



# Space and time in the similarity structure of memory

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## Abstract

Space and time are both essential aspects of human episodic memory. Yet, behavioral studies into the dynamics of recall have focused more on time than space. For instance, it is now well known that temporally contiguous events are more likely to be subsequently recalled than temporally remote events, as measured by the lag-conditional response probability (lag-CRP), which represents the probability of recalling item  $i + lag$  after recalling item  $i$ . The present study administered both verbal and spatial delayed free recall (DFR) tasks to a sample of 168 participants in order to measure lag-CRPs along both spatial and temporal associative dimensions. Whereas only the temporal lag-CRP could be measured in the verbal DFR task, both temporal and spatial lag-CRPs could be measured in the spatial DFR task. As expected, the results obtained in the verbal DFR task indicated the typical temporal contiguity effect. More importantly, the results obtained in the spatial DFR task indicated significant contiguity effects along both associative dimensions, and the spatial contiguity effect was found to be significantly larger than the temporal contiguity effect. In addition, the relatively small temporal contiguity effect observed in the spatial DFR task was also found to be significantly smaller than the temporal contiguity effect observed in the verbal DFR task. Altogether, the present findings provided novel evidence that spatial and temporal proximity can both cue sequential dependencies between successive recalls. As such, retrieved context models of episodic memory should be expanded to include spatial context as well as temporal context.

**Keywords** Spatial memory · Episodic memory and recall · Human memory

## Introduction

Recall of one event often elicits recall of other similar events. For instance, it is well established that the dimension of time can drive this chain of retrieval such that temporally contiguous events are more likely to be subsequently recalled, and especially those that occurred after the just-recalled event (see Healey et al., 2019, for a review). These temporal contiguity and forward temporal asymmetry effects are typically found in the laboratory when participants are instructed to study and then recall (either immediately or after a short delay) lists of words that are presented successively (either visually or aurally) at a common location. Within this context, the temporal contiguity and forward temporal asymmetry effects have been

quantified using lag conditional-response probability (lag-CRP) curves, which reflect the probability of successively recalling items as a function of their temporal distance from each other in the list (Kahana, 1996). However, because word lists have dominated the study of episodic memory search in the laboratory, surprisingly little is known about other possible dimensions of similarity that are capable of driving the chain of retrieval beyond those dimensions that are associated with words (such as semantic similarity; see Howard & Kahana, 2002a).

The present study examined the possibility that spatial similarity might also serve as an associative dimension underlying the search of episodic memory. Spatial similarity is an obvious candidate for exploration because space and time are both essential aspects of episodic memory and theoretical analyses have suggested a unified mathematical framework for representing temporal and spatial context within the medial temporal cortex (Howard, 2017; Howard et al., 2005; Howard et al., 2014; Howard & Eichenbaum, 2015). In addition, a variety of previous studies have examined the nature of spatial memory within the context of spatial (Bonanni et al., 2007; Dent & Smyth, 2006; Gmeindl et al., 2011; Guérard & Tremblay, 2008; Hurlstone, 2019; Hurlstone et al., 2014;

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Nairne & Dutta, 1992) and verbal (Miller et al., 2013) tasks. The results of these studies have suggested that spatial context may be encoded during study and used to cue retrieval during recall.

However, most previous studies of spatial memory have not examined the extent to which spatial similarity can cue sequential dependencies between successive recalls as is critically reflected in the lag-CRP. Furthermore, some previous studies that have attempted to measure such sequential dependencies have raised concerns that spatial similarity may sometimes be confounded with semantic similarity (Miller et al., 2013). For instance, when presented with a list of familiar physical landmarks, an item such as “Brooklyn Bridge” might have a higher probability of being subsequently recalled than “Gettysburg” following the correct recall of “Central Park,” but is this sequential dependency due to differences in spatial similarity or semantic similarity?

Thus, the present study developed a measure of spatial lag-CRP to examine the extent to which spatial proximity can cue sequential dependencies between successive recalls of stimuli that could only be distinguished spatially within the context of a delayed free-recall (DFR) task. On each trial of this spatial DFR task, participants viewed sequences of ten red squares that appeared within the context of a larger  $6 \times 10$  matrix of 60 locations, each of which was marked by a white rectangle. Following a brief spatial distraction task, participants then attempted to recall these locations by clicking on the white rectangles in any order. As mentioned above, the lag-CRP reflects the probability of recalling  $i + lag$  after recalling item  $i$ . These probabilities are considered to be *conditional-response probabilities* because they are computed 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 (see Healey et al., 2019, and Kahana, 1996, for more detailed discussion).

The lag scale in the measure of spatial lag-CRP was based on the spatial distance of the study sequence and was conceptualized along both a horizontal (left-right) and vertical (above-below) axis. A spatial lag of 1 was defined as a location that was shifted one unit along either or both axes relative to the location of the just-recalled item, a spatial lag of 2 was defined as a location that was shifted two units along either or both axes relative to the location of the just-recalled item, and so on (see Fig. 1 and *Methods* section for a more detailed description). In this way, spatial lags were defined as concentric squares of locations drawn around the just-recalled item. Evidence that spatial similarity can serve as an associative dimension underlying the search of episodic memory would be provided by the presence of a spatial contiguity effect in which spatially contiguous items are more likely to be subsequently recalled than more distant items.

In addition, the present study also explored how spatial and temporal associative dimensions might interact within the

spatial DFR task. The lag scale in the measure of temporal lag-CRP was based on the temporal order of the study sequence and is the same measure that has been used in many previous studies (Howard, 2004; see also Healey et al., 2019, for a review). Previous studies have demonstrated that a temporal contiguity effect can be observed even when spatial stimuli serve as the memoranda (Cortis Mack et al., 2018); note however, that these studies did not measure spatial lag-CRPs and were therefore unable to directly compare spatial and temporal lag-CRPs. In the present study, we tested the hypothesis that the spatial contiguity effect might be larger than the temporal contiguity effect based on previous findings suggesting that spatial context may dominate temporal context in spatial tasks (Gmeindl et al., 2011).

Of course, it may be difficult to directly compare the relative magnitudes of the spatial and temporal contiguity effects observed in the spatial DFR task because there is no way to equate the lag scale underlying the spatial and temporal dimensions. Although this concern may be mitigated to some extent by the fact that the temporal contiguity effect has been observed to exhibit at least some scale invariance (and thus be independent of any absolute unit of time; see e.g., Healey et al., 2019), we also attempted to corroborate this comparison by comparing the temporal contiguity effect obtained in the spatial DFR task with the temporal contiguity effect obtained in a standard verbal DFR task involving lists of unrelated words. If the use of temporal context is diminished when the memoranda involve spatial stimuli, then the temporal contiguity effect observed in the spatial DFR task should be smaller than the temporal contiguity effect observed in the verbal DFR task.

In summary, the present study sought evidence that spatial and temporal similarity may both serve as associative dimensions underlying the search of episodic memory. In addition, the present study also examined the extent to which the spatial associative dimension might dominate the temporal associative dimension when both dimensions were encoded within the spatial DFR task.

## Method

**Participants** Participants were 168 adolescents, aged 10–13 years, recruited from three public middle schools (grades 6–8) in a school 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 the memory performance of young adults (see e.g., Gibson et al., 2019). 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

Above-Below lag	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>i</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
			L 5	L 4	L 3	L 2	L 1	0	R 1	R 2	R 3	R 4

Left-Right lag

**Fig. 1** The 120 possible spatial locations arrayed around the just-recalled item. 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)

involved three assessment periods – pretest, immediate post-test, and 6-month follow-up – the present study focused exclusively on the pretest period, before any working memory training had been initiated. Adolescents were informed that they would receive \$40.00 for each assessment appointment and \$100.00 for completion of the entire working-memory training program.

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. In order to be enrolled, adolescents needed to meet the following inclusion criteria: (1) access to a computer with stable internet connection, (2) no previous exposure to working memory training interventions, (3) no parent-reported motor problems that might interfere with use of a computer mouse, and (4) no ongoing participation in another research study.

Sample size was determined by an a priori power analysis in order to achieve 80% power within the context of the original working memory training study, which involved 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. Adequate power was therefore assumed to be at least 80% in the present study because all analyses involved only within-subjects factors.

**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 in the Department of Psychology at the University of Notre Dame. After this brief introduction, 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 (e.g., age, grade, handedness, and race and ethnicity), a brief educational and mental health history including a list of current medications, as well as ratings of attention-deficit hyperactivity disorder (ADHD) symptoms and executive functioning. The full battery of assessments is listed in Table 1. All participants received the same order of tasks.

As the current study focused on the verbal and spatial DFR tasks, solely those measures were reported here. However, it is worth pointing out that we decided to exclude the verbal and spatial immediate free recall (IFR) tasks from analysis in the present study because participants were explicitly instructed to begin their recalls toward the end of the list which may have emphasized the encoding of temporal context (see Howard & Kahana, 1999, for a comparison of different types of free recall tasks). Although participants always performed the verbal and spatial IFR tasks prior to the verbal and spatial DFR tasks, there was no evidence that the recall initiation

**Table 1** List of measures administered to the primary caregiver or adolescent in the Teen Learning and Reasoning Study. The tasks were administered in the same order as listed below to all participants

Measure	Respondent
Demographics	Parent
Educational history	Parent
Physical and mental health history	Parent
DuPaul ADHD rating scale	Parent
BRIEF inventory	Parent
TOWRE	Adolescent
Verbal IFR task	Adolescent
Spatial IFR task	Adolescent
Verbal DFR task	Adolescent
Spatial DFR task	Adolescent
ETS inference	Adolescent
BOMAT	Adolescent
MAP reading	Adolescent
MAP mathematics	Adolescent
IMI	Adolescent

*ADHD* attention-deficit hyperactivity disorder, *BRIEF* Behavior Rating Inventory of Executive Functions, *TOWRE* Test of Word Reading Efficiency, *IFR* Immediate Free Recall, *DFR* Delayed Free Recall, *ETS* Educational Testing Service, *BOMAT* Bochum Matrices-Advanced-Short Version, *MAP* Measures of Academic Progress, *IMI* Intrinsic Motivation Inventory

instructions received before the IFR tasks carried over into the DFR tasks (see [Results](#) section for details).

The verbal DFR task included six lists of ten 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-pt white font on a black background. Each word was presented in the middle of the computer screen for 1 s with no inter-stimulus interval (ISI). After presentation of the entire word list, a fixation-cross appeared to signify the start of the delay period. During the delay, participants saw a series of three-digit numbers that they needed to reorder aloud from smallest to largest. For example, if participants saw 597 they needed to say “5,” “7,” and “9.” A total of eight three-digit numbers, one every 2 s, appeared during the 16-s delay. Following the delay, question marks appeared in the center of the screen signifying the recall period. Participants then had 30 s to recall aloud as many words as possible in any order, and they needed to wait for the recall period, as signified by a brief tone, to end before moving to the next trial. Prior to the test trials, two practice trials using letter stimuli were presented. Participant responses were recorded via a microphone and digital recorder and scored as correct if they matched a word on the list, if they uttered a plural version of a list

item that was singular, or if they said a past tense version of a list item that was in the present tense.

For the spatial DFR task, participants were shown six lists of ten different spatial locations marked by white squares on a black background presented on a standard CRT monitor. Each of the ten locations per list was cued by temporarily changing color from white to red for one second with no ISI. Squares appeared at any one of 60 ( $6 \times 10$ ) 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. After all of the locations were cued in a list, the computer screen went blank to signify the start of the 16-s delay period, during which participants completed as many puzzles as possible. For each puzzle, participants arranged a set of Styrofoam shapes on a paper template that contained outlines for each puzzle piece; the test administrator collected each finished puzzle and replaced it with a new template and pieces until the delay period expired. Because participants were focused on placing the puzzle pieces in their appropriate locations, the test administrator informed the participant when the delay period ended (i.e., when the spatial locations re-appeared for recall). Participants then had 30 s to recall as many locations as possible in any order, and they needed to wait for the recall period, as signified by a brief tone, to end before moving to the next trial. Participant responses were recorded by the computer and included the location of the mouse clicks, the order of the mouse clicks, and the number of correct responses. Two practice trials that were identical to the test trials were presented before the six test trials.

**Outcome measures** Five outcome measures were obtained from the verbal and spatial DFR 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” is similar to the probability of first recall, but it reflects the overall proportion of items correctly recalled as a function of study list position. Third, “total errors” were recorded in both DFR tasks. In the verbal DFR task, these errors consisted of extra-list intrusions, prior-list intrusions, and repetitions, whereas in the spatial DFR task these errors consisted of clicking on one of the 30 visible squares that had not been presented on the current trial or that had already been selected. Fourth, 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. Note that large absolute values of temporal lag are not always possible relative to a given just-recalled item, resulting in a greater number of missing values for large absolute values of lag. The solution in this literature has typically

been to restrict the analysis to temporal lag values between +5 and –5 (Healey et al., 2019).

In addition to these four common outcome measures, a fifth measure – the “spatial lag-CRP” – was also introduced in this study. This outcome was analyzed solely within the spatial DFR task because the spatial location of the list items did not vary in the verbal DFR task. The spatial lag-CRP reflects the probability of recalling an item as a function of its spatial direction and distance (or lag) relative to the just-recalled item. Figure 1 shows 120 possible spatial locations arrayed around the just-recalled item. More specifically, 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.

As mentioned above, analyses of temporal lag-CRP has 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. For instance, Fig. 3b shows that the number of participants who encountered any one of the 120 individual spatial lag conditions decreased to near zero as a function of spatial distance from the just-recalled item across all spatial directions. 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 168 participants encountered all spatial lag conditions. In order 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 preserved an examination of the spatial contiguity effect, but it eliminated examination of any directional asymmetries.

For instance, as shown in Fig. 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, A1), (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,

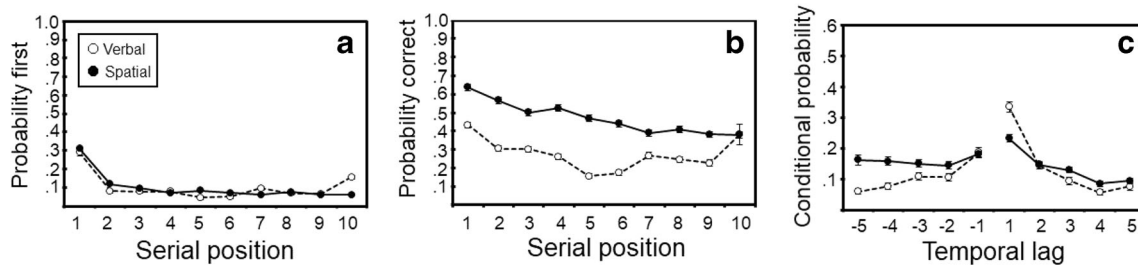
B5), (L2, B5), (L3, B5), and (L4, B5). Notice that there were five times as many cells in the spatial lag 5 condition as in the spatial lag 1 condition because the number of cells within each band increased by eight cells each time the spatial lag condition increased from one band to the next. Such expansion was necessary to offset the increasing number of missing cases in the more distant bands.

**Design and analyses** The probability of first recall and serial position curve outcomes were analyzed using a two-way, repeated-measures ANOVA with stimulus modality (verbal vs. spatial) and serial position (1–10) as the within-subjects factors. The total errors outcome was analyzed using a one-way repeated-measures ANOVA with stimulus modality (verbal vs. spatial) as the within-subjects factor. The temporal lag-CRP outcome was obtained in both the verbal and spatial DFR tasks, and it was analyzed using a three-way, repeated-measures ANOVA with stimulus modality (verbal vs. spatial), temporal direction (forward vs. backward), and temporal lag (1–5) as the within-subjects factors. The spatial lag-CRP outcome was obtained solely within the spatial DFR task and it was analyzed using a one-way, repeated-measures ANOVA with spatial lag (1–5) as the sole within-subjects factor. In addition, the relative magnitudes of the spatial and temporal lag-CRP curves were also compared within the context of the spatial DFR task using a two-way, repeated-measures ANOVA with associative dimension (spatial vs. temporal), and lag (1–5) as the within-subjects factors. Wilk’s lambda multivariate tests were used in all analyses to avoid violation of the sphericity assumption.

## Results

**Probability of first recall** There was a significant main effect of serial position,  $F(9,159) = 29.11, p < .0001, \eta_p^2 = 0.62$ , but the main effect of stimulus modality did not attain significance,  $F(1,167) = 0.18, p = .67, \eta_p^2 = 0.001$ . Most importantly, there was a significant two-way interaction between stimulus modality and serial position,  $F(9,159) = 6.05, p < .0001, \eta_p^2 = 0.26$ . As can be seen in Fig. 2a, this interaction indicated that participants were most likely to initiate recall at the beginning of the list across both stimulus modalities, though participants did occasionally begin recall at the end of the list when words were presented.

**Serial position curve** There was a significant main effect of stimulus modality,  $F(1,167) = 272.01, p < .0001, \eta_p^2 = 0.62$ , which indicated overall higher accuracy in the spatial DFR task than in the verbal DFR task. There was also a significant main effect of serial position,  $F(9,159) = 34.19, p < .0001, \eta_p^2 = 0.66$ , which generally indicated higher accuracy for items that were presented at the beginning of the list than for items



**Fig. 2** **a** Probability of first recall shown as a function of serial position in each of the verbal and spatial DFR tasks. **b** Proportion correct shown as a function of serial position (serial position curves) in each of the verbal and spatial DFR tasks. **c** Temporal lag-CRP curves shown as a function of

temporal direction and temporal distance (lag). Negative lag values represent items that appeared before the just-recalled item; whereas, positive lag values represent items that appeared after the just-recalled item. The error bars represent standard error of the mean

that were presented at the end of the list. However, there was also a significant two-way interaction between stimulus modality and serial position,  $F(9,159) = 19.54, p < .0001, \eta_p^2 = 0.52$ . As can be seen in Fig. 2b, and consistent with the probability of first recall curves, there was a linear decrease in accuracy as serial position increased in the spatial DFR task, whereas accuracy was more bow shaped in the verbal DFR task, with higher accuracy for items that were presented either at the beginning of the list (primacy effect) or at the end of the list (recency effect), and with lower accuracy for items that were presented in the middle portion of the list.

**Total errors** Participants committed more errors, on average, in the spatial DFR task ( $M = 0.91, SE = 0.04$ ) than in the verbal DFR task ( $M = 0.26, SE = 0.02$ ),  $F(1,167) = 231.73, p < .0001, \eta_p^2 = 0.58$ . Although this difference might raise concerns that the main effect of stimulus modality reported above in the analysis of the serial position curve might simply reflect a higher rate of guessing in the spatial DFR task than in the verbal DFR task, it was not supported by subsequent analyses. In particular, the correlation observed between total average errors and overall proportion correct was small, negative, and non-significant in the spatial DFR task ( $r(167) = -0.127, p = .11$ ); and, this correlation was small, positive, and non-significant in the verbal DFR task ( $r(167) = 0.128, p = .10$ ). Thus, there did not appear to be any systematic relation between total average errors and overall proportion correct, and the small relation that was observed in the spatial DFR task suggested that overall proportion correct actually *decreased* as total average errors increased.

**Temporal lag-CRP** Altogether, there was a total of 24 unique participants with missing data in one or more of the ten temporal direction  $\times$  lag positions ( $n = 20$  in the verbal DFR task; and,  $n = 8$  in the spatial DFR task), and they were excluded from the analysis. As can be seen in Fig. 2c and Table 2, there was a significant main effect of stimulus modality,  $F(1,143) = 43.85, p < .0001, \eta_p^2 = 0.24$ , indicating higher lag-CRPs in the spatial modality ( $M = .15, SE = .003$ ) than in the verbal modality ( $M = .13, SE = .003$ ). It is known that all else being

equal, the level of the lag-CRP averaged across lags increases as the number of items recalled increases (Healey, 2018; Healey et al., 2019), thus the main effect of stimulus modality may be driven by the fact that subjects recalled more items in the spatial condition.

There was also a significant main effect of temporal lag,  $F(4,140) = 57.69, p < .0001, \eta_p^2 = 0.62$ , indicating the typical temporal contiguity effect: namely, the probability of recall was greater for items that were adjacent to the just-recalled item ( $M = .24, SE = .007$ ) than for items that were in more remote study-list positions ( $M$ s ranged from .09 to .14;  $SE$ s ranged from .005 to .006). Although the main effect of temporal direction did not attain significance,  $F(1,143) = 1.63, p = .28, \eta_p^2 = 0.01$ , there was a significant temporal direction  $\times$  lag interaction,  $F(4,140) = 19.73, p < .0001, \eta_p^2 = 0.36$ , indicating the typical forward temporal asymmetry effect: namely, the temporal contiguity effect was overall larger for lag position +1 ( $M = .29, SE = .01$ ) than it was for lag position -1 ( $M = .19, SE = .01$ ).

In addition, the effects of temporal direction and lag were each modulated by stimulus modality. For instance, there was a significant stimulus modality  $\times$  temporal direction interaction,  $F(1,143) = 29.99, p < .0001, \eta_p^2 = 0.17$ , indicating that the temporal distinction between “before” versus “after” the currently-recalled item was smaller in the spatial modality than in the verbal modality. In fact, temporal lag-CRPs in the spatial task modality were actually slightly larger overall in the backward temporal direction ( $M = .16, SE = .006$ ) than in the forward temporal direction ( $M = .14, SE = .004$ ), whereas lag-CRPs in the verbal modality were larger in the forward temporal direction ( $M = .14, SE = .004$ ) than in the backward temporal direction ( $M = .12, SE = .008$ ).

There was also a significant stimulus modality  $\times$  temporal lag interaction,  $F(4,140) = 10.72, p < .0001, \eta_p^2 = 0.24$ , which indicated a steeper effect of lag in the verbal modality than in the spatial modality. Figure 3c and Table 2 shows the effect of temporal lag in each of the two task modalities when it was averaged across the forward and backward temporal directions. As can be seen, the temporal contiguity effect observed in temporal lag 1 condition was significantly larger in the

**Table 2** Mean temporal lag-CRPs and missing values associated with the main effects, two-way interactions, and three-way interaction reported in the repeated-measures ANOVA. Standard errors are given in parentheses

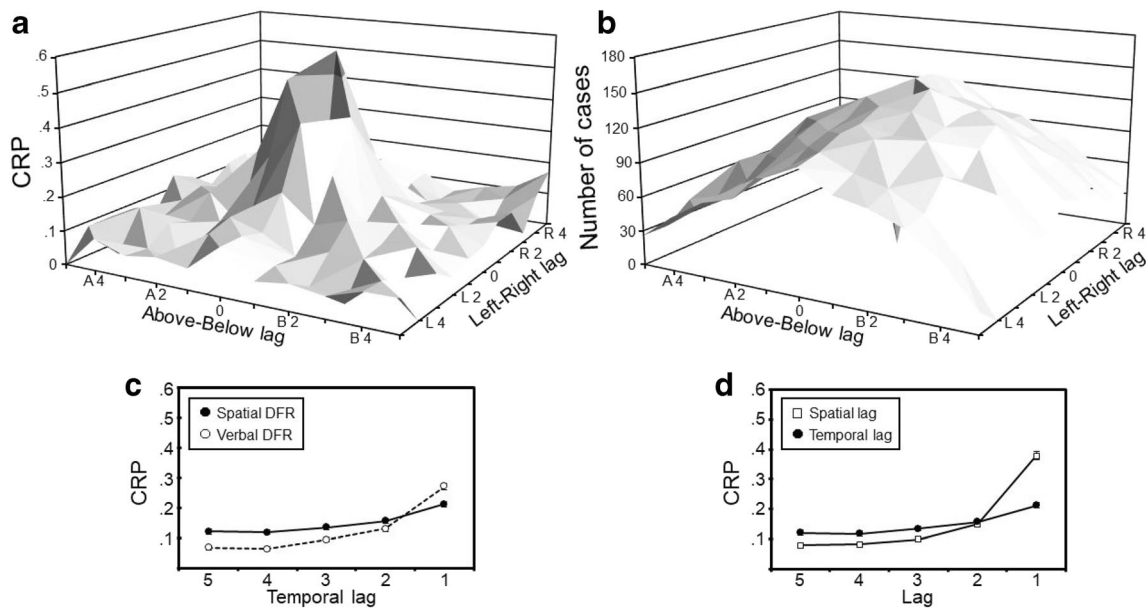
	Verbal	Spatial	Average
	Modality × Lag		Lag
5	0.07 (.008) Missing values = 1	0.12 (.008) Missing values = 0	0.10 (.006) Missing values = 0
4	0.06 (.007) Missing values = 1	0.12 (.008) Missing values = 0	0.09 (.005) Missing values = 0
3	0.10 (.008) Missing values = 1	0.14 (.008) Missing values = 0	0.12 (.005) Missing values = 0
2	0.13 (.009) Missing values = 1	0.16 (.008) Missing values = 0	0.14 (.006) Missing values = 0
1	0.27 (.011) Missing values = 1	0.21 (.008) Missing values = 0	0.24 (.007) Missing values = 0
	Modality × Direction		Direction
Backward (-)	0.12 (.008) Missing values = 3	0.16 (.006) Missing values = 0	0.14 (.005) Missing values = 0
Forward (+)	0.14 (.004) Missing values = 2	0.14 (.004) Missing values = 0	0.14 (.003) Missing values = 0
	Modality × Direction × Lag		Direction × Lag
-5	0.06 (.010) Missing values = 16	0.16 (.016) Missing values = 5	0.11 (.010) Missing values = 2
-4	0.08 (.012) Missing values = 13	0.15 (.012) Missing values = 3	0.11 (.010) Missing values = 1
-3	0.11 (.012) Missing values = 8	0.14 (.013) Missing values = 1	0.13 (.010) Missing values = 0
-2	0.12 (.012) Missing values = 5	0.16 (.014) Missing values = 1	0.14 (.009) Missing values = 0
-1	0.20 (.016) Missing values = 3	0.19 (.010) Missing values = 0	0.19 (.010) Missing values = 0
+1	0.35 (.018) Missing values = 2	0.24 (.011) Missing values = 0	0.29 (.011) Missing values = 0
+2	0.14 (.011) Missing values = 3	0.16 (.010) Missing values = 0	0.15 (.01) Missing values = 0
+3	0.08 (.010) Missing values = 2	0.13 (.010) Missing values = 1	0.11 (.007) Missing values = 0
+4	0.05 (.010) Missing values = 4	0.09 (.010) Missing values = 2	0.07 (.006) Missing values = 0
+5	0.08 (.013) Missing values = 4	0.09 (.010) Missing values = 3	0.08 (.008) Missing values = 0
Average Modality	0.13 (.003) Missing values = 1	0.15 (.003) Missing values = 0	

verbal DFR task ( $M = .27$ ,  $SE = .01$ ) than in the spatial DFR task ( $M = .21$ ,  $SE = .01$ ),  $F(1,166) = 22.51$ ,  $p < .0001$ ,  $\eta_p^2 = 0.12$ .

Furthermore, although the three-way interaction between stimulus modality, temporal direction, and temporal lag did not attain significance in this experiment (see Fig. 2c and Table 2),  $F(4,140) = 1.87$ ,  $p = .12$ ,  $\eta_p^2 = 0.05$ , a contrast that specifically tested the magnitude of the forward temporal asymmetry effect (lag position +1 – lag position -1) indicated

that this effect was significantly larger in the verbal modality ( $M_D = .15$ ,  $SE = .03$ ) than in the spatial modality ( $M_D = .05$ ,  $SE = .02$ ),  $F(1,163) = 11.40$ ,  $p = .001$ ,  $\eta_p^2 = 0.06$ , though both effects were significantly larger than zero (both  $ps < .001$ ). (Note that there were four missing cases in this analysis.)

**Spatial lag-CRP** A clear spatial contiguity effect can be seen in the full surface graph depicted in Fig. 3a and in the average spatial lag-CRPs depicted in Fig. 3d, which was supported by



**Fig. 3** **a** Spatial lag-CRPs shown as a function of the full complement of 120 spatial locations arrayed around the just-recalled item. **b** The number of cases with missing values in the full complement of 120 spatial locations arrayed around the just-recalled item. **c** Temporal lag-CRPs averaged across the backward and forward temporal directions in each of the

verbal and spatial DFR tasks. **d** Comparison of the average temporal and spatial lag-CRPs obtained in the spatial DFR task. Note that the temporal lag-CRP curve shown in **(d)** is identical to the temporal lag-CRP curve shown in the spatial DFR task condition of **(c)**. The error bars shown in **(c)** and **(d)** represent standard error of the mean

a significant effect of lag when the spatial lag-CRP was analyzed separately,  $F(4,164) = 99.52$ ,  $p < .0001$ ,  $\eta_p^2 = 0.71$ . In addition, there was a significant two-way interaction between associative dimension and lag,  $F(4,164) = 26.62$ ,  $p < .0001$ ,  $\eta_p^2 = 0.39$ , when the spatial lag-CRP was compared to the temporal lag-CRP. As can be seen in Fig. 3d, there was a steeper effect of lag in the spatial dimension than in the temporal dimension. In particular, the spatial contiguity effect observed in the lag 1 condition ( $M = .38$ ,  $SE = .01$ ) was significantly larger than the corresponding temporal contiguity effect ( $M = .21$ ,  $SE = .01$ ),  $F(1,167) = 102.84$ ,  $p < .0001$ ,  $\eta_p^2 = 0.38$ .

## General discussion

The present study introduced a novel measure of spatial lag-CRP and showed that items that are spatially contiguous with the just-recalled item are more likely to be recalled than items that are more distant in space (see Fig. 3d). In addition, the present study showed that the effect of spatial contiguity was significantly larger than the effect of temporal contiguity when both measures were derived within the context of the same spatial DFR task (see Fig. 3d). And, the present study also showed that the effect of temporal contiguity was significantly larger when it was derived within the context of the verbal DFR task than when it was derived within the context of the spatial DFR task (see Fig. 3c). Altogether, these findings establish spatial similarity as an important associative dimension

underlying the search of episodic memory, and they suggest that spatial similarity may dominate temporal similarity when there is variation across both associative dimensions, as in the spatial DFR task.

Although the precise reason why the spatial dimension appeared to dominate the verbal dimension cannot be resolved here (see Clark & Bruno, 2021, for further discussion), the strong spatial and more modest temporal contiguity effects observed in the spatial DFR task are important because they reveal theoretical gaps in our understanding of the nature of mental context. For instance, one influential interpretation of the temporal contiguity effect is that it supports various “retrieved context models” (RCMs) of episodic memory. RCMs are a family of models that assume new events become associated with the current state of a drifting mental context representation, and that when an event is recalled, it retrieves, or reinstates, its associated mental context (Healey & Kahana, 2016; Howard & Kahana, 2002b; Lohnas et al., 2015; Polyn et al., 2009; Sederberg et al., 2008). Like many theories of episodic memory (Bower, 1967; Estes, 1955; Tulving, 1972), RCMs assume that successfully searching memory for a particular item depends on the similarity between the mental context at the time of memory search and the mental context that prevailed at the time of its encoding. Critically, within the framework of RCMs, changes in the state of mental context over time are not random but are driven by both external (e.g., stimuli presentation) and internal (e.g., recalling an item) events activating their contextual representations via pre-existing associations (Howard & Kahana, 2002b).



However, the stimuli used in the vast majority of previous studies that have examined the RCM were common words that likely had rich pre-existing associations capable of driving context drift over time (see, e.g., Healey & Kahana, 2016). In contrast, the stimuli used in the spatial DFR task of the present study were lists of identical red squares that likely had relatively impoverished pre-existing associations, and that could only be individuated by their locations. To accommodate the findings of strong spatial and more modest temporal contiguity effects, RCMs would therefore need to be elaborated to include a representation of spatial position that is capable of driving context drift across both space and time in the absence of strong semantic information. In so doing, this elaboration may also lead to novel theoretical conceptions of the relation between semantic space and physical space.

In conclusion, space and time are both essential aspects of episodic memory, but no existing RCM has attempted to implement a spatial associative dimension that would allow spatial relations to guide memory search. By serving as an empirical existence proof for the spatial associative dimension, the present findings therefore urge RCMs to expand theoretical understanding by accommodating spatial as well as temporal context.

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