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BRIEF REPORT

A mind-wandering account of the testing effect: Does context variation matter?

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Abstract
The learning benefits of retrieval practice have been linked to reduced mind-wandering, but the reasons why testing offers such an attentional advantage have scarcely been explored. Here, we investigate the extent that the inherent change in learning context during retrieval practice (i.e., interleaved study and retrieval) attenuates mind-wandering, relative to restudy (i.e., massed study). Learners (N = 120) either restudied video lectures (*SSSS*) or engaged in a combination of study and retrieval (*SRSR*). Further, they used either the same study mode – the video lecture (*S*) or its corresponding transcript (*S′*) only (i.e., *SSSS* or *S′S′S′S′*; *SRSR* or *S′RS′R*), or different study modes – alternated between the video and its transcript (i.e., *SS′SS′* or *S′SS′S*; *SRS′R* or *S′RSR*). Learners' mind-wandering tendencies were captured using a direct-probing approach, and a free-recall test was administered 1 week later. Retrieval practice produced less mind-wandering than restudy, and this attentional difference mediated the recall advantage of retrieval practice. Of note, in the restudy condition, alternating between study modes inoculated against mind-wandering relative to using the same mode, but only for as long as the study mode remained "new" to learners – when they returned to a previously encountered "old" study mode, mind-wandering surged. In contrast, retrieval practice consistently sustained learners' attention over time, whether or not their study modes were the same or different. Theoretical implications for an attentional account of retrieval-based learning are discussed.

Keywords Retrieval practice · Testing effect · Mind-wandering · Attention · Video-recorded lecture learning

Introduction

Over more than a decade of cognitive science research has revealed the learning benefits of retrieval practice (Dunlosky et al., 2013; Karpicke, 2017). Typically, learners practice retrieving information during an initial test, which enhances subsequent knowledge retention. To explain why retrieval practice improves learning, two recent theories have been developed. The first is an elaborative retrieval account (Carpenter, 2009, 2011; Carpenter & Yeung, 2017; Kornell et al., 2015; Rawson et al., 2015), which suggests that semantic elaboration occurs during retrieval when learners generate cue-relevant knowledge, thereby yielding an elaborated memory trace that aids future recall. Alternatively, the episodic context account (Karpicke et al., 2014; Lehman et al., 2014) proposes that: During retrieval, learners attempt to reinstate the episodic context associated with an item and, upon successful retrieval, update that context representation to integrate features of the original versus present test contexts. Consequently, the updated context representation facilitates future recovery of the learned items.

Notwithstanding the promising theories to date, there remains considerable room for progress toward a more holistic understanding of the potential mechanisms underlying retrieval-based learning. Of particular interest is the extent that retrieval practice may sustain learners' attention on the to-be-learned material, hence reducing mind-wandering and improving learning.

Mind-wandering and retrieval practice

Mind-wandering is a ubiquitous phenomenon in everyday life (Killingsworth & Gilbert, 2010), involving a shift in executive control away from a primary task to task-irrelevant goals (Smallwood & Schooler, 2006). In an educational context, successful learning predicates substantively on learners'

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ability to maintain executive control. While there have been some reported benefits of mind-wandering for learning outcomes such as creativity (Baird et al., 2012), increased mind-wandering has more often been associated with poorer performance (Randall et al., 2014).

To date, few studies have investigated mind-wandering in retrieval-based learning, with some exceptions. For instance, Szpunar et al. (2013) demonstrated that learners who had been tested after each of four segments of a statistics video-recorded lecture reported less mind-wandering than non-tested learners, and also performed better on a final cumulative test. These data indicate that practicing retrieval of previously studied material can produce downstream benefits in reducing mind-wandering and promoting retention when learning new material (see Chan et al., 2018, for a review of the forward testing effect). More recently, Peterson and Wissman (2020) investigated the extent to which retrieval practice sustained attention when reviewing previously learned information by probing learners' mind-wandering tendencies when they either restudied or practiced retrieving word lists after initial study. Retrieval practice produced less mind-wandering, which in turn mediated the relationship between study method and learners' performance on a delayed cued-recall test. This suggests that learners are more likely to stay on task when practicing retrieval than restudying, thus boosting their final test performance.

But *why* is mind-wandering reduced during retrieval practice? Of note, in the standard retrieval-based learning paradigm, control participants typically restudy via massed encoding, whereas retrieval practice initiates variation in learning contexts when interleaving study (encoding) and retrieval. This context variation potentially confounds with the role of retrieval practice per se in explaining learners' mind-wandering tendencies. Indeed, it is well-known that attention is oriented toward novel situations, whereas stimulus repetition often results in habituation and disengagement of attention (e.g., Kahneman, 1973). For instance, mind-wandering has been implicated in the interleaving effect, whereby spaced studying of exemplars from various categories produces less mind-wandering and correspondingly better inductive learning than massed studying (Metcalfe & Xu, 2016). Presumably, learners' attention is more likely to be sustained when exemplars from different categories are interleaved, whereas learners' attention tends to lapse when experiencing exemplars from the same category in massed succession. Likewise, the change in learning context during retrieval practice (interleaved study and retrieval) may inherently produce less mind-wandering than restudying the same material in the same way (massed study). We investigated this suggestion in the present research.

Study overview

In unravelling why retrieval practice reduces mind-wandering tendencies, we employed the now-classic retrieval-based learning paradigm of testing after completion of a study episode (e.g., Karpicke & Blunt, 2011; Roediger & Karpicke, 2006), comparing restudy (Study–Study–Study–Study; SSSS) versus retrieval practice (Study–Retrieve–Study–Retrieve; SRSR). As an index of mind-wandering, we adopted the commonly used "probe-caught" method – a thought-sampling technique that involves intermittently presenting participants with probes (e.g., visual prompts or auditory cues) that explicitly ask them to report whether they had been mind-wandering just before the probe's onset (Smallwood & Schooler, 2006; Szpunar et al., 2013; Weinstein, 2018).[1] Since mind-wandering has been found to increase over time-on-task (Thomson et al., 2014), we also assessed learners' mind-wandering at multiple points during the learning task, as opposed to only during the review phase after initial study (Peterson & Wissman, 2020).

Foremost, we expected retrieval practice to attenuate mind-wandering, thereby benefiting learners during a final delayed recall test. Second, and more important, we sought to ascertain whether mind-wandering during restudy could be reduced by varying the way that participants experienced the learning material during each study period. Specifically, to rule out the possibility that any observed differences in mind-wandering are simply artifacts of the SSSS–SRSR paradigm that arise from a change in learning context during retrieval practice but not restudy, we manipulated the mode of study across both learning conditions. Thus, learners either studied by alternating between watching a video-recorded lecture versus reading an exacting transcript of that same lecture (i.e., different study modes), or learned the material using either the video-recorded lecture or corresponding transcript only. This allowed us to determine the extent that mind-wandering is reduced when learners restudy via non-exact, rather than exact, repetition. If context variation alone is sufficient to reduce mind-wandering, then such tendencies should remain at bay even in a SSSS procedure with both video and transcript components, as opposed to a traditional SSSS procedure with a single study mode. In contrast, if context variation does not suffice, then mind-wandering tendencies would prevail during restudy even with alternated modes, relative to retrieval practice.

Method

Participants

The participants were 120 undergraduate students (87 women), aged 19–28 years ($M = 21.71$, $SD = 1.86$), at the National University of Singapore. A power analysis (G*Power 3; Faul et al., 2007) indicated that this sample size afforded sufficient

[1] The probe-caught method has been established to be non-reactive in measuring mind-wandering without fundamentally altering performance on cognitive tasks such as those involving attention and inhibition (Wiemers & Redick, 2019).

sensitivity to detect medium between-subjects effects (f = 0.26) at 80% power and α = .05; a sample of at least 13 participants per condition was required for 80% power to observe a basic testing effect (η_p^2 = .25 reported by Karpicke & Blunt, 2011, Experiment 1, for their comparison of SSSS vs. SRSR participants' final test performance) at α = .05, while a sample of at least 16 participants per condition was required for 80% power to detect differences in mind-wandering frequency across the restudy and retrieval practice groups (d = 1.05 reported by Szpunar et al., 2013) at α = .05. All participants reported English as their first language, and received either course credit or cash reimbursement for their participation. This study received ethics approval from the Institutional Review Board of our university, and all participants provided written informed consent.

Design

A 2 × 2 fully between-subjects experiment was conducted. The first independent variable was Learning Strategy: *restudy* (*SSSS*), in which learners (re)studied the material, versus *retrieval practice* (*SRSR*), in which learners alternated study with retrieval practice in learning the material. The second independent variable was Study Mode: the *same study mode* (*S* or *S′*), in which learners learned using either the video-recorded lecture or the corresponding transcript throughout the study periods (e.g., *SSSS* or *SRSR*), versus *different study modes* (*S* and *S′*), in which learners alternated between the video-recorded lecture and the corresponding transcript (e.g., *SS′SS′* or *SRS′R*). With counterbalancing, four further (counterpart) combinations were derived (*S′S′S′S′*; *S′SS′S*; *S′ RS′R*; *S′RSR*), yielding a total of eight combinations.

The dependent variables were: (a) the proportion of idea units that learners correctly recalled in a final test 1 week later, and (b) the proportion of mind-wandering that occurred during the learning phase.

Materials

Video-recorded lectures and transcripts

To ascertain the extent that the advantages of retrieval practice for mind-wandering and learning generalize to various lecture topics, we used two *Coursera* video-recorded lectures (with permission from both the host provider and the respective course lecturers) and their corresponding transcripts on "Brain Matter" and "Music History", respectively, beyond the statistics lectures featured in previous research (Szpunar et al., 2013). Learners were randomly assigned to learn either of the two lecture topics; 60 learners studied "Brain Matter" and 60 learners studied "Music History". The two video-recorded lectures were controlled for both duration and word count: The "Brain Matter" video lasted 2 min 52 s with its transcript comprising 465 words, whereas the "Music History" video lasted 2 min 40 s with its transcript comprising 496 words. For scoring purposes, each video-recorded lecture was decomposed into 30 idea units – one mark was awarded for recalling a unit correctly, half a mark for recalling a unit partially (correctly), or no mark for an incorrect unit. In both videos, the lecture slides and lecturers remained visible to learners. The transcripts detailed all content arising from the lecturers' speech, as well as the lecture slides.

Post-learning questionnaire

A questionnaire comprising ten phenomenological items was administered to learners after they had completed the learning phase. Learners rated the following phenomenological items via a 7-point Likert scale: (i) how much they felt their mind had wandered during the lecture/while reading the transcript (1 = *not at all*; 7 = *very much*), (ii) how much they felt their mind-wandering had increased as the lecture progressed (1 = *not at all*; 7 = *very much*), (iii) how anxious they felt about the final test (1 = *not at all*; 7 = *very much*), (iv) how mentally taxing they found the experience of learning the lecture to be (1 = *not at all*; 7 = *very much*), (v) how interesting they found the lecture to be (1 = *very boring*; 7 = *very interesting*), (vi) how understandable they found the content to be (1 = *very difficult to understand*; 7 = *very easy to understand*), (vii) how well they thought they would remember the lecture content after 1 week (1 = *not very well*; 7 = *very well*), (viii) whether they had watched that particular lecture before (*yes* or *no*), (ix) how well they knew the subject matter before watching the lecture/reading the transcript (1 = *not very well*; 7 = *very well*), and (x) how comfortable they were learning from video-recorded lectures (1 = *not at all*; 7 = *very much*).

Procedure

Upon learners' arrival at the lab, they were briefed on the study's proceedings. Specifically, learners were instructed: (a) to make full use of the time given in the learning phase, as the information learned would be required for the test phase; (b) not to take notes whilst watching the video-recorded lecture or make annotations on the printed lecture transcripts; (c) regarding the mind-wandering procedure. Learners watched the video lectures whilst listening via headphones; this insured that they did not communicate with one another during the experiment. They were provided with standard Panasonic RP-HT010 headphones; auditory output volume was adjusted to a comfortable listening level. Learners then underwent two experimental phases: learning and test.

Learning phase

The learning phase consisted of four contiguous 6-min learning periods (e.g., Karpicke & Blunt, 2011; Roediger & Karpicke, 2006). Learners in the *SSSS* condition viewed the video lecture for four consecutive 6-min periods. Within each *S* period, learners were instructed to first view the lecture once through and, subsequently, revisit any lecture segments that they found to be difficult. Learners in the *S′S′S′S′* condition, in contrast, read the lecture transcript for four consecutive 6-min periods. Learners in the *SS′SS′* condition studied the video-recorded lecture in the same way as those in the *SSSS* condition in the first 6-min (*S*) period, switched to studying the lecture transcript for the second 6-min (*S′*) period, returned to view the video-recorded lecture for the third 6-min (*S*) period, and finally read the transcript again for the fourth 6-min (*S′*) period. In contrast, learners in the *S′SS′S* condition studied using the transcript during the first and third 6-min periods, and using the video-recorded lecture during the second and fourth 6-min periods.

Learners in the *SRSR* and *S′RS′R* conditions underwent, foremost, a 6-min study period (using either the video-recorded lecture or transcript), followed by a 6-min period in which they practiced freely retrieving by writing down as much of what they had studied as they could remember, a third 6-min study period that involved restudying (using the *same* study mode – either the video-recorded lecture or transcript – as in the first period), and a final 6-min retrieval practice period. In contrast, learners in the *SRS′R* condition studied using the video lecture in the first period, engaged in retrieval practice in the second period, studied using the alternative study mode (lecture transcript) in the third period, and practiced retrieving the material again in the final period. The procedure involved in the *S′RSR* condition was virtually identical to that in the *SRS′R* condition, except that learners started with studying using the lecture transcript in the first period, and the video lecture in the third period.

Mind-wandering was assessed via a direct-probing approach. Specifically, at random points during the lecture, the experimenter rang a bell, which was to be taken literally as a question of whether learners' attention had strayed away from the lecture content at that moment in time ("Are you mind-wandering?"). Upon hearing the bell, which was hidden from view, participants had to quickly write down a yes/no response on a blank piece of paper without pausing the lecture video. Participants were not told how many mind-wandering probes to expect, when, in fact, a total of four mind-wandering probes would randomly occur at four specific times during the lecture, once during each of the four learning periods (quartiles; e.g., Szpunar et al., 2013). Mind-wandering was taken as the proportion of "yes" responses over the four time points at which they were prompted.

The learning phase was followed by a post-learning questionnaire, in which participants responded to ten phenomenological items concerning their learning experience. Upon completing the questionnaire, participants were reminded to return for the test phase of the study exactly 1 week later.

Test phase

The test phase was designed to mimic naturalistic examination settings. Participants completed a 10-min free recall test – they wrote down as much of the material that they had earlier studied in the learning phase as they could recall at the same venue whilst sitting separately, preventing any interactions between them.

Results

Preliminary checks

All participants reported that they had not watched the presented lecture prior to the experiment. In addition, restudy versus retrieval practice participants did not significantly differ in their ratings of how anxious they felt about the final test, how mentally taxing it had been to learn the lecture, how interesting the lecture content was, their prior knowledge of the lecture content, and how comfortable they were learning from video-recorded lectures, all *p*s > .05, although restudy participants reported greater understandability of the lecture content than retrieval practice participants, $t(118) = 2.59$, $p = .011$, 95% CI [0.10, 0.74]. Means and standard deviations are presented in Table 1.

Recall test performance

We conducted a 2 (Learning Strategy) × 2 (Study Mode) × 2 (Lecture Topic) between-subjects ANOVA on the proportion of idea units that learners correctly recalled on the final delayed test. The analysis yielded only a significant main effect of Learning Strategy, $F(1, 112) = 23.51$, $p < .001$, $\eta_p^2 = .17$. Replicating the classic testing effect, retrieval practice ($M = .45$, $SD = .16$) produced superior recall-test performance than restudy ($M = .31$, $SD = .15$). There was no main effect of Study Mode, $F(1, 112) = 0.16$, $p = .69$, $\eta_p^2 = .001$. Across both learning strategies, recall performance did not differ whether learners alternated between the video-recorded lecture and its corresponding transcript ($M = .39$, $SD = .16$) or used the same study mode throughout ($M = .38$, $SD = .18$). In addition, the main effect of Lecture Topic was non-significant, $F(1, 112) = 1.43$, $p = .24$, $\eta_p^2 = .01$, indicating that recall performance did not differ across the "Brain Matter" ($M = .40$, $SD = .17$) and "Music History" ($M = .36$, $SD = .17$) lectures. All interactions were also non-significant, all *p*s >

Table 1 Means and standard deviations of participants' responses on the post-learning questionnaire by learning strategy

Variable	Restudy		Retrieval practice	
	M	*SD*	*M*	*SD*
Test anxiety	2.68	1.54	2.48	1.62
Mentally taxing	2.77	1.33	3.07	1.34
Content interestingness	4.62	1.51	4.65	1.25
Content understandability	6.25	0.80	5.83	0.96
Prior knowledge	2.38	1.70	2.50	1.68
Comfortable learning from video-recorded lectures	5.37	1.45	5.10	1.20

Note. $N = 120$. All ratings were made on a 7-point scale

.05. Accordingly, we collapsed learners' recall performance across lecture topics in all subsequent analyses. Table 2 presents the means and standard deviations of participants' test performance.

Mind-wandering

Analyzing the rate of mind-wandering over time across the four learning periods, a 2 (Learning Strategy) × 2 (Study Mode) × 4 (Quartile) mixed ANOVA revealed a significant three-way interaction, $F(3, 348) = 2.75$, $p = .043$, $\eta_p^2 = .02$, which we decomposed by examining the Learning Strategy × Quartile interaction at each level of Study Mode.

When learners used the same study mode throughout, there was a significant Learning Strategy × Quartile interaction, $F(3, 174) = 5.42$, $p = .001$, $\eta_p^2 = .09$. As shown in Fig. 1A, mind-wandering rates did not differ between the restudy and retrieval practice conditions in Quartile 1, $p = 1.00$. However, restudy produced significantly more mind-wandering than retrieval practice across Quartile 2, $F(1, 58) = 12.73$, $p = .001$, $\eta_p^2 = .18$, Quartile 3, $F(1, 58) = 5.36$, $p = .024$, $\eta_p^2 = .09$, and Quartile 4, $F(1, 58) = 20.08$, $p < .001$, $\eta_p^2 = .26$. Whereas retrieval practice participants' mind-wandering rate did not differ across all four quartiles, all $ps = 1.00$, restudy participants reported greater mind-wandering in all quartiles as compared to the first, all $ps < .05$.

When learners alternated between study modes, there was likewise a significant Learning Strategy × Quartile interaction, $F(3, 174) = 5.27$, $p = .002$, $\eta_p^2 = .08$, albeit with a different pattern. As Fig. 1B illustrates, mind-wandering did not differ between the restudy and retrieval practice conditions during Quartiles 1 and 2 when learners were exposed to different study modes, both $ps > .05$. However, mind-wandering was considerably greater in the restudy than the retrieval practice condition in Quartiles 3 and 4 when learners reverted to using the study modes that they had earlier experienced, $F(1, 58) = 9.61$, $p = .003$, $\eta_p^2 = .14$, and $F(1, 58) = 5.04$, $p = .029$, $\eta_p^2 = .08$, respectively. While restudy participants' mind-wandering did not differ across Quartiles 1 and 2 when they were exposed to different study modes, $p = .44$, they mind-wandered significantly more in Quartiles 3 and 4 than in the first two quartiles, all $ps < .05$. Conversely, retrieval practice participants' mind-wandering did not differ across all four quartiles, all $ps = 1.00$.

Planned contrasts further revealed that restudy participants mind-wandered significantly less in Quartile 2 when they used a different study mode instead of the same one, $F(1, 58) = 10.05$, $p = .002$, $\eta_p^2 = .15$. However, in Quartiles 3 and 4 when the changes in study modes involved those that restudy participants had earlier used, this attentional benefit dissipated – instead, mind-wandering surged to a level (up to 57%) that was as rampant as when participants had continued to use the exact same mode for the third and fourth times in succession, both $ps > .05$. In contrast, mind-wandering during retrieval practice did not differ across the same versus different study modes in each of the four quartiles, all $ps > .05$, and did not exceed 20% in any given quartile.

Taken together, these results suggest that: In the restudy condition, alternating between study modes buffered against mind-wandering, but only up till the quartile when the study

Table 2 Means and standard deviations of participants' recall-test performance across conditions

Study mode	Restudy		Retrieval practice	
	M	*SD*	*M*	*SD*
Same				
"Brain Matter" lecture	.34	.15	.45	.18
"Music History" lecture	.25	.15	.46	.14
Different				
"Brain Matter" lecture	.36	.12	.44	.19
"Music History" lecture	.30	.16	.45	.14

Note. $N = 120$. Recall test performance was measured as the proportion of idea units from the lecture that learners correctly recalled on a final delayed test 1 week later

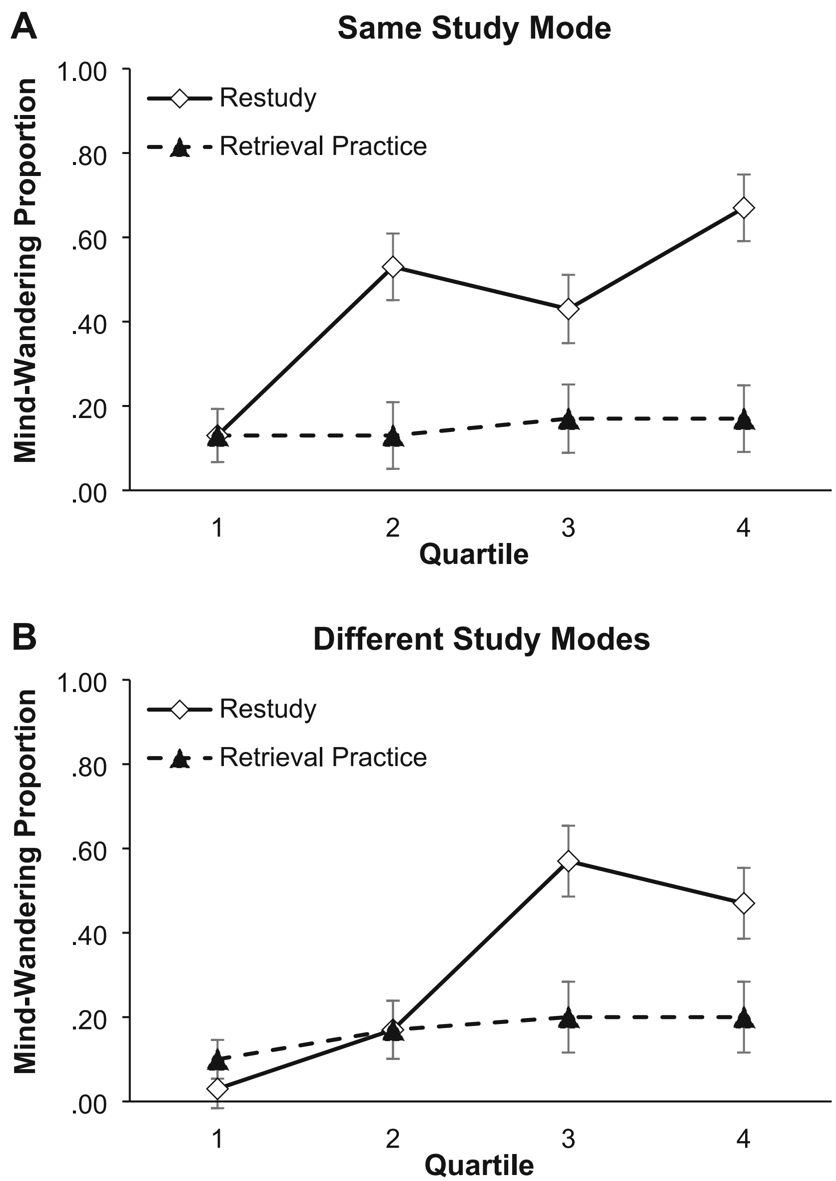

Fig. 1 Mind-wandering proportion across quartiles by learning strategy with same versus different study modes. (**A**) and (**B**) show the proportion of learners in the restudy and retrieval practice conditions who reported mind-wandering during each quartile when using the same versus different study modes, respectively. Error bars indicate standard errors

mode remained "new" to learners. In contrast, retrieval practice consistently sustained learners' attention on the task over time, regardless of whether their study modes were kept the same or varied.

Mediating role of mind-wandering

Learners who mind-wandered more during the learning phase tended to perform more poorly on the final recall test, $r(118) = -.46$, $p < .001$. The significant negative correlation between mind-wandering and recall-test performance held in both the restudy condition, $r(58) = -.29$, $p = .024$, and the retrieval practice condition, $r(58) = -.47$, $p < .001$ (see Fig. 2).[2]

To test the mediation effect of mind-wandering on the relationship between learning strategy and final test performance, we employed regression analysis using Model 4 of Hayes' (2013) PROCESS macro for SPSS. The total effect of learning strategy on recall performance was significant, $b = .14$, $SE = .03$, $p < .001$, with learning strategy accounting for 16.8% of the variance in learners' recall performance. In

[2] We note that these sample sizes are relatively modest for correlational analyses; we report the correlations separately for the restudy versus retrieval practice conditions here for completeness.

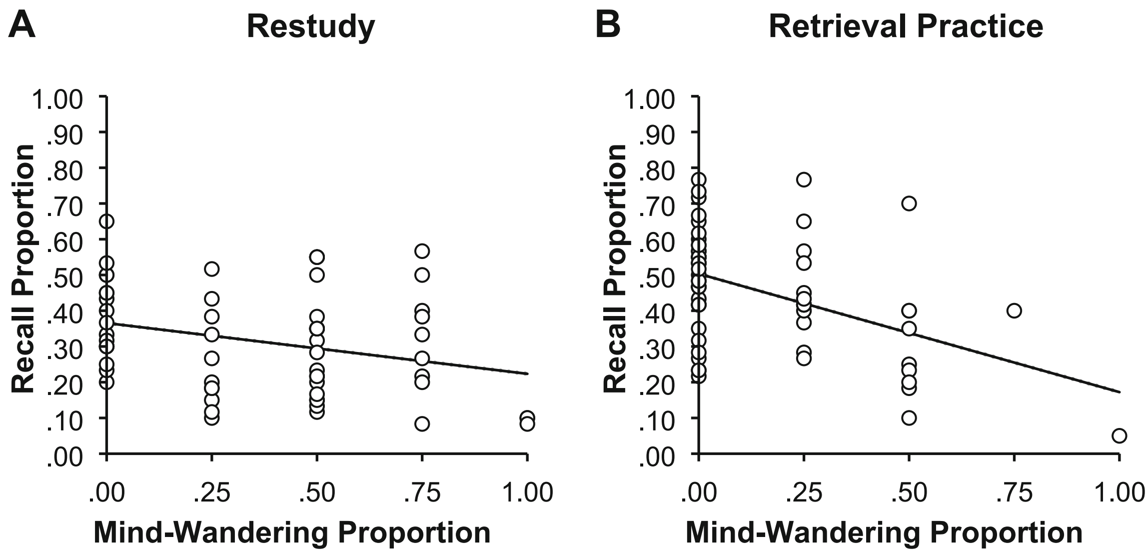

Fig. 2 Correlations between mind-wandering and recall-test performance across the restudy and retrieval practice conditions. (**A**) and (**B**) show the correlations between mind-wandering and recall-test performance in learning strategies, respectively. Mind-wandering was measured as the proportion of "yes" responses to the mind-wandering probes that were presented over four time points (quartiles) during the learning phase

addition, learning strategy negatively predicted mind-wandering, b = -.22, SE = .05, p < .001, whereby retrieval practice was associated with less mind-wandering than restudy. In turn, controlling for learning strategy, mind-wandering was negatively associated with learners' recall performance, b = -.21, SE = .05, p < .001, accounting for an additional 11.0% of variance in recall performance over and above learning strategy. The full model with both learning strategy and mind-wandering explained 27.9% of the variance in learners' final recall-test performance, F(2, 117) = 22.60, p < .001. Learning strategy remained a significant predictor of recall performance after controlling for mind-wandering as the mediator (i.e., the direct effect of learning strategy), b = .09, SE = .03, p = .002. We then tested the indirect effect of learning strategy on recall performance via mind-wandering using a percentile bootstrap estimation approach with 5,000 samples (Preacher & Hayes, 2004). Crucially, the indirect effect of .05 (SE = .01) was significant; zero was not included in the 95% CI [.02, .08]. Thus, mind-wandering partially mediated the relationship between learning strategy and recall performance (see Fig. 3).[3]

Metacognitive judgments

Participants made fairly accurate metacognitive judgments of their level of mind-wandering. When asked how much they felt their mind had wandered during the learning phase, restudy participants (M = 3.63, SD = 1.74) gave significantly higher ratings than retrieval practice participants (M = 2.32, SD = 1.21), t(118) = 4.81, p < .001, 95% CI [0.78, 1.86]. Restudy participants (M = 4.60, SD = 1.75) also gave higher ratings than their retrieval practice counterparts (M = 3.22, SD = 1.71) when asked how much they felt their mind-wandering had increased as the lecture progressed, t(118) = 4.38, p < .001, 95% CI [0.76, 2.01].

Yet, participants' predictions of their learning were largely inaccurate. When asked how well they thought they would remember the lecture content after a week, restudy participants (M = 4.20, SD = 1.36) made significantly higher estimates than their retrieval practice counterparts (M = 3.45, SD = 1.19), t(118) = 3.22, p = .002, 95% CI [0.29, 1.21]. Moreover, participants' predictions of their learning did not significantly correlate with their actual final test performance, r(118) = -.11, p = .24. As in previous research (e.g., Karpicke & Roediger, 2008; Roediger & Karpicke, 2006), learners appeared to be oblivious to the mnemonic benefits of retrieval practice.

Discussion

Relative to learners who had repeatedly studied the material, learners who practiced retrieval displayed less mind-wandering, which in turn partially mediated their superior recall performance on a final test after a 1-week delay.[4] Importantly, by probing participants' mind-wandering over the course of the learning task, our findings illuminate the fine-grained attentional dynamics of the testing effect. Except during the initial study phase,

[3] We further ascertained that the role of mind-wandering in mediating the learning benefits of retrieval practice separately persisted both when the same study mode was used, indirect effect =.05 (SE = .03, 95% CI [.003, .11]), and when different study modes were used, indirect effect = .04 (SE = .02, 95% CI [.004, .07]).

[4] We note that this attentional account is not mutually exclusive with other extant theories of retrieval-based learning (e.g., Carpenter 2009, 2011; Karpicke et al., 2014; Lehman et al., 2014).

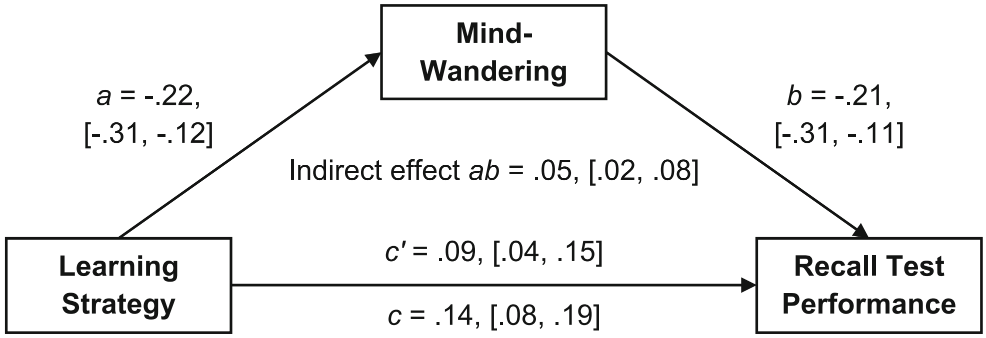

Fig. 3 Relation between learning strategy and recall-test performance as mediated by mind-wandering. Unstandardized regression coefficients are presented for each path. Values in brackets represent the 95% confidence intervals for the regression coefficients using a percentile bootstrap estimation approach with 5,000 samples

restudy participants consistently displayed more mind-wandering than retrieval practice participants when the exact same study material was used throughout the task (i.e., as per the paradigm in most retrieval-based learning studies; see Kornell et al., 2012, for a discussion). Can such mind-wandering during restudy be reduced? Yes – to some extent. When we varied the way that learners experienced the study material by alternating between a video-recorded lecture versus its corresponding transcript, mind-wandering rates did not differ across learning conditions. That is, restudy via non-exact repetition sustained learners' attention on the task just as effectively as retrieval practice did. Crucially, however, for restudy participants, this attentional boost lasted only as long as the study modes remained "new" to them – when they reverted to using a previously encountered "old" study mode, their attention lapsed. This pattern of results aligns with the notion that lack of change during restudy contributes to greater mind-wandering. In contrast, retrieval practice consistently sustained learners' attention throughout the task even when they restudied the material after having tested themselves, regardless of whether they used the same or different study modes to review it.

Besides replicating the classic testing effect involving the same study mode, we further found that even when study mode was varied, restudy still produced poorer final test performance than retrieval practice. This outcome follows logically from our findings that mind-wandering mediated the effects of learning strategy on final test performance, and that alternating study modes only temporarily buffered against mind-wandering during restudy up till the first half of the learning task. Indeed, our results dovetail with those of Butler and Roediger (2007), who found that learners' long-term retention was superior when they had taken an initial short-answer test after watching a video-recorded lecture, as opposed to restudied via reading a lecture summary. Taken collectively, these findings suggest that the advantage of retrieval practice can persist over restudy with non-exact repetition. Thus, the change in learning context conferred by testing is, in itself, insufficient to account for the mnemonic benefits of this strategy.

Future directions

These findings have implications for the research design of future work. Whereas restudy has commonly been the control condition of choice in numerous studies on retrieval-based learning (Kornell et al., 2012), we found that restudy inherently encouraged more mind-wandering that impaired learners' final test performance. To the extent possible, it may be prudent for future studies to consider adopting more rigorous controls that sustain learners' attention as effectively as does retrieval practice.

To enrich the present attentional account of the testing effect, a key question worth pursuing in future research pertains to how and why retrieval practice reduces mind-wandering. It is possible that there are different mechanisms at work across various stages of retrieval practice. For instance, since mind-wandering did not differ in the second quartile whether learners practiced retrieval or restudied the material in a different mode, it seems that the change in learning context helped to protect against mind-wandering during this period. Conversely, in the third quartile, both learning groups diverged in their mind-wandering tendencies despite similarly engaging in restudy, implying underlying differences in the mental processes that they engaged in. For instance, it may be that retrieval practice enabled learners to more accurately monitor their knowledge while alerting them to what they do not know, thus orienting them toward more effective utilization of the restudy opportunity (Little & McDaniel, 2015; Soderstrom & Bjork, 2014). In contrast, restudy often leads learners to overestimate their learning – in part because it induces a misleading sense of fluency (Bjork et al., 2013), such that learners made less effective use of their subsequent study time. Future investigations of these mechanisms will be helpful in providing a more nuanced view of how exactly retrieval practice sustains attention and enhances learning.

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Open Practices Statement

The data and materials of this study are available from the authors upon reasonable request. The experiment reported in this study was not preregistered.