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Empirical article

Pretesting Reduces Mind Wandering and Enhances Learning During Online Lectures

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Although online lectures have become increasingly popular, their effectiveness at promoting learning can be attenuated by *mind wandering* (shifts in attention away from the task at-hand towards unrelated thoughts). We investigated whether taking tests on to-be-studied information, also known as *pretesting*, could mitigate this problem and promote learning. In two experiments, participants viewed a 26-min video-recorded online lecture that was paired with a pretest activity (answering questions about the lecture) or a control activity (solving algebra problems), and with multiple probes to measure attention. Taking pretests reduced mind wandering and improved performance on a subsequent final test compared to the control condition. This result occurred regardless of whether pretests were interspersed throughout the lecture (Experiment 1) or were administered at the very beginning of the lecture (Experiment 2). These findings demonstrate that online lectures can be proactively structured to reduce mind wandering and improve learning via the incorporation of pretests.

General Audience Summary

Although video-recorded lectures have become increasingly prevalent at many levels of education, such lectures are often highly susceptible to the effects of *mind wandering*—that is, shifts in attention away from external stimulation towards unrelated thoughts. These shifts in attention are especially difficult to prevent in online settings. We investigated whether *pretesting*, or being tested on information before it is presented for learning, helps reduce the incidence of mind wandering during video lectures. Across two experiments, undergraduate students viewed a lecture that was accompanied by pretesting or a control algebra problem-solving activity. Pretesting occurred either between portions of the lecture or entirely before the lecture. Mind wandering was measured at multiple points throughout the lecture and learning was measured on a subsequent final test. In both experiments, pretesting—whether it occurred between parts of the lecture or entirely before it—resulted in significantly less mind wandering and better final test performance than the control activity. Overall, these findings have broad implications for online learning: Administering pretests before a video lecture, or during the lecture itself, can substantially benefit student learning.

Keywords: Pretesting, Prequestions, Mind wandering, Online learning, Video lectures

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Pretesting Reduces Mind Wandering and Enhances Learning During Online Lectures

During lectures, students often engage in *mind wandering*—that is, shifts in focused attention away from external stimulation and towards self-generated thoughts that are unrelated to the task at hand (Smallwood & Schooler, 2006; for a meta-analysis, see D'Mello, 2018). Although the prevalence and timing of such mind wandering varies (Stuart & Rutherford, 1978; Wilson & Korn, 2007), it is not uncommon for a third to well over half of the students attending a lecture to mind wander and with increasing frequency as the lecture progresses (e.g., Bunce, Flens, & Neiles, 2010; Lindquist & McLean, 2011). Mind wandering during lectures is, unsurprisingly, associated with poorer learning outcomes (e.g., Risko, Anderson, Sarwal, Engelhardt, & Kingstone, 2012; Szpunar, Khan, & Schacter, 2013a; for a review see Schacter & Szpunar, 2015).

The growing popularity of online education (including Massive Open Online Courses (MOOCs), flipped classrooms, and by necessity due to the global coronavirus pandemic) further exacerbates the problem of mind wandering for learning. Online courses rely heavily on video-recorded lectures. Although such lectures have increased the accessibility of learning, they are often viewed in distraction-prone settings (Hollis & Was, 2016) and commonly in the absence of an instructor that might be able to improve students' focus on lecture content. Many students also report that paying attention is more difficult, and rates of student engagement appear to drop more rapidly, when lectures are online as opposed to in-person (Guo, Kim, & Rubin, 2014; Jensen, 2011; Kim et al., 2014; Timmons, 2020). All of these concerns heighten the urgency of finding solutions to address the problem of mind wandering during lectures.

Interventions to Prevent Mind Wandering During Lectures

Although some researchers have focused on detecting mind wandering when it occurs (e.g., Bixler & D'Mello, 2015) and intervening afterwards, other researchers have focused on preventing mind wandering altogether. Evidence for the efficacy of such techniques has been mixed (for reviews see Szpunar, 2017; Szpunar, Moulton, & Schacter, 2013b). For instance, Burke and Ray (2008) reported improvements in concentration when students were asked to generate questions or discuss them with peers during lectures, as did Bunce et al. (2010) when instructor-provided clicker questions and demonstrations were implemented during lectures. The techniques used in both studies, however, have yet to be investigated under fully controlled experimental conditions and in online settings. Martin, Mills, D'Mello, and Risko (2018) observed that another technique, namely re-watching videos, exacerbated rates of mind wandering during online lectures. Other potential interventions include shortening videos and modifying their visual layout (for discussions see Guo et al., 2014; Inman & Myers, 2018).

Interspersing practice tests throughout a lecture or other learning materials, a technique known as *interpolated testing*, ranks as one of the most promising mind wandering interventions investigated to date. In two experiments, Szpunar et al. (2013a) had undergraduate students view a 21-minute video-recorded online lecture on a statistics topic that was divided into four clips. After each clip, students (a) took a cued recall test on the content that had just been covered, (b) solved arithmetic problems, or (c) studied the test questions with the answers provided. Across both experiments, interpolated testing yielded fewer bouts of mind wandering, increased the quantity of notes that students took during the lecture, lowered test anxiety, and improved performance on a cumulative final test. In a follow-up study, Jing, Szpunar, and Schacter (2016) found that interpolating tests throughout a 40-minute, eight-segment video-recorded online lecture on the subject of public health also increased note taking and improved final test performance. Although no overall reductions in mind wandering relative to a non-testing condition were found, interpolated testing caused participants to integrate units of information more effectively and increased their proportion of self-reported lecture-related thoughts; these thoughts were positively associated with final test performance. The results of both studies suggest that interpolated testing alters the extent to which learners think about the content of video lectures as they are viewing them, leading to improved learning.

The Benefits of Pretesting for Learning and Memory

The efficacy of interpolated testing for reducing mind wandering constitutes a further benefit of *retrieval practice* (taking recall tests to enhance memory; for reviews see Bjork, 1975; Pan & Rickard, 2018; Roediger & Butler, 2011), which is one of the most potent learning techniques discovered to date. In the present study we investigated whether another promising test-based technique, pretesting (otherwise known as prequestioning or errorful generation) might also reduce mind wandering during lectures. Similar to retrieval practice, pretesting also involves taking tests, but such tests occur *before* the study of to-be-learned information (for reviews see Kornell & Vaughn, 2016; Metcalfe, 2017; see also Pan & Bjork, in press), rather than afterwards. Owing to their lack of preexisting knowledge, learners often generate many incorrect answers during pretesting and only learn of the correct answers upon subsequent study or when they receive feedback (e.g., Pan, Lovelett, Stoeckenius, & Rickard, 2019). Crucially, pretesting followed by studying of target materials or correct answer feedback yields improved long-term memory—also known as the *pretesting effect*—relative to conditions that lack pretests and in which information is simply studied (e.g., Richland, Kornell, & Kao, 2009).

The pretesting effect has been successfully demonstrated across a plethora of educationally-relevant circumstances. Benefits of pretesting have been found for stimuli ranging from semantically-related word pairs and trivia facts (e.g., Kornell, Hays, & Bjork, 2009) to text passages (e.g., Little & Bjork, 2016) and educational videos (e.g., Toftness, Carpenter, Lauber, & Mickes, 2018), and in both laboratory and classroom settings (e.g., Carpenter, Rahman, & Perkins, 2018). There are also theoretical reasons to expect that pretesting might improve learners' ability to stay focused during lectures and in other pedagogical contexts. For instance, Carpenter and Toftness (2017; see also Bjork, Dunlosky, & Kornell, 2013) noted that pretesting

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might serve as a metacognitive "reality check"—that is, highlighting the gaps in one's knowledge and facilitating a search for the relevant information during subsequent study. Another possibility is that pretesting may stimulate curiosity, which in turn improves attention for the information that follows (Geller et al., 2017; see also Metcalfe & Finn, 2011). Although these accounts focus on how pretesting benefits memory, they also imply that pretests can substantially influence attention during learning—and more broadly, raise the possibility that attentional changes may contribute to the pretesting effect itself.

A recent study provides additional insights. Across four experiments, St. Hilaire and Carpenter (2020) had participants take a pretest prior to viewing a lecture video, during which they either took notes or filled out a worksheet that contained the pretest questions. A pretesting effect was only observed when participants had successfully identified the answers to the pretest questions while watching the video (as indicated in their notes or on the worksheet). This finding suggests that the pretesting effect relies on learners' memory for pretest questions, with learning enhanced via the focusing of attention on previously tested information. If so, then reduced mind wandering might be a consequence of pretesting.

The Present Study

In two experiments, we investigated whether pretesting might reduce mind wandering and help learners stay more focused during video lectures. Experiment 1 investigated *interpolated pretesting*, wherein pretests occur at several points during a lecture, and Experiment 2 compared interpolated pretesting against *conventional pretesting,* wherein all pretest questions precede an entire lecture. Our implementation of interpolated pretests was similar to the arrangement of recall tests in Szpunar et al. (2013a), with the crucial difference that test questions were administered before, rather than after, each portion of the lecture. In both experiments, we measured mind wandering via attention probes presented after each of four parts of the lecture, and assessed any learning benefits via a cumulative final test that included both previously pretested and new questions drawn from the lecture (cf. James & Storm, 2019; Toftness et al., 2018). Additionally, in both experiments we asked participants to provide a metacognitive judgment of learning after viewing the entire lecture (similar to Szpunar, Jing, & Schacter, 2014), and in the second experiment, we also assessed participants' memory for the pretest questions.

Experiment 1

Experiment 1 investigated whether *interpolated pretesting*—interspersing pretest questions at four points throughout a video lecture—decreases mind wandering and improves learning.

Method

Participants. Undergraduate psychology students from the participant pool at a large university on the west coast of the United States participated in exchange for partial course credit (i.e., students from a variety of psychology courses could enroll in the experiment). All participants gave informed consent and the experiment was approved by the Institutional Review Board (IRB) of the university. A power analysis using the G*Power program (Faul, Erdfelder, Lang, & Buchner, 2007) indicated that a sample of 84 participants would be needed to detect small to medium-sized effects ($f = 0.20$) using a 2 × 2 mixed factorial design with $\alpha = 0.05$ and power of 0.95. Compliance with experiment instructions, which included sitting through each part of the lecture and answering a series of questions that were interpolated throughout the lecture, was critical given that learning was assessed on a memory test at the end of the experiment. Therefore, we recruited in excess of 84 participants; data from 105 participants (*control* condition, $n = 52$; *pretest* condition, $n = 53$) were included in the analyses.

Design. As shown in Figure 1, the video lecture was divided into four parts, and each part appeared within a segment that included a series of pre-video activities and a post-video attention probe. Similar to Szpunar, Khan et al. (2013; Experiment 1), all participants were randomly assigned to one of two conditions in which the pre-video activity consisted of algebra problems that were unrelated to the lecture (control condition) or pretest questions that were drawn from the part of the lecture that was shown in that given segment (pretest condition). To assess learning, all participants took a final test at the end of the experiment that included *pretested* questions (questions that appeared on the pretests) and *new* questions (questions on content that was not pretested but covered in the lecture). As such, this experiment employed a 2 (condition: control vs. pretest; between-subjects) × 2 (test questions: pretested vs. new) mixed factorial design.

Materials. The materials consisted of a 26-minute video lecture, 32 questions that were used to assess the learning of lecture content, 32 algebra problems that were used in place of pretest questions in the control condition, an attention probe to measure mind wandering, and a post-lecture metacognitive probe that involved making a prediction of final test performance.

Video-recorded online lecture. We used a video lecture on signal detection theory that was previously featured in Toftness et al. (2018). Because this lecture was prepared for an actual course, it consisted of a series of slides with visuals, along with a voiceover of an instructor explaining the content (i.e., the instructor was heard but not seen). For the purpose of the present study, we divided the video into four approximately equal parts of 5–6 minutes in length, with each part beginning and ending at a natural transition point in the lecture. The videos, which were always presented in chronological order, were hosted on YouTube and embedded within the experiment.

Pretest and final test questions. We created eight multiple-choice questions for each video part, with half of those questions appearing as pretest questions and all of them appearing on the final test (wherein they were categorized as pretested questions or new questions). All 32 questions included four options with one correct answer. Similar to Carpenter et al. (2018), the questions were based on facts taken almost verbatim from the lecture (e.g., "*Anything that complicates detection of a signal is referred to as. . .?*" and the four options were "*A: Noise", "B: Delta", "C: Interference", and "D: Residual*"). We also created 32 algebra

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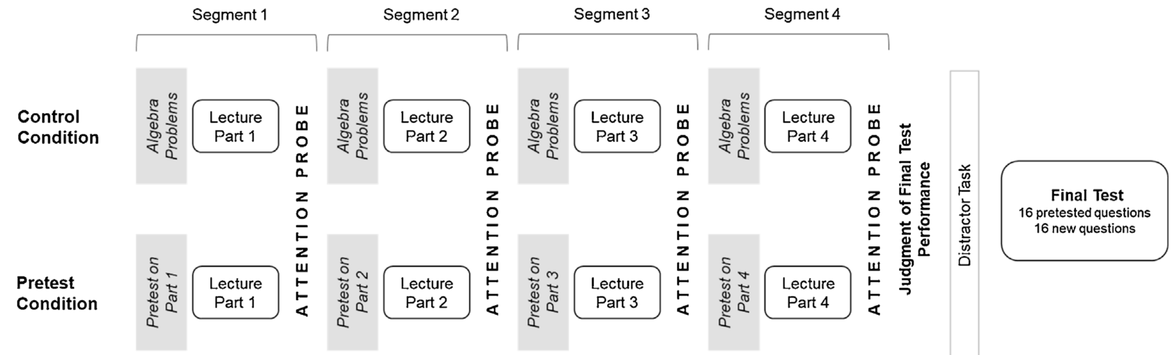

Figure 1. Design and Procedure of Experiment 1. All participants watched a 26-minute video-recorded online lecture that was divided into four approximately equal parts, during which they (a) spent 4 minutes answering pretest or algebra problems prior to each part and (b) responded to an attention probe after each part. The attention probe prompted participants to indicate how focused they were during the video presentation. After the fourth segment, participants provided a judgment of test performance, completed a 5-minute distractor task, and then took the final test.

problems for the control condition that were relatively difficult but did not require a calculator to solve (e.g., "*Solve for x: 5x – 6 = 3x – 8*").

Mind wandering and metacognitive probes. To measure participants' self-reported mind wandering during each part of the lecture, we used an attention probe that stated: "*You just watched a portion of a lecture for about 5 minutes. During that time, how closely was your ATTENTION focused on the video?*" (cf. Weinstein, 2018). Participants typed in a number from 0 ("not focused on the video at all") to 100 ("entirely focused on the video"). To assess participants' ability to predict their performance on a memory test of the lecture content, we used a judgment of test performance probe that stated: "*You just watched, across four segments, a lecture on Signal Detection Theory. If you were to take a test on that lecture, what PERCENTAGE OF QUESTIONS would you expect to ANSWER CORRECTLY?*" Participants typed in a number from 0 ("none correct") to 100 ("all correct"). The instructions that accompanied both probes urged participants to respond as honestly and accurately as possible.

Procedure. The entire experiment was programmed and accessed using LimeSurvey (Limesurvey GmbH), presented via the Google Chrome Internet browser, and took approximately one hour to complete. Participants completed the study in a laboratory testing room that was equipped with web-enabled desktop computers. The instructions for the experiment stated that participants would be completing a series of tasks (e.g., watching videos, answering questions or solving simple algebra problems, and taking surveys), that such tasks would be randomly chosen by the computer, and that they should not take any notes. They were instructed to approach each task seriously as if they were in an actual classroom (Szpunar et al., 2013a), pay attention to the best of their ability, and wear headphones.

Study phase. As illustrated in Figure 1, the study phase included four segments, each consisting of a 4-minute pre-video activity, one part of the video lecture, and an attention probe (in that order). The only difference between the two experimental conditions was the pre-video activity within each segment: the control condition included eight algebra problems, each presented for 30 seconds; whereas, the pretest condition included four multiple-choice questions that pertained to the lecture content of the subsequently presented video, each presented for 60 seconds. Participants in the latter condition were told that they might not know the correct responses to the questions, but that they should still select their best guess. The four pretest questions for each segment were initially randomly selected from a set of eight questions but then remained the same for all participants, with the order of those selected questions randomized within each segment for each participant. No specific feedback was provided, but the correct answers to the pretest questions in a given segment could be discovered during the viewing of the video that was presented in that segment.

Following the pre-video activities, all participants then watched the appropriate part of the lecture by selecting the play icon on the screen. Each video was introduced as "a portion of a lecture on Signal Detection Theory." Although participants were reminded to watch each video in its entirety and all other video controls were hidden from view, it was still technically possible to skip to the next screen using the browser controls; the data from any participant who did so were removed from analysis. After the presentation of each lecture segment, participants responded to an attention probe, and after the fourth segment, to a judgment probe as well (they were made explicitly aware that this probe was different from the attention probe that they had just seen on the previous screen). The judgment probe marked the end of the study phase.

Distractor task and final test. After the judgment probe, all participants completed a 5-minute distractor task in which they answered a series of questions that were unrelated to the lecture content (e.g., list as many world currencies, U.S. states, and U.S. presidents as you can recall). That task was followed by a final memory test that was self-paced and consisted of 32 multiple-choice questions (16 of which had been presented during the four tests in the pretest condition and 16 of which were never-before-seen questions). Participants in the pretest condition had been previously exposed to 16 of the 32 final-test questions, but participants in the control condition had not been exposed to any of the 32 final-test questions. The questions were presented one at a time in a random order determined anew for each participant.

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Once participants completed the final test, they were debriefed and dismissed.

Results and discussion.

Pretest performance. Mean performance on the pretests was 51% ($SD = 15\%$). When the pretested questions were re-presented on the final test, mean performance on them was 83% ($SD = 13\%$) in the pretest condition, an indication of significant learning improvements from watching the lecture, $t(51) = -19.25$, $p < .001$, $d = 2.67$.

Final test performance. Control and pretest condition performance on the pretested and new questions of the final test are listed in Table 1 and were analyzed using a 2 (condition: control vs. pretest) × 2 (test questions: pretested vs. new) mixed-design Analysis of Variance (ANOVA). This analysis involved participant-level mean data for all final test questions; however, as is evident upon inspection of Table 1, similar patterns were observed for final test questions from the different study phase segments. Overall test performance was found to be significantly higher in the pretest condition ($M = 79\%$, $SD = 15\%$) than in the control condition ($M = 72\%$, $SD = 15\%$), $F(1, 103) = 7.75$, $MSE = .04$, $p = .006$, $\eta_p^2 = .07$. Consistent with expectations, test performance was also found to be significantly higher on pretested questions ($M = 77\%$, $SD = 15\%$) than new questions ($M = 73\%$, $SD = 16\%$), $F(1, 103) = 8.10$, $MSE = .01$, $p = .005$, $\eta_p^2 = 07$.

In addition, a significant interaction between condition and test questions was observed, $F(1, 103) = 9.06$, $MSE = .01$, $p = .003$, $\eta_p^2 = .08$. Test performance was similar between pretested questions ($M = 72\%$, $SD = 14\%$) and new questions ($M = 72\%$, $SD = 16\%$) in the control condition, $t(52) = .11$, $p = .910$—an expected pattern of results given that the questions labeled as pretest items for participants in the control condition were that in name only. In fact, none of the questions appearing on the final test had been previously seen by the control participants. In contrast, for the pretest participants, only half of the questions appearing on the final test were new given their exposure to pretested questions during the study phase. Consistent with this difference, final-test performance was indeed greater on pretested questions ($M = 83\%$, $SD = 13\%$) than on new questions ($M = 75\%$, $SD = 17\%$) for participants in the pretest condition, $t(51) = 4.22$, $p < .001$, $d = 0.56$.

Finally, test performance on pretested questions was higher in the pretest condition than in the control condition, $t(103) = 4.31$, $p < .001$, $d = 0.82$. This observed pretesting effect replicates prior findings that show the same learning benefit in a variety of other content domains (e.g., Little & Bjork, 2016; Richland et al., 2009). The benefits of pretesting for learning of the lecture, however, appeared to be specific to the content that was previously pretested and did not transfer to new, yet related, content (cf. Carpenter & Toftness, 2017), a pattern demonstrated by the lack of a significant difference between the pretest and control conditions on new question performance, $t(103) = .88$, $p = .379$.

Mind wandering probes. The results from the mind wandering probes are listed in Table 2. To analyze whether interpolated pretests increased attention to the lecture content, we compared the reported attention averaged across the four probes between the control and pretest conditions. Across the four probes, participants in the pretest condition ($M = 67\%$, $SD = 18\%$) did report paying more attention during the lecture compared to participants in the control condition ($M = 59\%$, $SD = 23\%$), $t(103) = 1.99$, $p = .049$, $d = 0.39$.

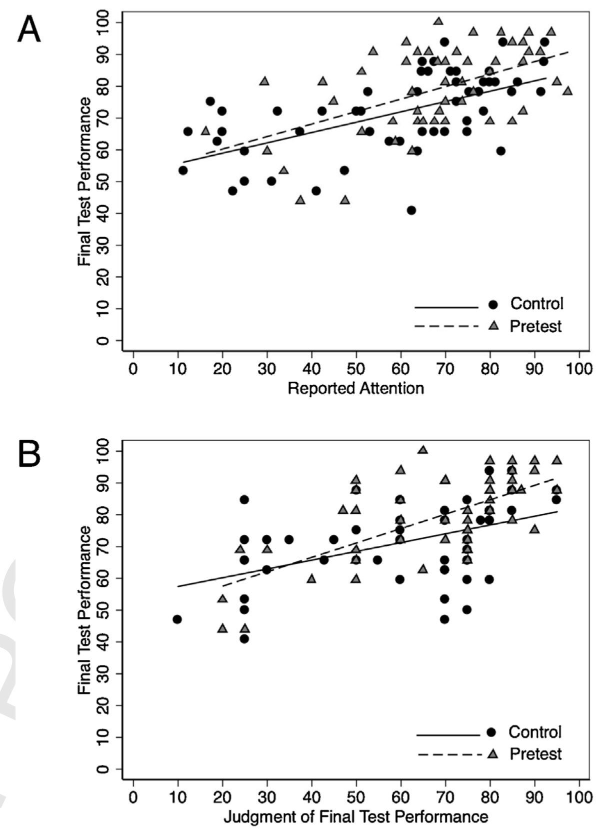

Figure 2. Relationship of final test performance with mind wandering (Panel A) and the judgment of final test performance (Panel B) in Experiment 1.

We conducted an additional analysis to examine the relationship between reported attention and final test performance across control and pretested conditions. As illustrated in Panel A of Figure 2, we observed a significant relationship between reported attention and test performance ($\beta = .51$), $t(101) = 4.95$, $p < .001$, but it did not interact with condition, as indicated by a non-significant interaction, $t(101) = .63$, $p = .528$. Together, these results suggest that although pretesting increased attention to the lecture content, it was not related to sustaining attention throughout the entire lecture, given that the slopes related to reported attention and test performance did not differ across the two conditions.

Finally, further inspection of the mind wandering probe data indicates that participants' attention to the lecture gradually waned across attention probes in both conditions, which is consistent with the finding that mind wandering can increase as time passes (e.g., Thomson, Seli, Besner, & Smilek, 2014), but not in all cases (e.g., Wammes, Boucher, Seli, Cheyne, & Smilek, 2016).

Judgment of final test performance. For the judgments of final test performance that were administered at the conclusion of the study phase, no significant difference between the pretest ($M = 67\%$, $SD = 20\%$) and control ($M = 62\%$, $SD = 22\%$)

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Table 1
Final test mean percent correct (SD).

Condition	Test Questions	Overall	Segment 1	Segment 2	Segment 3	Segment 4
Experiment 1						
Pretest	Pretested	83 (13)	97 (08)	91 (15)	71 (28)	73 (27)
	New	75 (17)	76 (23)	83 (21)	67 (27)	72 (24)
Control	Pretested	72 (14)	93 (12)	74 (20)	64 (26)	55 (27)
	New	72 (16)	73 (24)	87 (21)	57 (23)	71 (26)
Experiment 2						
Interpolated Pretest	Pretested	76 (19)	91 (18)	80 (22)	71 (31)	61 (30)
	New	73 (19)	71 (24)	80 (25)	72 (27)	68 (28)
Conventional Pretest	Pretested	81 (14)	92 (16)	87 (16)	70 (24)	77 (24)
	New	75 (18)	72 (24)	87 (23)	71 (29)	69 (26)
Control	Pretested	67 (19)	85 (23)	64 (29)	59 (28)	60 (25)
	New	61 (23)	60 (32)	73 (28)	56 (27)	62 (30)

Table 2
Mean reported percent attention (SD) during the online video lecture.

Condition	Overall	Segment 1	Segment 2	Segment 3	Segment 4
Experiment 1					
Pretest	67 (18)	73 (22)	73 (22)	63 (24)	59 (25)
Control	59 (23)	67 (21)	64 (22)	54 (24)	52 (25)
Experiment 2					
Interpolated Pretest	67 (21)	75 (18)	72 (22)	61 (27)	59 (29)
Conventional Pretest	71 (21)	80 (15)	77 (21)	66 (26)	60 (30)
Control	50 (25)	59 (26)	59 (27)	45 (28)	42 (27)

conditions was observed, $t(103) = 1.34$, $p = .182$. We conducted an additional analysis to examine the relationship between the judgment of test performance and actual test performance across control and pretested conditions, wherein we observed a significant overall relationship between predicted and actual performance ($\beta = .43$), $t(101) = 4.03$, $p < .001$, but no interaction with condition as indicated by a non-significant interaction, $t(101) = 1.71$, $p = .091$. These results, which are depicted in Panel B of Figure 2, suggest that the accuracy with which participants were able to predict how well they would score on the final test did not differ as a function of their assigned condition.

Experiment 2

Experiment 1 gave rise to two critical findings: Interpolated pretests reduce mind wandering and improve learning of pretested content. The goals of Experiment 2 were two-fold: first, to replicate and extend the results of Experiment 1 in a fully online learning context, and second, to investigate how the effectiveness of interpolated pretesting, as used in Experiment 1, would compare to that of a more common type of pretesting; namely, when all pretest questions are presented prior to the presentation of the to-be-learned material, which we refer to as *conventional pretesting*. It was also thought that being able to make this comparison would help us more fully evaluate factors contributing to the benefits of interpolated pretesting as observed in Experiment 1. More specifically, were the benefits observed in Experiment 1—that is, reduced mind wandering and improved learning—primarily due to (a) the presence of pretest questions at multiple points throughout the lecture and (b) the close proximity between those questions and relevant lecture content? We surmised that both factors would be more effective due to their acting, in essence, as repeated interventions during the lecture rather than a single intervention prior to it.

Method

Experiment 2 was preregistered at: https://aspredicted.org/wv36s.pdf.

Participants. Experiment 2, which was conducted entirely online, involved participants recruited from a large university in eastern Canada in exchange for partial course credit. Similar to the prior experiment, the participants were undergraduate psychology students. All participants gave informed consent and the experiment was approved by the Institutional Review Board (IRB) of the university. A power analysis using the G*Power program indicated that a sample of 102 participants would be needed to detect small to medium-sized effects ($f = 0.20$) using a 3 × 2 mixed factorial design with alpha at 0.05 and power of 0.95. We again recruited in excess of that amount; data from 143 participants (*control* condition, $n = 47$; *interpolated pretest* condition, $n = 47$; *conventional pretest* condition, $n = 49$) were ultimately included in the analyses.

Design. All participants were randomly assigned to one of three conditions: control, interpolated pretest, and conventional pretest. As illustrated in Figure 3, for the control and interpolated

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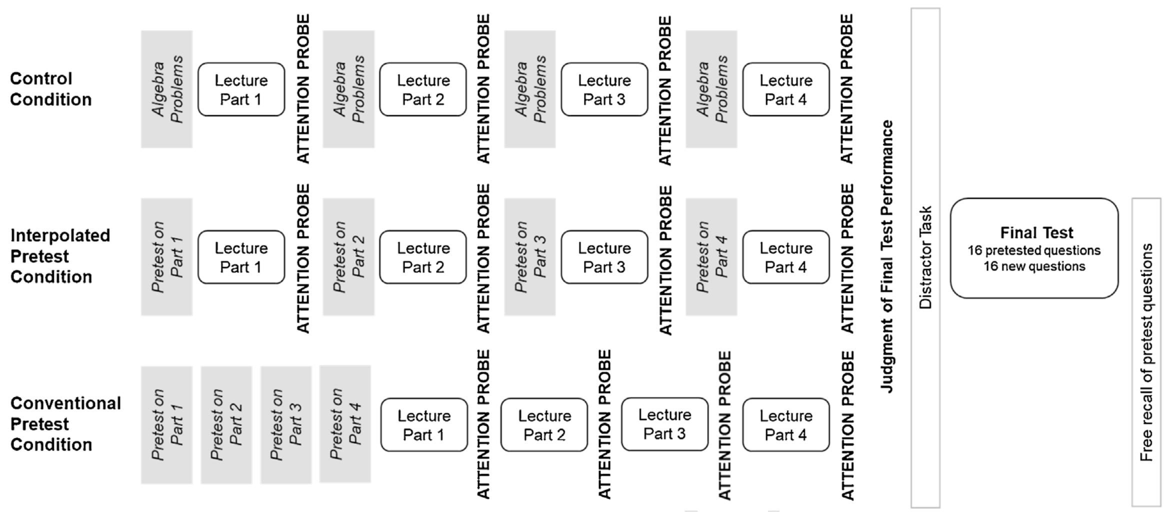

Figure 3. Design and Procedure of Experiment 2. The control and interpolated pretest conditions were identical to those of Experiment 1. The conventional pretest condition differed from the interpolated pretest condition in one design aspect: All four pretests were presented at the very beginning instead of being interpolated throughout the lecture. Additionally, at the end of Experiment 2, participants in either of the two types of pretest conditions were asked to recall as many of the pretest questions as they could. All other aspects of Experiment 2 were identical to those of Experiment 1.

pretest conditions, respectively, the presentation of each of the four parts of each lecture was preceded by an activity involving solving algebra problems or by taking a 4-minute pretest about the content of the to-be-presented lecture segment. In the conventional pretesting condition, however, participants were given all four pretests prior to presentation of any of the four lecture presentations, which were then shown successively and only separated by the presentation of an attention probe. The final test was identical to that of Experiment 1. As such, Experiment 2 employed a 3 (condition: control vs. interpolated pretest vs. conventional pretest; between-subjects) × 2 (test questions: pretested vs. new) mixed factorial design.

Materials and procedure. The materials and procedure were the same as those of Experiment 1 except for the following changes. All participants completed the experiment online, using their own personal laptops or computers, and from any location that provided a stable Internet connection. A conventional pretest condition was added wherein all four pretests appeared prior to presentation of the lecture. These pretests were presented in the same order as they appeared in the interpolated pretest condition (i.e., consecutively ordered in accordance with the lecture parts that followed). Furthermore, after the final test, participants in both pretest conditions were probed for their memory of the pretest questions. The probe consisted of the following question: "*You were given a set of questions to answer before you watched the videos. These are what we call PRETESTS. Please recall as many of the PRETEST questions as you can.*" This probe was included to explore potential differences between the two pretesting conditions (we hypothesized that the differential placement of the pretest questions might affect the recallability of those questions). After participants finished answering that question, they were debriefed and the experiment concluded.

Results and Discussion

Pretest performance. Overall, participants in the interpolated pretest condition performed significantly better on the pretests ($M = 48\%$, $SD = 15\%$) than participants in the conventional pretest condition ($M = 38\%$, $SD = 13\%$), $t(94) = 3.52$, $p = .001$, $d = 0.71$. Further inspection of the pretest data reveals that this disparity was not apparent on the first pretest ($M = 45\%$, $SD = 27\%$ and $M = 42\%$, $SD = 26\%$, in the interpolated and conventional pretest conditions, respectively) but rather manifested across subsequent pretests (the conventional pretest condition declined to $M = 28\%$, $SD = 21\%$ on the final pretest, whereas no such decline was observed in the interpolated pretest condition). Possible reasons for the decreased performance in the conventional pretest condition include the need to answer progressively more challenging pretest questions without the benefit of viewing any portion of the video lecture, as well as reduced motivation or effort that may have occurred over an extended set of pretest questions. Crucially, both the interpolated ($M = 76\%$, $SD = 19\%$) and the conventional ($M = 81\%$, $SD = 14\%$) pretest conditions demonstrated significant learning improvements between the pretest and final test as measured by performance on the matching final test questions, $t(46) = -10.74$, $p < .001$, $d = 1.58$, and $t(48) = -17.59$, $p < .001$, $d = 2.47$, respectively.

Final test performance. We conducted a 3 (condition: control vs. interpolated pretest vs. conventional pretest; between-subjects) × 2 (test questions: pretested vs. new) mixed-design ANOVA to examine final test performance on pretested and new questions across the three different conditions. As with the prior experiment, this analysis involved participant-level mean data for the entire final test (see Table 1); the same overall patterns were observed across segments for all conditions. A significant main effect of condition was observed, F(2,

140) = 7.54, $p < .001$, $\eta_p^2 = .10$, suggesting that test performance was significantly lower in the control condition (M = 65%, SD = 19%) than in the interpolated pretest condition (M = 74%, SD = 17%), t(92) = −2.47, p = .015, d = 0.50, and the conventional pretest condition (M = 78%, SD = 15%), t(94) = −3.79, $p < .001$, d = 0.76. These findings thus replicate the results from Experiment 1 and from other studies demonstrating a pretesting effect. Contrary to our expectations, however, there was no significant difference in overall test performance between the two pretest conditions, t(94) = 1.22, p = .227, which suggests that both forms of pretesting, either interpolated throughout the lecture or one in which all pretest questions occur before the entire lecture is presented, were comparable in their effectiveness at enhancing learning compared to not providing any pretests at all. As expected, test performance was higher on pretested questions (M = 75%, SD = 18%) than on new questions (M = 70%, SD = 20%), as indicated by a significant main effect of test questions, F (1, 140) = 13.30, $p < .001$, $\eta_p^2 = .09$.

The interaction between condition and test questions, however, was not significant, F (2, 140) = .67, p = .513. As reflected by the two main effects, test performance on pretested questions was significantly lower in the control condition (M = 67%, SD = 19%) compared to the interpolated pretest condition (M = 76%, SD = 19%), t(92) = −2.19, p = .031, d = 0.47, and the conventional pretest condition (M = 81%, SD = 14%), t(94) = −4.21, $p < .001$, d = 0.84, but similar between the two pretest conditions, t(94) = 1.70, p = .092. Similar patterns were observed for test performance on new questions, such that performance was significantly lower in the control condition (M = 63%, SD = 22%) compared to the interpolated pretest condition (M = 73%, SD = 19%), t(92) = -2.34, p = .022, d = 0.49, and the conventional pretest condition (M = 75%, SD = 18%), t(94) = -2.91, p = .005, d = 0.60, but similar between the two pretest conditions, t(94) = .56, p = .577.

We also investigated any differences in final test performance between pretested and new questions for each of the three conditions. Final test performance was significantly higher on pretested questions than on new questions in the conventional pretest condition, t(48) = 3.22, p = .002, d = 0.43, but not in the control condition, t(46) = 1.99, p = .052, or in the interpolated pretest condition, t(46) = 1.26, p = .214. Together, these results suggest that the benefits of pretesting for memory, at least in an online context with minimal supervision, are not always specific to final test questions that are identical to those that were used during prior pretesting.

Mind wandering probes. The results from the mind wandering probes are depicted in Table 2. A between-subjects ANOVA on the mind wandering probe data from across the three conditions yielded a significant effect of condition, F(2, 140) = 11.12, $p < .001$, $\eta_p^2 = .14$. Pairwise comparisons revealed that reported attention was significantly lower in the control condition (M = 50%, SD = 25%), versus the interpolated pretest condition (M = 67%, SD = 21%), t(92) = -3.44, p = .001, d = 0.74, and the conventional pretest condition (M = 71%, SD = 21%), t(94) = -4.32, $p < .001$, d = 0.91. These results indicate that incorporating pretests into situations involving video lectures can

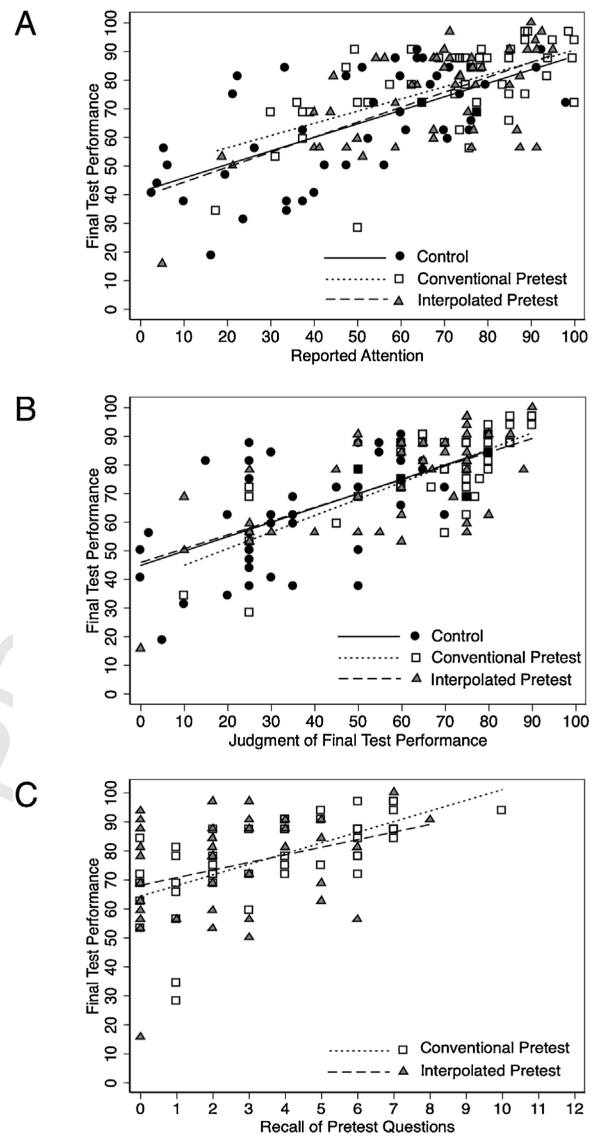

Figure 4. Relationship of final test performance with mind wandering (Panel A), the judgment of final test performance (Panel B), and free recall of pretest questions (Panel C) in Experiment 2.

increase focused attention. However, contrary to expectation, reported attention did not significantly differ across the two pretest conditions, t(94) = .94, p = .348. Furthermore, as illustrated in Panel A of Figure 4 and similar to the results obtained in Experiment 1, we observed a significant relationship between reported attention and test performance (β = .64), t(137) = 6.09, $p < .001$, but it did not interact with the different conditions, as indicated by non-significant tests for interactions ($p > .05$).

Judgment of final test performance. The analysis of judgments of final test performance (which is missing data from two participants owing to their not providing a response) revealed a significant effect of condition, F(2, 138) = 21.27, $p < .001$, $\eta_p^2 = .24$. Pairwise comparisons revealed that participants' predicted test scores were significantly lower in the control condition (M = 40%, SD = 22%), as compared to the interpolated pretest condition (M = 59%, SD = 22%), t(91) = -4.21, $p < .001$, d = 0.86, and the conventional pretest condition

($M = 68\%$, $SD = 19\%$), $t(93) = -6.52$, $p < .001$, $d = 1.36$. Predicted scores, however, did not differ across the two pretest conditions, $t(92) = 1.94$, $p = .056$. Furthermore, as illustrated in Panel B of Figure 4, a significant relationship was observed between predicted test performance and actual test performance ($\beta = .68$), $t(135) = 5.82$, $p < .001$, but this was a general pattern that did not interact with the different conditions ($p > .05$). Overall, these results suggest that participants' ability to predict how well they would score on the final test did not differ with respect to their assigned condition.

Free recall of pretest questions. Participants' free recall of pretest questions, which occurred after the final test, was scored by the first and third authors by counting the number of pretest questions that a given participant recalled. A high interrater reliability was obtained (Cronbach's $\alpha = .938$) and all discrepancies were discussed and addressed. Participants in the conventional pretest condition ($M = 3.71$, $SD = 2.59$) recalled significantly more pretest questions compared to those in the interpolated pretest condition ($M = 2.28$, $SD = 2.13$), $t(94) = 2.95$, $p = .004$, $d = 0.60$. This finding is intriguing because performance on the final test was similar between the two pretest conditions, although conventional pretesting did result in numerically higher performance than interpolated pretesting ($M = 81\%$ vs. 76%). Further, better recall of pretest questions was observed in the conventional pretest condition despite a longer time interval from pretesting to free recall of the questions than in the interpolated pretest condition. Finally, as indicated in Panel C of Figure 4, a significant relationship between pretest questions recalled and final test performance was observed ($\beta = .57$), $t(92) = 4.70$, $p < .001$, but this was a general pattern that did not interact with the different conditions ($p > .05$). Overall, the pattern of results obtained suggests that recall of pretest questions was equally predictive of final test performance across both pretest conditions.

Mediation Analyses

In both experiments we observed indications of a relationship between pretesting, reported attention, and final test performance. Moreover, reported attention and final test performance were positively correlated. To further examine whether reported attention mediated the link between pretesting and final test performance, we performed a mediation analysis for each experiment. This analysis used the PROCESS macro for SPSS (International Business Machines Corp.) developed by Hayes (2015) to test for indirect effects by calculating confidence intervals (CI) with 5,000 bootstraps. Results for Experiments 1 and 2 are depicted in Panels A and B of Figure 5, respectively. The mediation analysis for Experiment 1 indicated that the total effect of pretesting on final test performance ($\beta = .07$; $p = .006$) was smaller upon inclusion of the mediator (reported attention) and the direct effect was not significant ($\beta = .04$; $p = .051$), whereas the indirect effect was significant, $\beta = .03$; 95% CI = [.00; .06]. The mediation analysis for Experiment 2 indicated that the total effect of pretesting on final test performance ($\beta = .11$; $p < .001$) was smaller upon inclusion of the mediator (reported attention) and the direct effect was not significant ($\beta = .02$; $p = .343$), whereas the indirect effect was significant, $\beta = .09$; 95% CI = [.04; .13]. Thus, both analyses suggest that reported attention mediated the associations between pretesting and final test performance. In other words, pretesting improved attention, which in turn improved learning from the video lecture.

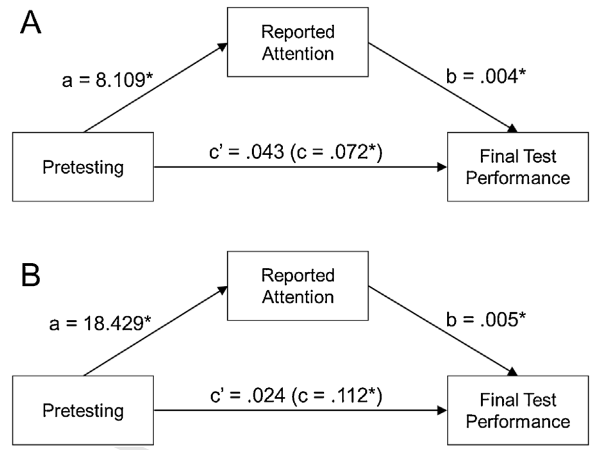

Figure 5. Relationships between pretesting, reported attention and final test performance as indicated by mediation analyses of Experiment 1 (Panel A) and Experiment 2 (Panel B). The paths with a's and b's are direct, c is the total effect from pretesting to final test performance, and c' is the direct path from pretesting to final test performance, controlling for reported attention. *$p < .05$.

General Discussion

In both experiments, pretesting reduced mind wandering and improved learning during video lectures as compared to the learning of lecture material when no pretests were given. That pattern was evident when participants viewed the lectures in a controlled laboratory environment (Experiment 1) and when they viewed the lectures in remote, less-controlled environments (Experiment 2). Exemplifying the feasibility of integrating pretesting into online learning, participants completed each experiment entirely via Internet browsers, without the benefit of interacting with an instructor, and without close supervision. These characteristics are common to many forms of online education. Although reported attention did gradually wane in both the pretest and control conditions as the lecture progressed, which is consistent with commonly observed patterns in some prior studies of mind wandering during lectures (e.g., Bunce et al., 2010; Thomson et al., 2014; cf. Wammes et al., 2016), participants in the pretest conditions reported greater average levels of attention at all measured time points (8–21% higher than the control condition when averaged across the entire lecture). That improved level of attention translated into better final test performance: Participants that had taken pretests exhibited an average final test score improvement of 11% for pretested questions in Experiment 1 and up to 14% for pretested and new questions in Experiment 2. Overall, these results indicate that pretesting is a viable way to help learners stay focused on, and hence learn more from, video lectures.

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Revisiting and Expanding Upon the Benefits of Pretesting

The finding that pretesting reduces mind wandering is consistent with theoretical accounts suggesting that pretesting modifies the cognitive processes that are engaged during subsequent study opportunities (i.e., test-potentiated learning). Increased attention to lecture content could conceivably be facilitated by a search to "fill in" knowledge gaps (Carpenter & Toftness, 2017), increases in curiosity (Geller et al., 2017), improved motivation to learn (Szpunar et al., 2013a, 2013b), or any combination of these factors, although the present study was not designed to adjudicate between those accounts. Perhaps relatedly, some researchers have theorized that mind wandering is less frequent when learners are engaged in cognitively demanding tasks that require considerable mental resources (e.g., Smallwood, 2010; Smallwood & Schooler, 2006; Metcalfe & Xu, 2016), and it would seem that searching for the answers to pretest questions in a lecture video, or simply paying greater attention to previously pretested content, would be more cognitively demanding and more resource-intensive than viewing that video without objectives in mind. Such processes are potentially even more cognitively demanding when learners do not have control over the pace of the video (Carpenter & Toftness, 2017), as was the case in the present experiments.

The fact that both interpolated and conventional pretesting yielded similar benefits in the present experiments suggests that the method of pretesting may not always be critical for achieving beneficial outcomes. That is, having pretest questions appear at multiple points during a lecture, with each set of pretest questions immediately preceding the relevant portion of that lecture, is not always required; in fact, administering all of the pretest questions prior to the lecture was, in numerical terms, slightly more effective at reducing mind wandering and enhancing learning (although it remains to be determined if the same results would hold for longer lectures, when the order of pretest questions differs from the order of lecture content, and for different levels of pretest performance). Overall, it appears that the critical factor for the mind wandering benefits of pretesting is simply the fact that all pretest questions, regardless of their placement relative to a lecture, target information that learners have yet to encounter (nor do learners typically know exactly where in the lecture that information will be presented), and as such may spur a search for the correct answers (Carpenter & Toftness, 2017; St. Hilaire & Carpenter, 2020) or simply increase attention to relevant lecture content.

Self-reported rates of mind wandering were predictive of final test performance in both experiments, but that relationship did not differ across the pretest and control conditions (for similar findings, see Szpunar et al., 2013a; cf. Jing et al., 2016, Experiment 1). Pretesting also did not decelerate the occurrence of mind wandering across the lecture relative to the control condition, with similar and gradual increases observable in all conditions. Thus, although pretesting did not influence the degree to which mind wandering affects learning, nor reduce its upward trend over time, it did reduce the overall rate of mind wandering and consequently enhance learning. That conclusion is strengthened by the results of mediation analyses, which provide evidence for pretesting having an indirect effect—that is, mediated by reported attention—on learning in both experiments. Similarly, judgments of final test performance were predictive of the final test results in all conditions, but those judgments were not more accurate following pretesting. Thus, unlike interpolated testing (Szpunar et al., 2014), pretesting did not enhance metacognitive calibration, and possibly because pretests do not provide as much diagnostic information for the learning that is to follow. Additionally, free recall of pretest questions in the interpolated and conventional conditions was equally predictive of final test performance in Experiment 2 despite greater levels of recall in the latter (although the rate of successful recall in both conditions was relatively low, at less than 25%). That result is broadly consistent with the finding that memory for pretest questions is predictive of the pretesting effect (St. Hilaire & Carpenter, 2020).

Finally, in both experiments we observed a traditional pretesting effect for memory of lecture content, but it manifested differently across experiments. In Experiment 1, the pretesting effect was specific to pretested questions that were identical to those used earlier in the experiment. That finding is consistent with the recent pretesting literature, in which the pretesting effect has repeatedly been shown to exhibit specificity of learning (e.g., Carpenter et al., 2018; Hausman & Rhodes, 2018; James & Storm, 2019; Richland et al., 2009; Toftness et al., 2018). In contrast, we observed positive transfer in Experiment 2, with pretesting improving performance for both pretested and new questions (which is a relative rarity in the pretesting literature; e.g., Carpenter & Toftness, 2017; Pan et al., 2019; St. Hilaire, Carpenter, & Jennings, 2019). Given that the same materials and similar training paradigms were employed in both experiments, the source of the positive transfer in Experiment 2 remains to be determined and could be explored in future research (along with other types of transfer such as to conceptual and higher-order questions). Overall, the present results affirm that the most reliable benefit of pretesting is improved memory for, and likely better attention to, pretested information.

Future Directions

Follow-up investigations could further explore the extent to which pretesting reduces mind wandering and enhances learning from video-recorded, live, and other types of lectures (e.g., lectures with on-screen narrators, which can be more engaging; Guo et al., 2014). Following Jing et al. (2016) and Toftness et al. (2018), it will be important to determine whether the benefits observed in the present experiments generalize to longer lecture videos, to different content domains, and to wholly online courses wherein students are accustomed to web-based lectures and testing activities. Other measures of mind wandering, such as randomly-inserted probes that ask participants to categorize the proportion of task-related and task-unrelated thoughts (e.g., Jing et al., 2016), may also provide further insights into how pretesting influences attention during lectures and allow testing of the hypothesis that attention is greatest for previously pretested content. Further, such probes could avoid potential limitations of the global mind wandering probes used in the present

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experiments (i.e., across entire lecture parts), which include reliance on participants' memories over extended periods of time, the inability to measure attention at smaller timescales, and potential biasing effects of experimental manipulations on the accuracy of such probes.

From the perspective of the pretesting literature, different implementations of pretesting (such as multiple-choice pretests with competitive answer alternatives that trigger productive learning processes; e.g., Little & Bjork, 2016) could be used to explore the specificity or generalizability of the pretesting effect for lecture videos. The role of pretest performance, which has been addressed inconsistently in the literature (e.g., analyses of correctly versus incorrectly answered pretested items), could be investigated further and potentially with respect to interpolated versus conventional pretesting. Finally, the relative efficacy of pretesting versus other reference conditions (i.e., a control condition that is more competitive with pretesting, such as studying) and other testing techniques (e.g., retrieval practice) could be informative directions for future research (Pan and Sana, 2020).

Practical Implications

The present research provides compelling evidence that pretesting can be an effective technique to ameliorate the negative effects of mind wandering on learning during video-recorded online lectures. Accordingly, instructors and educators seeking to improve students' attention to lecture content should consider implementing pretest questions either before or during lectures. Such pretesting should be fairly easy to administer—simply add practice questions before showing all or part of the lecture. That pretesting is likely to have dual benefits: Students will pay greater attention to the lectures and learn more from them. Overall, these results reinforce the status of pretesting as an emerging "desirable difficulty" (Bjork, 1994; Pan & Bjork, in press)—that is, a technique that commonly makes learning more challenging, at least initially, but improves it over the long term. In the case of pretesting during lectures, the extra effort that is needed to answer pretest questions ultimately yields more focused attention and enhances learning of lecture content.

Author Contributions

S.C.P., F.S., and A.G.S. conceived and designed the experiments; F.S. programmed the experiments with assistance from S.C.P. and A.G.S.; A.G.S. performed the experiments; and F.S. analyzed and interpreted the data. S.C.P. and F.S. wrote the manuscript with assistance from A.G.S and E.L.B. All authors approved the manuscript for submission.

Conflict of interest

The authors declare that they have no conflict of interest.

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