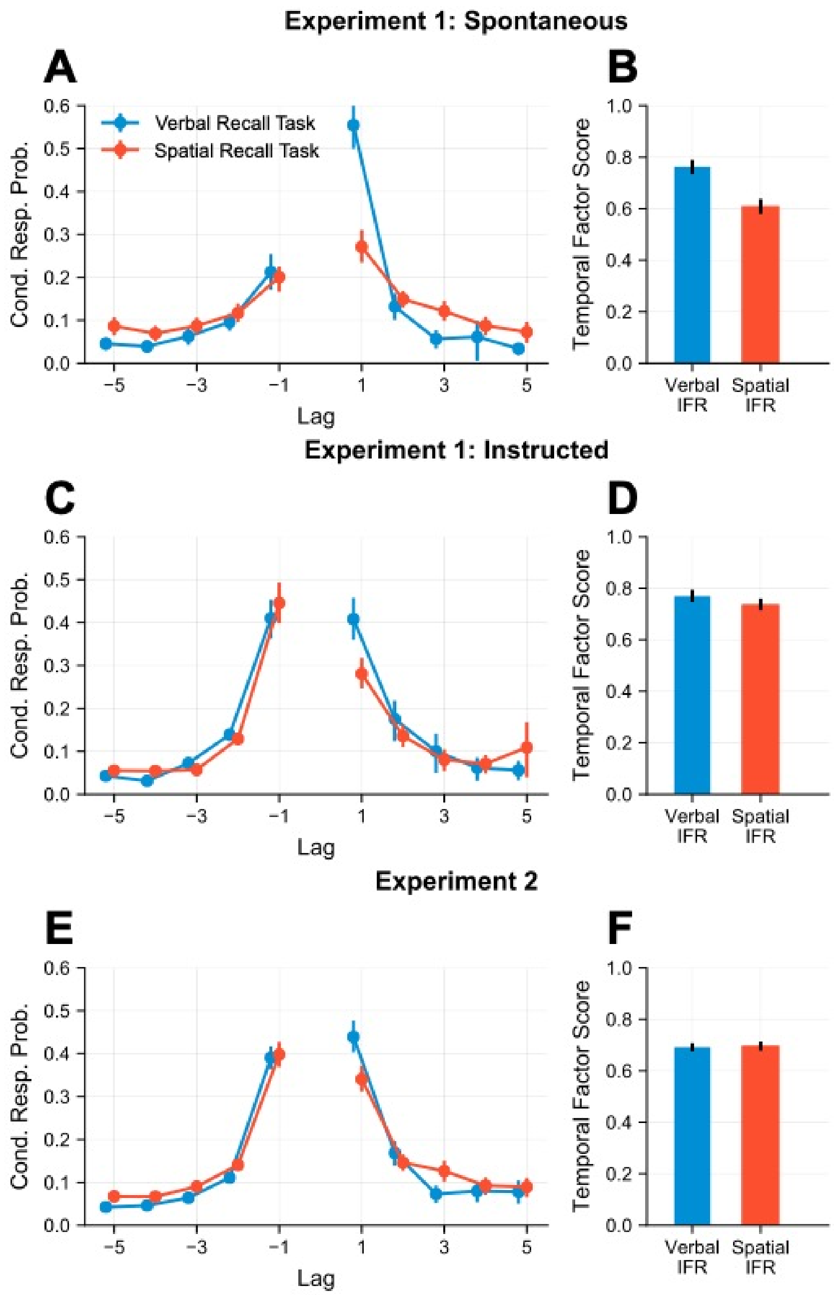
Recall Initiation and Overall Recall Accuracy



Note: Panels A, C, E: Probability of first recall curves shown as a function of serial position in each of the verbal and spatial recall tasks and for each experiment. Panels B, D, F: Serial position curves in each of the verbal and spatial recall tasks and for each experiment. All error bars are bootstrapped 95% confidence intervals.

Figure 3

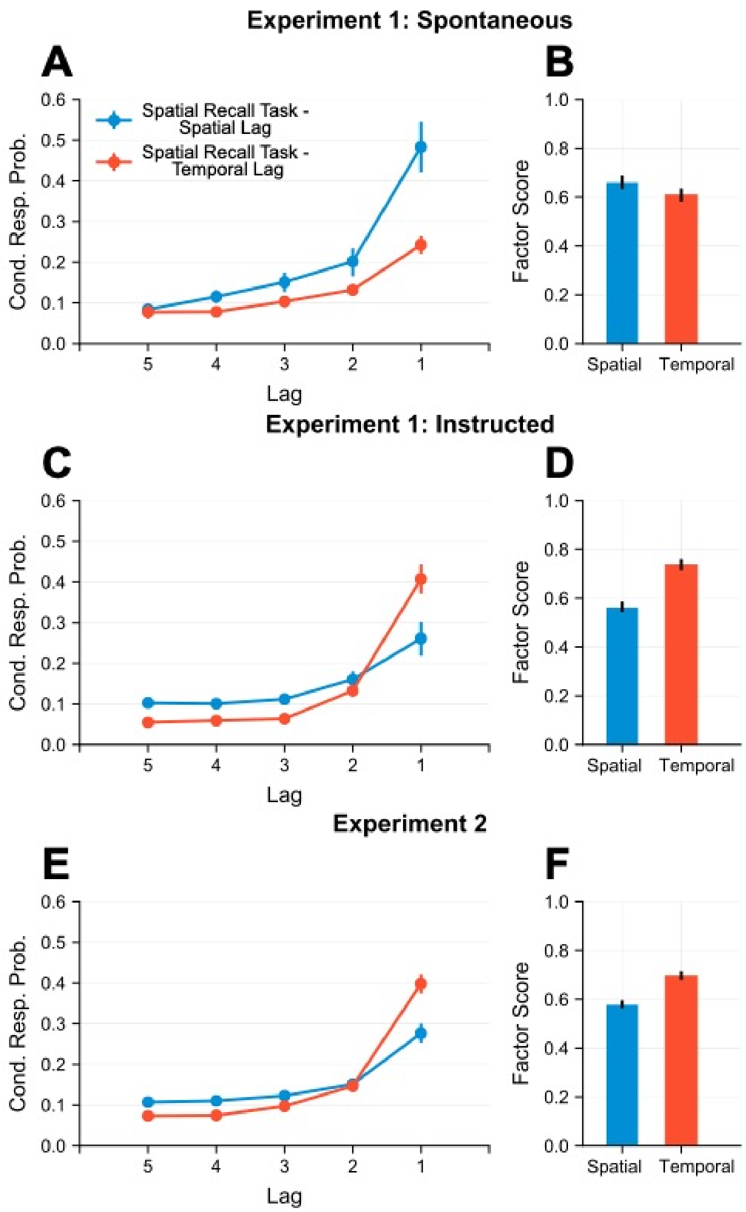
Temporal Contiguity



Note: Panels A, C, E: Temporal lag-conditional response probability functions in each of the verbal and spatial recall tasks and for each experiment. Panels B, D, F: Temporal contiguity factor scores in each of the verbal and spatial recall tasks and for each experiment. All error bars are bootstrapped 95% confidence intervals.

Figure 4

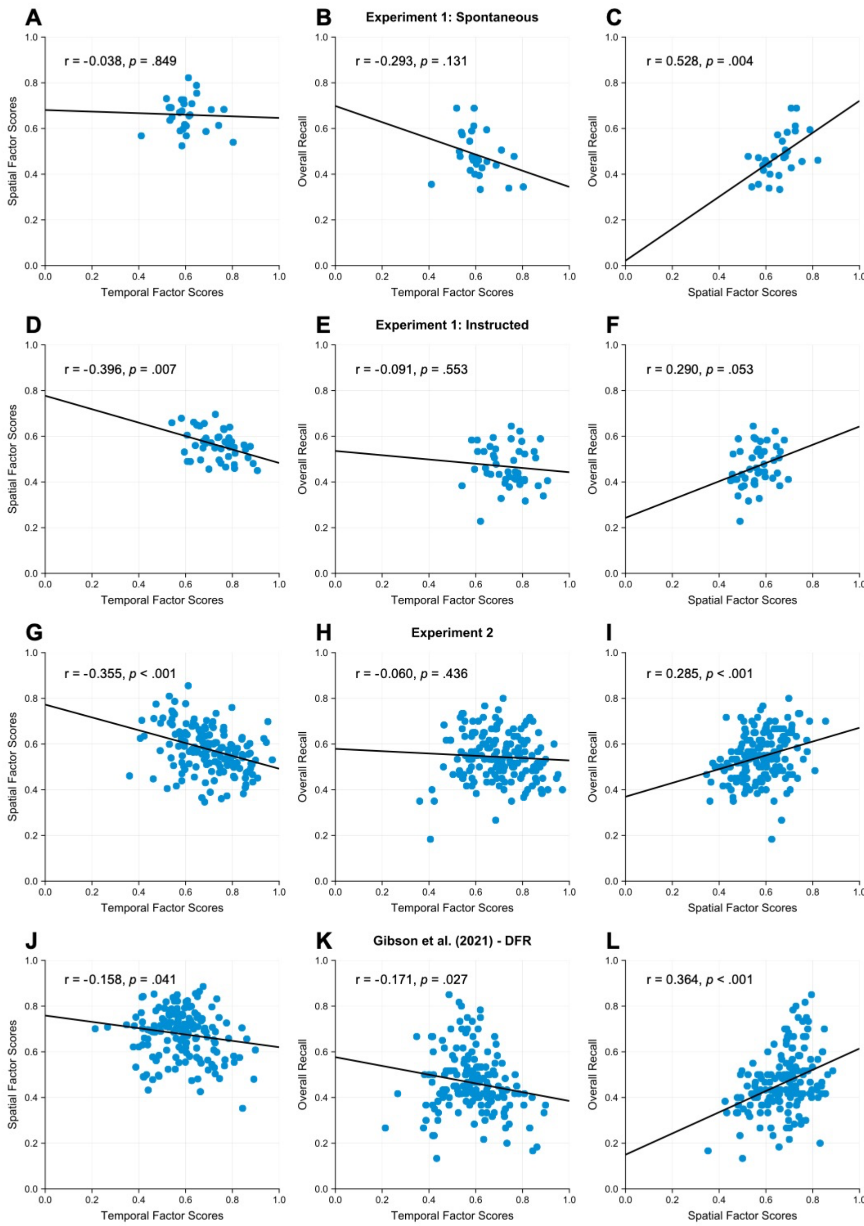
Spatial Contiguity



Note: Panels A, C, E: Lag-conditional response probability functions comparing temporal and spatial lags in the spatial recall tasks for each experiment. Here, temporal lags have been collapsed across temporal direction. Panels B, D, F: Contiguity factor scores comparing temporal and spatial in the spatial recall tasks for each experiment. All error bars are bootstrapped 95% confidence intervals.

Figure 5

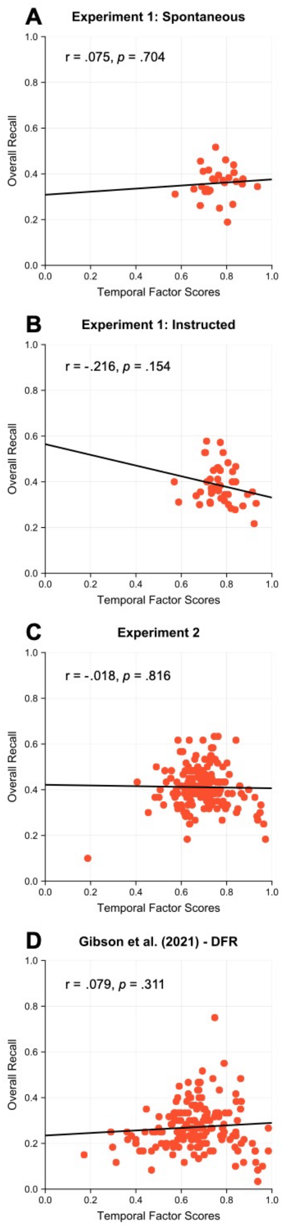
Correlations Comparing Temporal Contiguity Factor Scores, Spatial Contiguity Factor Scores, and Overall Recall in the Spatial Immediate Recall Tasks for Experiment 1



Note: Spontaneous (Panel A-C), Experiment 1: Instructed (Panel D-F), Experiment 2 (Panel G-I), and in the spatial delayed recall task of Gibson et al. (2021) (Panel J-L).

Figure 6

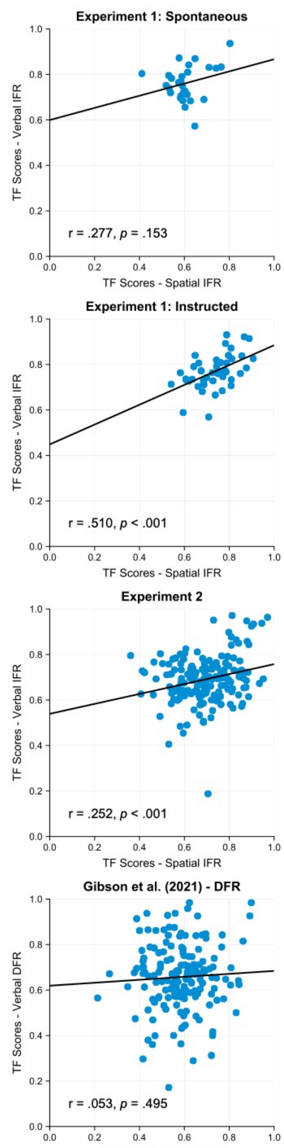
Correlations Comparing Temporal Contiguity Factor Scores and Overall Recall in the Verbal Immediate Recall Tasks for Experiment 1



Note: Spontaneous (Panel A), Experiment 1: Instructed (Panel B), Experiment 2 (Panel C), and in the verbal delayed recall task of Gibson et al. (2021) (Panel D).

Figure 7

Correlations Comparing Temporal Contiguity Factor Scores in the Spatial Immediate Recall Task and the Temporal Contiguity Factor Scores in the Verbal Immediate Recall Task for Experiment 1



Note: Spontaneous (Panel A), Experiment 1: Instructed (Panel B), and Experiment 2 (Panel C), and comparing the temporal contiguity factor scores in the spatial delayed recall task and temporal contiguity factor scores in the verbal recall of Gibson et al. (2021) (Panel D).