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Deconstructing the effect of self-directed study on episodic memory

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Abstract Self-directed learning is often associated with better long-term memory retention; however, the mechanisms that underlie this advantage remain poorly understood. This series of experiments was designed to "deconstruct" the notion of self-directed learning, in order to better identify the factors most responsible for these improvements to memory. In particular, we isolated the memory advantage that comes from controlling the *content* of study episodes from the advantage that comes from controlling the *timing* of those episodes. Across four experiments, self-directed learning significantly enhanced recognition memory, relative to passive observation. However, the advantage for self-directed learning was found to be present even under extremely minimal conditions of volitional control (simply pressing a button when a participant was ready to advance to the next item). Our results suggest that improvements to memory following self-directed encoding may be related to the ability to coordinate stimulus presentation with the learner's current preparatory or attentional state, and they highlight the need to consider the range of cognitive control processes involved in and influenced by self-directed study.

Keywords Memory · Metacognition · Self-directed learning · Self-regulated learning · Volitional control · Decision making · Metamemory · Object recognition · Spatial cognition

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One way to characterize different learning tasks is along a dimension of volitional control. In a *self-directed* task learners exert influence over the flow of information, including the order and timing of new study episodes. In contrast, in a fully passive task information flow is determined by the dynamics of the environment in which the learner is simply an observer. Experimental paradigms for studying learning and memory often fall at the passive end of this continuum. In many studies of memory the experimenter determines the sequence and timing of study items, precluding any significant influence by the participant over the flow of events. Yet volitional interaction with the environment—deciding what to learn about and when—is a ubiquitous feature of human learning and may have consequences for basic learning processes (Gureckis & Markant, 2012; Kornell & Bjork, 2007; Kornell & Metcalfe, 2006).

Previous studies have shown that self-directed study leads to better episodic memory than passive observation in a variety of tasks, including face recognition (Liu, Ward, & Markall, 2007), object recognition (Harman, Humphrey, & Goodale, 1999; Voss, Galvan & Gonsalves 2011; Voss, Gonsalves, Federmeier, Tranel & Cohen 2011; Voss, Warren, Gonsalves, Federmeier, Tranel and Cohen 2011), and spatial learning (Meijer & Van der Lubbe, 2011; Plancher, Barra, Orriols, & Piolino, 2013). Memory improvements have also been found in tasks in which learners choose which items to study in preparation for future cued recall tests (Kornell & Metcalfe, 2006). At the same time, people often have incorrect beliefs about how their own memory works, leading them to pursue inefficient study strategies (Bjork, Dunlosky, & Kornell, 2013). For example, students often believe that massed practice (e.g., cramming for a test) will benefit memory more than distributing practice over time (Kornell & Bjork, 2007; Simon & Bjork, 2001), which runs counter to robust evidence that spacing study sessions improves memory (Dempster, 1988).

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A challenge in understanding the effect of self-directed learning is determining what constitutes an appropriate control condition in which such decisions are not present. Kornell and Metcalfe (2006) compared performance between items on the basis of whether learners' study decisions were honored or not (e.g., in the dishonor condition, only items that were *not* chosen by a participant would appear during restudy). However, under this method the kind of items studied in the honor and dishonor conditions are not matched. Indeed, people tended to choose items for restudy that were easier, raising the possibility that differences between conditions result from studying different kinds of items, rather than from the process of making self-directed study decisions.

One solution to this concern is an experimental design in which the information selected by a self-directed learner is replayed to a "yoked" partner, thereby holding the learning experience constant and providing a direct test of self-directed decision-making on learning (Gureckis & Markant, 2012; Markant & Gureckis, 2014). In this design, a self-directed learner has greater control over the stimulus presentation than their yoked partner. Of course, given that a yoked observer always has *some* measure of control (e.g., where to direct attention), it is the level of control that defines self-directed behavior in a given context. The key question is how such control can lead to different outcomes even when the content of the learning experience appears to be matched.

Self-directed advantages for memory: selecting content versus coordinating attention

Self-directed study is not a unitary behavior, as it involves a range of decision-making and control processes that are not present during passive observation. As a result, the cognitive basis for memory enhancements following self-directed study remains unclear. For example, one possible benefit of self-directed learning is that it allows a person to select information on the basis of their own uncertainty or existing memory. One activity in which this figures prominently is making decisions about what material to study for a future test. Given a finite amount of study time, a person should allocate effort so as to maximize the amount of material that will be recalled in the future. For example, they should not waste time on items that can already be recalled with ease, nor should they attempt to learn items that are too difficult to be acquired within the allotted time (Metcalfe, 2002, 2009; Nelson & Narens, 1994; Son & Metcalfe, 2000). Making adaptive encoding decisions thus relies on relating external sources of information to internal judgments of learning (Metcalfe & Finn, 2008; Metcalfe & Kornell, 2003). To the extent that a person can make these decisions accurately, self-directed learning can improve performance by structuring the content of study to the individual's needs (which may be different from those of a yoked partner).

At the same time, the control associated with self-directed learning may allow a person to optimize their experience with respect to short-term fluctuations in their own motivational or attentional state. Waiting to access a source of information until one is prepared to learn or prolonging a stimulus presentation (e.g., due to a lapse in attention) reflects a qualitatively different kind of adaptive control that enhances the coordination between ongoing experience and learning. In contrast to the metacognitive processes described above, this coordination may facilitate the learning of material independently of its actual content or a person's preexisting memory of it. As with decisions about the content of study, however, the experience that results from control over the timing of new information may be mismatched to the needs of a yoked partner.

Self-directed study is thus associated with at least two kinds of adaptive choice: (1) selecting content that is useful with respect to the learner's goals and existing memory, and (2) coordinating stimulus presentation with their attentional or motivational state. These two levels of control have frequently been confounded in existing studies that have found differences in memory between self-directed and yoked study. In the present study, we deconstructed a recent example of a self-directed memory enhancement in order to assess how these different levels of control impact performance.

Enhanced memory through self-directed exploration

A recent set of studies (Voss et al. 2011a; Voss et al. 2011b; Voss et al. 2011c) revealed a robust benefit for self-directed memory encoding in a spatial-exploration task in which participants memorized the identity and location of icons presented in a series of 5×5 grids (see Fig. 1). At any given time, a single item in the grid was visible through a "window" that moved throughout the display. Each participant alternated between self-directed blocks, in which they controlled the movement of the window, and yoked blocks, in which they followed the window movements that had been executed by a previous participant. After studying six grids of items, participants were tested for their recognition memory and their ability to recall the spatial locations in which items had appeared during study. The results from Voss, Gonsalves, et al. showed an advantage for self-directed encoding for both recognition and spatial recall. A consistent pattern of results was found in a separate follow-up experiment, showing that the benefit from self-directed encoding was still evident a week after the initial study session (Voss et al. 2011a).

Interestingly, the benefit for self-directed encoding was related to how people studied different items. Voss et al. (2011a) found better memory for items studied for longer durations specifically in the self-directed condition, whereas, surprisingly, the memory results for items studied in the yoked condition were equivalent for brief and for long durations.

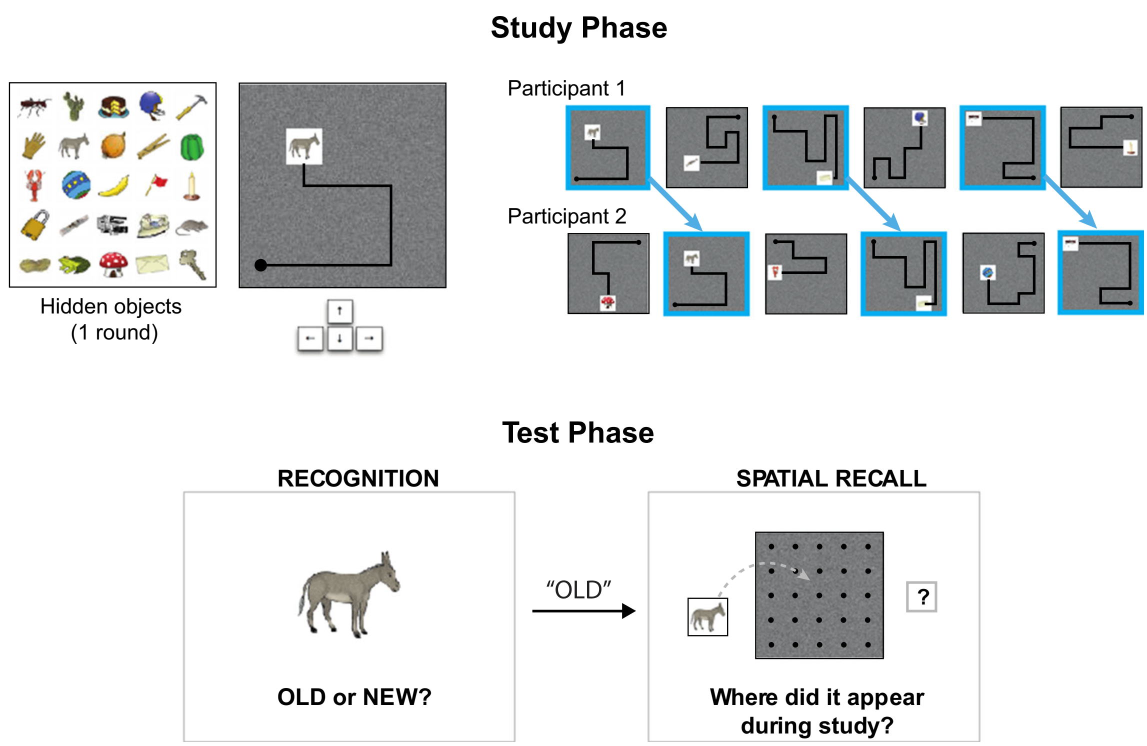


Fig. 1 Graphical summary of the experiment design used in all four experiments. (Top) In each study block, 25 objects were "hidden" inside a grid, and the participant could only view a single object at a time through a moving window. Each participant completed six study blocks, alternating between self-directed and yoked study. During self-directed blocks, the participant controlled the movement of the window. During yoked blocks, the sequence of movements was identical to that of a previous participant. (Bottom) During the test phase, the participants made a recognition decision for every item that had been studied (as well as for 150 new objects). If they responded "OLD," they were then given a spatial recall test in which they had to place the item onto the study grid on the basis of their memory for where it had appeared. If they could not recall its studied location, they could "opt out" of the spatial response by clicking on the question mark to the side of the grid

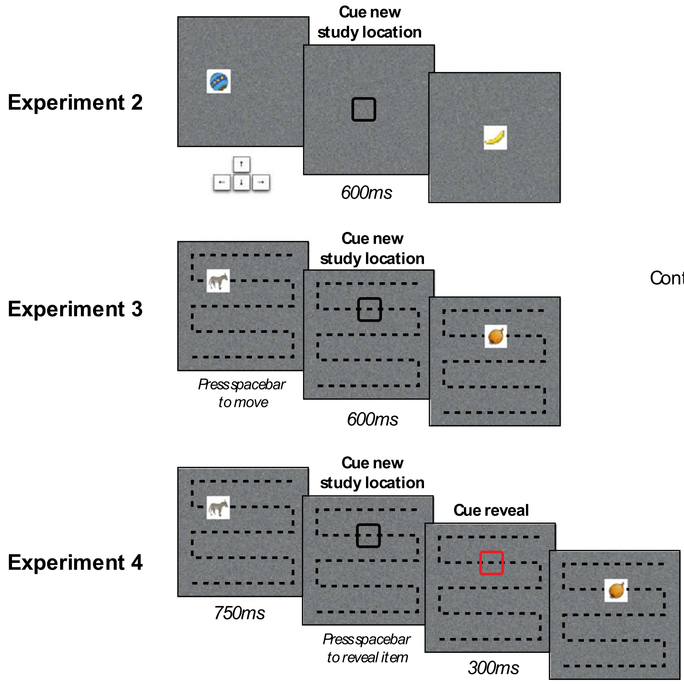
Voss et al. (2011c), in a later analysis of the same data, showed a similar selective benefit for items that were "revisited" within a short period of time. Although the authors ascribed this advantage to decision-making processes present during self-directed encoding, the lack of a simple relationship between study time and later memory under yoked conditions suggests that this condition could be disadvantaged at a more basic level.

Overview of the present study

Although prior studies have revealed a robust advantage for self-directed encoding, this condition has involved control over multiple aspects of the learner's environment that are absent in passive, observational learning. The goal of the present study was to determine whether control over the content of study is necessary for producing an advantage for self-directed learning, or whether simpler forms of control over the timing of study are sufficient to produce differences between self-directed and yoked study. We modified the spatial exploration paradigm across a series of experiments, beginning with a replication of Voss et al. (2011a) to establish a self-directed memory benefit (Exp. 1), and then incrementally removing potential sources of the self-directed advantage (Exps. 2–4; see Fig. 2 for an overview).

Experiment 1: Replicating the self-directed memory advantage

The first experiment aimed to replicate the memory advantage for self-directed study in the spatial exploration paradigm employed by Voss et al. (2011a). We made three minor modifications to the previous design. First, we used a fully opaque (rather than semitransparent) mask such that stimuli were only visible when revealed by the moving window. We reasoned that this would provide more accurate data on the items being attended during study. Second, Voss et al. (2011a) allowed the window to move freely through the display via mouse movements, enabling rapid transitions between items in different regions of the display. In our design participants could only move the window in cardinal directions. Finally, instead of using separate sets of items for the recognition and spatial memory tests, we employed a two-step procedure in which all items that were recognized were subsequently tested for



	Experiment 1	2	3	4
Queing of next location *(all blocks)*		✓	✓	✓
Control selection of next item *(self-directed blocks)*	✓	✓		
Control item duration *(self-directed blocks)*	✓	✓	✓	
Control duration of ISI *(self-directed blocks)*				✓

Fig. 2 Design manipulations for Experiments 2–4. In Experiments 3 and 4, the window followed a fixed, "snaking" path through the array, an example of which is shown by the dotted line (which was not visible to participants)

spatial recall. In addition, we added an "opt-out" response during spatial recall to minimize the influence of random guessing. We predicted that these changes to the testing procedure would deconfound recognition and spatial memory and provide a more sensitive measure of each.

Method

Participants

A total of 31 members of the NYU community participated either for course credit or a $10 payment. One person was a "seed" whose data were used for yoking the subsequent participant but were not included in the analysis.

Materials

The experiment was run in a single session on Macintosh computers.

The stimuli were the same as those used in Voss et al. (2011a) and included 300 line drawings of commonplace items. For the seed participant, half of these stimuli were randomly sampled and assigned to one of six encoding blocks and a location in the grid. For all subsequent participants, the stimuli experienced during yoked blocks were the same in identity and location as in the previous participant's self-directed blocks. Items were then randomly sampled from the set of remaining stimuli and assigned to the participant's self-directed blocks. Following random assignment of items to study blocks, the 150 remaining stimuli were retained for the test phase to be used as foils.

Procedure

Study phase

The study phase comprised six encoding blocks. In each block, the goal was to memorize the identities and spatial locations of 25 objects that were hidden in a 5×5 grid. The duration of each study block was 1 min, and each block was preceded by a 20-s break.

At any point in time, a single object was visible through a "window" that moved in the four cardinal directions. Each participant alternated between self-directed and yoked encoding blocks, with the type of the first block counterbalanced across participants. Participants were instructed that there would be six study blocks of two types ("MOVE" and "FOLLOW") that would differ in whether they would move the window themselves. The instructions excluded any mention of "active" or "self-directed" learning or differences in "control" other than through the terms "move" and "follow." The instructions included a practice self-directed round in which the participant moved the window around the grid for 1 min (only a single example item was present at every location and they were not trying to memorize items).

Self-directed encoding During self-directed blocks, the participant moved the window by pressing one of the arrow keys on the keyboard, causing it to "slide" in one of the four directions. Once the window had transitioned to the chosen location, it revealed the object at that position. The participant could initiate the next movement at any time.

Yoked encoding During yoked blocks, the self-directed blocks of the previous participant determined the movement of the window. Between the two participants, the stimuli, sequences of positions, and durations of item presentation were the same.

Test phase

The test phase was preceded by a 2-min break. During the test, items were presented in a pseudorandom order such that every 12 items included six new objects and one object from each of the six study blocks. On each test trial, a fixation cue (500 ms) preceded the presentation of the item. Once the item was displayed the participant had 3 s to respond, with the options (1) "Definitely OLD," (2) "Probably OLD," (3) "Probably NEW," and (4) "Definitely NEW."

When a participant responded "OLD," the recognition test was followed by a spatial recall test for the same item. For each spatial recall trial, the study grid was presented with small black circles marking the 25 positions. The current stimulus appeared in a random location and the participant used the mouse to reposition it according to their memory of its location. Participants were not required to place the stimulus directly above one of the 25 locations, but could indicate uncertainty about its location by placing it between positions. The participant then clicked the mouse button to enter their response (with a response deadline of 10 s). Alternatively, they could "opt out" from making a spatial response by clicking a button on the edge of the screen. Participants were instructed to make "opt-out" responses when they were completely uncertain about where an item had appeared during the study phase.

Results

Study sequences

Two participants failed to visit a small number of items during study (nine and six items, respectively), and as a result the same items were not studied by the following participants during their yoked blocks. All remaining participants viewed every training item at least once. Items were visited an average of 3.5 times (SD = 0.94), for an average median study duration of 473 ms per visit (SD = 210 ms). The average cumulative study time per item (summed across separate episodes of studying each item and averaged for each participant) was 1,948 ms (SD = 122 ms).

Recognition

The results of the recognition test are summarized in Table 1 for all experiments. The analysis of recognition was limited those items that were visited at least once. A greater proportion of studied items were recognized from self-directed blocks than from yoked blocks, with a significant advantage for self-directed study (see Table 1).

Our next goal was to determine how the features of an item's study experience were related to whether it was recognized during the test. We used mixed-effects logistic regression on the recognition response for studied items (HIT/MISS, combining low- and high-confidence items since there were relatively few low-confidence responses). Items were grouped by participant (random effect), with the following variables modeled as fixed effects: encoding condition (self-directed/yoked), number of visits, block index (1–6), and recency (measured using the minimum reversed serial position across presentations of an item; e.g., an item visited last in the sequence was assigned Position 1, regardless of whether it had been visited earlier in the sequence). The purpose of this analysis was to assess whether an effect of encoding condition was still present after controlling for the frequency and recency of study episodes, and to assess whether these factors interacted with encoding condition.

The results of the best-fitting models are shown in Table 2 for all experiments. Notably, in addition to the effects of recency and number of visits, we found a significant effect of encoding condition, such that yoked study decreased the likelihood of an item being recognized, consistent with the result of the paired t test reported above. On the basis of the results of Voss et al. (2011a, c), we expected to see an interaction between encoding condition and number of visits, such that a greater number of visits would lead to a larger advantage under self-directed encoding than under yoked encoding. However, including this interaction did not significantly improve the fit of the model [$\chi^2(1) = 0.62$, p = .43].[1]

Spatial recall—Opt-outs

Our analysis of spatial recall was limited to items that had been studied at least once and correctly recognized by the participant. We found no difference between the proportions of opt-out responses for items from the self-directed and yoked blocks (self-directed, M = .10, SD = .11; yoked, M = .12, SD = .15; signed rank test, W = 79, p = .21).

Spatial recall—Placement error

Comparisons of spatial errors are summarized in Table 3 for all experiments. Spatial error was measured as the Euclidean

[1] All model comparisons were performed using likelihood-ratio tests.

Table 1 Recognition test results

		FA Rate	Self-Directed Hit Rate	Yoked Hit Rate	Difference in Hit Rates (Self-Directed – Yoked)				
Experiment	*N*	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*t*	*p*	95 % CI	Cohen's *d*
Exp. 1 (Replication)	30	.11 (.08)	.71 (.19)	.61 (.16)	.10 (.10)	5.67	<.001	.06–.13	1.03
Exp. 2 (Attentional cueing)	30	.13 (.10)	.71 (.16)	.64 (.18)	.07 (.13)	2.70	<.01	.02–.11	0.49
Exp. 3 (Follow a fixed path)	32	.12 (.09)	.71 (.19)	.64 (.22)	.06 (.12)	2.89	<.01	.02–.10	0.51
Exp. 4 (Press to reveal)	30	.09 (.07)	.71 (.16)	.64 (.20)	.07 (.13)	2.71	.01	.02–.12	0.50

distance between the studied location and the participant's response, which was normalized such that an error of 1.0 corresponded to a single "grid unit" (the distance between two adjacent locations in any cardinal direction). Using this measure, the expected error from random guessing was approximately 2.5 grid units, after averaging across the possible locations where an item was actually studied. Note that random guessing would lead to smaller errors on average when the item appeared in the center of the grid ($M = 1.8$ grid units) rather than at the edges (e.g., $M = 3.2$ grid units at the corners).

Average error was relatively low for both the self-directed (M = 1.21 grid units, SD = .33) and yoked (M = 1.33 grid units, SD = .29) items across participants, and in both types of blocks error was lower than would be expected from random guessing [active, $t(29) = -22.5$, $p < .001$; yoked, $t(29) = -22.6$, $p < .001$]. In addition, spatial error was significantly lower for items from self-directed blocks than for those from yoked blocks (paired t test; see Table 3). A linear mixed-effects model was used to assess the impact of the number of visits on spatial error, and the results are shown in Table 2 for all experiments. In addition to the effect of training condition, we found a significant effect of the number of visits (with more visits leading to lower spatial error), but no effects of recency (measured by reversed serial position or block index). Including the interaction between condition and number of visits did not improve the fit of the model [$\chi^2(1) = 1.9$, $p = .17$].[2]

Revisitation

Our final analysis was an attempt to replicate the finding from Voss et al. (2011c) of a specific benefit of quickly revisiting items under self-directed study. We divided studied items according to whether they were part of a "revisitation" sequence of up to six items (with the longest possible sequence A–B–C–D–E–F–E–D–C–B–A, with all items being considered "revisited" except F). Note that this category does not include all items that are seen more than once, but only those that were part of a short sequence that was "doubled back" on. An average of 49 % (SD = 20 %) of items were part of at least one revisitation sequence (as compared to an average proportion of 31 % reported by Voss et al. 2011c).

We performed two-way analyses of variance with Condition and Revisitation as within-subjects factors. For the recognition test, in addition to the main effect of encoding condition [$F(1, 87) = 9.85$, $MSE = .19$, $p = .002$], we found a main effect of revisitation [$F(1, 87) = 4.76$, $MSE = .09$, $p = .03$], with revisited items more likely to be recognized during test. No condition by revisitation interaction was apparent [$F(1, 87) = 2.49$, $MSE = .05$, $p = .12$]. For the spatial recall test, we observed a significant main effect of condition [$F(1, 86) = 7.18$, $MSE = .80$, $p = .008$] but no effect of revisitation [$F(1, 86) = 1.26$, $MSE = .14$, $p = .26$], and no interaction [$F(1, 86) = 1.26$, $MSE = .14$, $p = .26$].

Voss et al. (2011c) reported that the effects of revisitation could not be explained by longer viewing durations or greater numbers of visits, because they found both to be decreased for "revisited" items. This was not the case for our data. The average total viewing duration was significantly higher for revisited items (M = 2,252 ms, SD = 332) than for other items (M = 1,775 ms, SD = 189) [paired $t(29) = -7.74$, $p < .001$]. Similarly, the overall number of visits was significantly higher for revisited (M = 4.3, SD = .72) than for nonrevisited (M = 2.8, SD = .66) items [paired $t(29) = -11.1$, $p < .001$].

Discussion

In the first experiment, we successfully replicated the finding that self-directed exploration is associated with a memory advantage for both item recognition and spatial recall (Voss et al. 2011a, b). Importantly, we found lower spatial error for items from self-directed blocks, despite the changes to the procedure that made the spatial recall test contingent on successful item recognition, which may have reduced the influence of random guessing on the spatial error measure. In addition, we found that increased study was beneficial

[2] A measure that is similar to the total number of visits is the total amount of time spent studying an item, which Voss et al. (2011b) found interacted with encoding condition, such that items studied for longer durations led to a specific benefit under self-directed conditions. The same analysis of our data revealed an effect of duration for both recognition and spatial recall, but no such interactions with encoding condition. Since study duration is closely related to number of visits, this analysis is not reported here, but the results are available on request.

Table 2 Results of mixed-effects models

Variable	Experiment 1				Experiment 2				Experiment 3				Experiment 4			
	β	*SE*	Wald *z*	*p*	*β*	*SE*	Wald *z*	*p*	*β*	*SE*	Wald *z*	*p*	*β*	*SE*	Wald *z*	*p*
	Recognition of Studied Items															
Intercept	1.29	0.18	7.1	<.001	0.557	0.184	3.0	.002	1.34	0.255	5.2	<.001	−0.734	0.368	−2.0	.05
Condition (yoked study)	−0.512	0.068	−7.5	<.001	−0.342	0.071	−4.8	<.001	−0.367	0.071	−5.2	<.001	−0.343	0.070	−5.0	<.001
Number of visits	0.068	0.022	3.1	.002	0.473	0.040	11.8	<.001	0.238	0.080	2.9	.003	1.19	0.167	7.1	<.001
Reversed serial position	−0.009	0.002	−4.1	<.001	0	0.002	−0.04	.97	−0.015	0.004	−3.9	<.001	0	0.003	0.16	.87
Block index	−0.144	0.021	−7.0	<.001	−0.182	0.021	−8.5	<.001	−0.164	0.024	−6.8	<.001	−0.223	0.021	−10.8	<.001
	Spatial Recall – Placement Error															
Intercept	1.29	0.080	16.1	<.001	1.39	0.117	11.9	<.001	1.11	0.106	10.5	<.001	1.57	0.263	6.0	<.001
Condition (yoked study)	0.144	0.040	3.6	<.001	0.053	0.058	0.90	.37	0.103	0.039	2.6	<.01	0.040	0.040	1.0	.30
Number of visits	−0.040	0.013	−3.0	.003	−0.009	0.032	−0.27	.78	0.002	0.046	0.05	.95	−0.154	0.129	−1.2	.24
Reversed serial position	0.001	0.001	1.1	.27	−0.001	0.002	−0.28	.78	0.012	0.002	5.4	<.001	0.002	0.002	1.4	.16
Block index	0.008	0.012	0.65	.52	−0.006	0.017	−0.36	.72	−0.014	0.013	−1.1	.29	−0.027	0.011	−2.3	.02

regardless of the encoding condition. Importantly, we did not find that self-directed study was disproportionately advantageous for items that were studied more or that were a part of "revisitation" sequences, suggesting that the interactions reported by Voss et al. (2011b, c) depended on features of the task design that were altered here (e.g., restricting the window movement to cardinal directions rather than unconstrained movement throughout the display).

Despite some differences, the finding that self-directed learning enhanced recognition memory and spatial memory appears to be robust even with the minor changes in procedure that we introduced. However, these results still leave the open question of why self-directed study is better than yoked study. Having successfully established the viability of the modified spatial exploration paradigm in Experiment 1, in each of the following experiments we introduced a manipulation that reduced the gap between the self-directed and yoked study conditions.

Experiment 2: Cueing to guide attention

Since self-directed study allowed people to choose the timing and location of each study opportunity in Experiment 1, they may have been better at coordinating their attention with new episodes than during yoked study. For example, by deciding where to move the window next, self-directed learners may be at an advantage in allocating endogenous attention to each new stimulus (Carrasco, 2011). In contrast, during yoked study it is uncertain when and where the window will move. If the yoked learner incorrectly predicts the next study location or duration of the current episode, this may incur a cost to reallocating spatial attention to the next item.

The goal of Experiment 2 was to reduce the difference between conditions in the ability to coordinate attention with the movement of the window, while maintaining a similar level of self-directed control over the study sequence. We modified the procedure such that, before the window moved

Table 3 Spatial recall results

Experiment	*N*	Self-Directed Placement Error (# Grid Units)	Yoked Placement Error (# Grid Units)	Difference in Spatial Placement Errors (Self-Directed – Yoked)				
		M (*SD*)	*M* (*SD*)	*M* (*SD*)	*t*	*p*	95 % CI	Cohen's *d*
Exp. 1 (Replication)	30	1.21 (0.33)	1.33 (0.29)	−0.13 (0.25)	−2.76	.01	–.22 to –.03	0.50
Exp. 2 (Attentional cueing)	30	1.35 (0.49)	1.36 (0.46)	−0.01 (0.29)	−0.13	.90	—	—
Exp. 3 (Follow a fixed path)	32	1.26 (0.34)	1.35 (0.41)	−0.09 (0.29)	−1.78	.09	—	—
Exp. 4 (Press to reveal)	30	1.24 (0.37)	1.27 (0.30)	−0.03 (0.29)	−0.65	.52	—	—

to a new location, that position was indicated with a visual cue that lasted 600 ms. (for comparison, it takes about 250–300 ms to deploy endogenous attention to a cued target, Carrasco, 2011; Posner, 1980). Cues were present in both self-directed and yoked study. Whereas participants likely found the cue redundant during self-directed blocks, during yoked blocks participants could use it to guide their attention to the upcoming stimulus. Since the cue was deterministically related to the movement of the window, it also removed some of the uncertainty associated with the yoked condition. The key question was whether memory for items studied under self-directed conditions would still be better than yoked items given this attentional aid.

Participants

A group of 31 NYU undergraduates participated for course credit or a $10 payment, including one seed participant whose data were not analyzed.

Procedure

Most aspects of the procedure were identical to that of Experiment 1. The only change was the addition of a cue (a black outline) that appeared when the window was moved to a new location, for both self-directed and yoked blocks. As in Experiment 1, each item presentation ended when the participant decided to move the window (self-directed blocks) or the duration matched that of the previous participant (yoked blocks). At that point, the window momentarily disappeared and a black outline was displayed around the next study location for 600 ms, followed by the appearance of the window in that new location (revealing the item hidden there). This cueing procedure was identical for both self-directed and yoked blocks.

Results

Study sequences

Since the duration of each study block was fixed at 1 min, the inclusion of a 600-ms cue before each item led to a smaller proportion of time in which a stimulus was present. As a result, we expected that participants would view each item a smaller number of times than in Experiment 1 and that a greater number of items would never be visited. An average of 2.6 self-directed items (out of 75) were never visited (SD = 5.2). For items that were seen at least once, the average number of visits was 1.9 (SD = 0.29), for an average median study duration of 484 ms per visit (SD = 169) and an average cumulative study time per item of 1,179 ms (SD = 184). Thus, people in this experiment tended to dwell on individual items for a similar length of time as in Experiment 1 but made fewer visits overall.

Recognition

A greater proportion of studied items were recognized from self-directed blocks than from yoked blocks (see Table 1). The average within-subjects difference in hit rates between the self-directed and yoked blocks was .07 (SD = .13), which was not significantly different from the average difference in Experiment 1 [$t(58) = 1.2$, $p = .26$].

We repeated the logistic regression analysis described in Experiment 1, which indicated significant effects of encoding condition, number of visits, and block index (but not reversed serial position). The model improved marginally when we included the interaction between encoding condition and the number of visits [$\chi^2(1) = 3.2$, $p = .07$], but the improvement was such that more frequent visits had a larger positive effect on the probability of recognizing items from yoked blocks than from self-directed blocks.

Spatial recall—Opt-outs

Participants chose to opt out of the spatial recall for the same proportion of self-directed and yoked items (self-directed, $M = .51$, $SD = .32$; yoked, $M = .52$, $SD = .29$; signed rank test, $W = 192$, $p = .59$).

Spatial recall—Placement error

We found no difference in placement errors between the conditions (see Table 3). The regression analysis revealed no significant effects of encoding condition, number of visits, or recency on placement error (see Table 2).

Discussion

Since a self-directed learner is aware of the “next step” in the study sequence as soon as he or she has decided what to view next, we hypothesized that such a learner could allocate attention to the next item more efficiently than could a yoked observer of the same material. In Experiment 2, we introduced a cueing procedure in order to minimize this attentional lag, giving yoked learners ample opportunity to direct their attention to the next location.

The results showed that cueing did not eliminate the advantage for self-directed study in terms of recognition memory. Note that an important consequence of the cueing procedure was that participants had less study time overall than in Experiment 1. As a result, a slightly greater proportion of items were never visited during study, and the cumulative amount of time devoted to each item was lower than in Experiment 1. Nevertheless, recognition performance on studied items was comparable to that of Experiment 1 ($M = .71$ in both experiments), with yoked hit rates being slightly increased ($M = .64$, as compared to $M = .61$ in Exp. 1).

Unlike in Experiment 1, we did not find evidence for an advantage in spatial recall for self-directed items, which is notable because self-directed study still required making exploratory decisions about where to move the window. For those items to which participants made a spatial response, the overall spatial error was similar to that of Experiment 1. However, participants chose to opt out of making a spatial response with much higher frequency, suggesting that the cueing manipulation did impair spatial encoding. This pattern of results suggests that the spatial memory benefit for self-directed study may be driven by differences in the ability to orient to relevant locations in space, or that cueing made spatial position less relevant by reducing the uncertainty associated with the window movements. However, the self-directed memory advantage for item recognition advantage was robust to attentional cueing, indicating that a simple attentional account does not fully explain the benefit of self-directed study.

Experiment 3: Following a fixed path

The spatial exploration paradigm used by Voss et al. (2011b) was designed to parallel research on exploration and learning in rodents (Ellen, Parko, Wages, Doherty, & Herrmann, 1982; O'Keefe & Nadel, 1978) and humans (Doeller, Barry, & Burgess, 2010; Doeller & Burgess, 2008). For example, rats placed in a novel environment will tend to explore vigorously, but this behavior will decline over time as the environment becomes more familiar (Save, Buhot, Foreman, & Thinus-Blanc, 1992). In the same way, self-directed learners may devote more effort to items that are unfamiliar, adaptively allocating attention in order to maximize learning (Metcalfe, 2002; Renner, 1990).

Self-directed study in Experiments 1 and 2 provided control over both the content of each encoding episode (i.e., what item to look at next) as well as its timing (i.e., how long to study the current item). In the next experiment, we restricted the self-directed condition by removing the ability to decide what items to look at, while preserving control over the duration of each study episode. If the self-directed advantage depends on adaptively selecting items to study, removing this ability should abolish any such memory advantage.

In this experiment, rather than choosing which item to study, self-directed participants simply decided when to move the window in a fixed "snaking" path across the grid. This task was similar to the "manual deterministic" control condition that Voss et al. (2011b) reported (Exp. 2), but it differed in a key way: In our experiment, although participants could not decide *which* items to visit, they could decide *how long* to study a item and when to move to the next item (rather than being externally cued). Thus, they retained some control over the content of study by deciding how long to view each item.

Method

Participants

A group of 33 NYU undergraduates participated for course credit, including one seed participant whose data were not analyzed. Due to an error during data collection, two participants were yoked to the same previous participant.

Procedure

The sole difference from the previous experiment was that during self-directed encoding the participant could not control the sequence of items. The window followed a fixed, "snaking" path through the grid. During self-directed encoding, the participant simply pressed the spacebar to initiate movement to the next location. As a result, they could control how long to dwell on each item, but not where to move next. When all items in a grid were visited, the study sequence was reversed such that the window "doubled back" on previously visited items.

Results

Study behavior

Since participants did not choose which items to visit, study opportunities were more evenly distributed in this experiment, with most items being visited one or two times (and no items receiving more than three visits). Twenty-two participants visited every item at least once during the self-directed blocks. Within the remaining ten people, an average of 14.7 items were never visited across all blocks ($SD = 9.7$). For items that were seen at least once, the average number of visits was 1.7 ($SD = 0.34$) for an average median study duration of 839 ms ($SD = 644$) and an average cumulative study time per item of 1,582 ms ($SD = 553$).

Recognition

The false alarm rate was similar to those in the previous experiments ($M = .12$, $SD = .09$). Of those items that were visited at least once, a greater proportion of items were recognized from self-directed blocks (see Table 1). The results of the logistic regression were similar to those of Experiment 1, with significant effects of encoding condition, number of visits, block index, and reversed serial position. The interaction between condition and number of visits was not significant [$\chi^2(1) = 0.29$, $p = .59$].

Spatial recall—Opt-outs

We found no difference in the proportions of items for which participants opted out of the spatial test between the self-directed and yoked blocks (self-directed, $M = .11$, $SD = .14$; yoked, $M = .12$, $SD = .15$; signed rank test, $W = 100$, $p = .16$).

Spatial recall—Placement error

As in the previous experiments, spatial errors were relatively low for both self-directed ($M = 1.26$, $SD = .34$) and yoked ($M = 1.35$, $SD = .41$) items. No difference was apparent in the overall errors for self-directed items relative to yoked items (see Table 3). A linear mixed-effects model revealed a significant effect of condition in the same direction, as well as a significant effect of recency as measured by reversed serial position (see Table 2).

Discussion

Removing control over the order of the study sequence did not disrupt the memory advantage in the self-directed condition, suggesting that, at least in this paradigm, the benefit of self-direction does not depend on an adaptive *selection* process through which items are chosen on the basis of the learner's existing memory. In this experiment the sequence of items was determined independently of how well each item had been learned, as people only controlled the length of time to study each item during self-directed blocks. Of course, the ability to select information on the basis of one's uncertainty undoubtedly benefits performance in a variety of other learning situations (Kornell & Metcalfe, 2006; Markant & Gureckis, 2014; Metcalfe, 2002, 2009). However, our results so far have pointed to a distinct and additional benefit from controlling the timing of study.

It is interesting to compare the results of this experiment to the "deterministic" control condition reported by Voss et al. (2011b), Exp. 2. As in the present design, Voss, Gonsalves, et al. removed participants' ability to select which items to view. However, they also removed their ability to decide how long to study each item, by using an auditory cue to schedule when to advance to the next item. Their results showed no self-directed advantage for either test measure. As compared to that design, participants in our experiment still had control over at least two factors: how long to study each item, and when to begin studying the next item. Thus, in the Experiment 4 we went one step further, by removing study duration as an element of adaptive control.

Experiment 4: Controlling the timing of study episodes

In this experiment, we sought to create a "minimal" self-directed condition in which the learner could only control when to reveal an item without controlling which item to look at or how long to dwell on the item. As in the previous experiment, the window followed a fixed path through the grid, but now each stimulus appeared the same number of times and for a fixed duration. During self-directed blocks, the participant only determined when to start viewing the next item (i.e., the duration of the interval between study episodes). As a result, the content of each study episode, including the time spent studying it, was entirely independent of the learner's current memory.

Method

Participants

A group of 32 NYU undergraduates participated for course credit, including one seed participant whose data were not analyzed.

Procedure

Most details of the procedure were identical to those of the previous experiment. The number of item presentations was fixed, such that each block consisted of two runs through the "snaking" pattern (after one run was complete, the sequence was then visited in the reverse order). Each stimulus was presented for a fixed duration of 750 ms. As a result, item exposures were matched across all participants for number of visits and study duration.

During self-directed blocks, the participant controlled the onset of the next item. On each trial, a cue appeared in the new study location. The participant then pressed the spacebar to advance the trial, after which the cue changed color and remained for 300 ms, followed by the item presentation. During yoked blocks, the interstimulus intervals (ISIs) from the previous participant's self-directed blocks were used.

Results

One participant was excluded from analysis for failing to respond during the test phase.

Encoding response times

During self-directed blocks, the delay before the onset of each item was determined by the participant's response time. The average median response time was 572 ms (SD = 445 ms). Since the number of visits was fixed in this experiment, the overall duration of each study block depended on the participants' response times. The overall study duration was somewhat longer than in the previous experiments (M = 92 s, SD = 27 s), but the total amount of time that items were viewed was similar to those in the previous experiments.

Recognition

A greater proportion of old items were recognized from self-directed study blocks than from yoked blocks (see Table 1). The regression analysis revealed effects of condition, number of visits, and block index (see Table 2) similar to those found in the previous experiments.[3]

Spatial recall

Participants opted out of a spatial recall response on similar proportions of recognized items between conditions (self-directed, M = .15, SD = .12; yoked, M = .16, SD = .13; signed rank test, W = 183, p = .46). For those items to which participants did make a spatial response, we observed no difference in spatial errors across conditions (see Table 3), a result that was confirmed by mixed-effects modeling (Table 2).

Pre- and postitem ISIs

Control over the timing of new study episodes could be associated with at least two processes. First, it might allow participants to rehearse the previous item before studying the next item. If so, the duration of the ISI following an item (*post-ISI*) should be related to successful memory, with longer durations allowing for more rehearsal. Second, control over the ISI might allow learners to postpone the presentation of the next item until they are prepared to study. In this case, the duration of the ISI preceding an item (*pre-ISI*) might predict successful memory.

We tested whether pre- or post-ISIs were related to later recognition through mixed-effects logistic regression. For each studied item we measured the total duration (summed across presentations) of the pre- and post-ISI (the last item of each sequence was excluded for the purposes of this analysis because it did not have a post-ISI). In addition to the set of predictors tested earlier (see Table 2), we tested whether the addition of pre-ISI or post-ISI as fixed effects improved the fit of the model. A significant effect of total pre-ISI emerged [$\chi^2(1) = 6.8$, $p < .01$], with longer pre-ISIs being associated with a higher likelihood of correctly recognizing the item. However, we observed no effect of post-ISI [$\chi^2(1) = 3.6$, $p = .06$], indicating that the amount of time following an item was not associated with it being successfully recognized. We found no interaction between condition and pre-ISI [$\chi^2(1) = 1.1$, $p = .30$], and no effects of either ISI measure on spatial errors.

[3] Note that in Exp. 4, the number of visits was not equal to 2 for all items studied, since items at the midpoint of each sequence (at which point the window doubled back) were only visited once. The effect of number of visits was thus dependent on a relatively small number of items; importantly, removing this explanatory variable from the model did not alter any conclusions from this analysis.

Discussion

The results from this experiment were remarkably consistent with those of the previous two experiments, despite the minimal control afforded during self-directed study and the procedural change in the number of visits. Participants could only control when to reveal the next item, without controlling its onscreen duration or content. This suggests that the ability to coordinate the onset of new study episodes with one's own preparatory or motivational state is sufficient to produce a self-directed advantage for recognition memory. Our analysis of the pre- and postitem intervals showed that the amount of time following an item did not affect whether it was recognized, suggesting that delaying the next study episode was not related to rehearsing the previous item. Instead, increased time to prepare for the next item presentation seems to be related to later recognition, consistent with an important role for attentional coordination in this paradigm.

General discussion

In the present article, we "deconstructed" the self-directed memory advantage and found that simply being able to control the timing of study led to recognition memory advantages. After replicating the basic advantage in Experiment 1, we found that controlling for attentional differences between conditions slightly improved the recognition of items from yoked study, but eliminated any differences in spatial memory (Exp. 2). In subsequent experiments, the self-directed advantage was preserved after removing learners' ability to decide which items to study (Exp. 3) and how long to study each item (Exp. 4).

Across all four experiments, we found surprisingly consistent evidence of a recognition memory advantage for self-directed study. Similar patterns have recently been observed in a range of tasks including object identification (Craddock, Martinovic, & Lawson, 2011), memory for 3-D faces or objects (Harman et al., 1999; Liu et al., 2007; Meijer & Van der Lubbe, 2011), and spatial learning (Chrastil & Warren, 2012; Luursema & Verwey, 2011; Plancher et al., 2013). However, the mechanism behind these effects has been unclear because self-directed conditions generally differ from passive observation in a variety of ways, each of which could potentially influence memory. Like other examples of goal-directed behavior, self-directed study entails a hierarchy of cognitive control processes (Botvinick, 2008). The present study highlighted the distinction between decisions about the content of study (a higher-level process) and coordination of the study experience with attention (a lower-level process). At the higher level, people may select information so as to maximize the number of items that can be memorized (e.g., preferring to study easy items first; Metcalfe, 2002) or to focus on items for which their existing memory is poor (Metcalfe & Finn, 2008). At the lower level, each study episode may require decisions about its onset and duration, and memory is tied to attentional and motivational processes involved in the execution of those decisions (Chun & Turk-Browne, 2007). Our results suggest that this kind of low-level control is sufficient to enhance recognition memory for visual objects.

Although we found a consistent advantage in terms of recognition memory, the effect on spatial recall was much less clear. In Experiment 1, we found improved spatial memory from self-directed study (replicating the finding from Voss et al. 2011b). In subsequent experiments in which study sequences were more constrained (due to precuing or fixed search paths), and thus the orientation of attention was better matched between conditions, the same effect was either absent or inconsistent across different analyses. It is possible that reducing self-directed learners' control over window movements led to less processing of spatial information; however, it is important to note that the need to make spatial decisions in Experiment 2 did not lead to any differences in spatial recall. Overall, our results add to evidence that a self-directed advantage for spatial memory is relatively inconsistent across different tasks (Chrastil & Warren, 2012), and suggest that it may closely depend on the nature of exploration in a given environment.

Our results also differed from those of Voss et al. (2011b, c), in that we did not find a larger self-directed advantage for items studied more often (Exps. 1–3) or that were quickly revisited (Exp. 1). Instead, additional study led to better memory regardless of encoding condition. One explanation for this discrepancy is that it was easier for the yoked learners in our task to coordinate attention with the study sequence, and as a result they also benefited from more exposure to an item. A selective benefit for self-directed study might occur in situations in which cues are not available to help yoked observers in the same way, but our findings suggest that such a pattern results from differences in coordination of attention rather than arising from a decision-making process that is only present during self-directed study.

What causes the recognition advantage for self-directed study?

We found that the self-directed advantage was present when control was limited to choosing when to reveal the next item, suggesting that during self-directed blocks participants were better able to coordinate new presentations with their own preparatory state. Increasing evidence indicates that prestimulus neural activity can predict subsequent memory (Guderian, Schott, Richardson-Klavehn, & Düzel, 2009; Otten, Quayle, Akram, Ditewig, & Rugg, 2006; Yoo et al., 2011), and that this activity is modulated by motivational factors including the anticipation of reward (Gruber & Otten, 2010). Self-directed learning might interact with these processes in a number of ways. One possibility is that learners monitor ongoing fluctuations in their internal state (e.g., due to distraction or mind-wandering) and can schedule new episodes in an adaptive manner. Alternatively, decisions to begin a new study episode might play a causal role in initiating those attentional or mnemonic processes.

One objection may be that during yoked blocks participants were not required to make a response, raising the possibility that the advantages were related to executing motor responses. However, we think it unlikely that the motor component can account for the memory enhancement. Voss et al. (2011b), Exp. 2 compared yoked observation with a "manual" condition that required key presses in response to an external cue in order to move the window along a predefined path. They found no advantage for this condition, with recognition performance similar to that of participants in our yoked condition. Other comparisons of self-directed and yoked study that included a secondary task in order to control attention and motor activity across conditions have also found advantages for active control (Liu et al., 2007; Meijer & Van der Lubbe, 2011).

It would be hard to argue against the hypothesis that selecting content during learning can influence later memory. For example, in richer contexts in which materials vary more in their difficulty (e.g., studying a textbook), an advantage from strategic selection of information would be expected to play a larger role. It is likely that the participants in Experiments 1 and 2 were engaged in strategic decision-making about how to navigate the array or making judgments about which items required further study. Collectively, however, our experiments showed that the self-directed advantage was maintained after removing elements of control that would allow the learner to make memory-based decisions about what to study and for how long.

Deconstructing self-directed study using yoked designs

The purpose of "yoked" experimental designs is to equate the content of study while isolating the impact of decision-making on performance. As we have demonstrated, comparing active exploration and passive observation via this method requires careful consideration of the many ways in which these conditions differ, particularly when the outcome of interest is subsequent memory. Although our experiments were based on the design of Voss et al. (2011b), a number of other examples of yoked designs have suffered from the same confound that we have described. For example, Meijer & Van der Lubbe (2011) used a task in which the goal was to memorize a set of 3-D objects. During self-directed study, the learners interacted with an object by rotating it with a mouse, whereas in yoked study they passively observed the interaction of another participant. The results showed a consistent benefit for self-directed study in terms of recognition, but it was unclear whether this advantage was related to low-level processes related to the interaction, or to higher-level metacognitive control (e.g., exploring parts of the object that were poorly encoded).

Rather than treating self-directed study as a unitary process, a more productive approach may be to decompose it into a hierarchy of control processes. A yoked design may be useful for testing the effects of individual decision-making processes while ensuring that the "passive" condition also experiences the outcomes of those decisions, but it is important that the influence of other forms of adaptive control is controlled for in the design. For example, the effect of high-level decision-making about the content of study may be best studied in paradigms in which self-directed learners cannot control the dynamics of individual study episodes (e.g., the honor/dishonor paradigm, in which the decision to study something is separated from the actual study opportunity; Kornell & Metcalfe, 2006).

Of course, comparing fully self-directed study with passive observation can reveal the magnitude of an advantage in a given learning problem, which may be especially relevant for educational contexts in which the most common format may be passive observation (e.g., viewing lectures). Our results add further insight to these comparisons, however, by revealing the extent to which different forms of "active learning" lead to differences in performance. Whereas people may be biased in how they make high-level decisions about how to sequence study episodes (Bjork et al., 2013), our results show that simply allowing people to control the temporal dynamics of study episodes may have widespread benefits for learning and memory.

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