AMERICAN PSYCHOLOGICAL ASSOCIATION

Journal of Experimental Psychology: Applied

ISSN: 1076-898X

2023, Vol. 29, No. 1, 124–135
https://doi.org/10.1037/xap0000375

Take Notes, Not Photos: Mind-Wandering Mediates the Impact of Note-Taking Strategies on Video-Recorded Lecture Learning Performance

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In two experiments ($N = 200$), we compared the effects of longhand note-taking, photographing lecture materials with a smartphone camera, and not taking any notes on video-recorded lecture learning. Experiment 1 revealed a longhand-superiority effect: Longhand note-takers outperformed photo-takers and control learners on a recall test, notwithstanding an equal opportunity to review their learning material right before being tested, and even when photo-takers and control participants reviewed an exact transcript of the lecture slides via their photos or printouts, whereas longhand note-takers accessed only a fraction of the content as captured in their handwritten notes. Photo-takers performed comparably to learners who had not taken any notes at all. Experiment 2 further showed that mind-wandering mediates the mnemonic benefits of longhand note-taking: Relative to learners who took photos or did not take any notes, longhand note-takers mind-wandered less and, in turn, demonstrated superior retention of the lecture content. Yet, across both experiments, learners were not cognizant of the advantages of longhand note-taking, but misjudged all three techniques to be equally effective. These findings point to key attentional differences between longhand note-taking and photo-taking that impact learning—knowledge that is easily and conveniently acquired in a snap may not be better remembered.

Public Significance Statement

Using one's smartphone to take photos enables students to conveniently capture more information, but may not enhance learning. Despite reviewing their photos of a video-recorded lecture right before being tested, photo-takers performed worse than learners who wrote and reviewed longhand notes, while faring no better than learners who did not take notes but simply reviewed lecture printouts. The longhand advantage occurred because it encouraged less mind-wandering than photo-taking or no-note-taking.

Keywords: note-taking, photo-taking, encoding, external storage, photo-taking impairment effect

Supplemental materials: https://doi.org/10.1037/xap0000375.supp

Today, whipping out one's smartphone to snap photos of information has become a ubiquitous phenomenon. Of note, smartphone ownership and usage are increasingly prevalent among youth. For instance, among Americans between the ages of 18 and 29, 96% now own a smartphone (Pew Research Center, 2019). With the advancement of technology, students are now equipped with more sophisticated means of note-taking beyond traditional longhand. This growing trend raises pertinent questions about how such newer note-taking methods fare against more traditional ones in regard to students' learning and performance.

Whereas present studies have focused predominantly on the effects of taking notes via writing versus typing on computers (e.g., Luo et al., 2018; Mueller & Oppenheimer, 2014; for a review, see Jansen et al., 2017), surprisingly little research has investigated the learning consequences of using one's smartphone to take photos of lecture materials. To date, the vast majority of research on photo-taking and memory has been done in the context of museum or gallery tours when participants take photos of objects and experiences (e.g., Barasch et al., 2017; Henkel, 2014; Soares & Storm, 2018), but not in lecture or educational settings. Moreover, although the effects of smartphone usage on academic performance have been heavily investigated, extant studies have often focused on students' use of such devices for media multitasking (for reviews, see Chen & Yan, 2016; May & Elder, 2018) and purposes that are lecture-unrelated (e.g., Wammes et al., 2019). In contrast, using one's smartphone to take photos of lecture materials is an act that is directly relevant to the learning task at hand, and has even been considered a useful function of smartphones that renders them convenient educational aids (Anshari et al., 2017).

Our central question relates to the extent that learners benefit from taking photos of lecture materials, as opposed to taking notes by

This article was published Online First June 24, 2021.
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This research was supported in part by two National University of Singapore Educational Research grants awarded to Sarah Shi Hui Wong and Stephen Wee Hun Lim, respectively.

The authors thank Nicholas Seng Yew Lim and Anyu Wang for their assistance with data collection and scoring. The data that support the findings of this study are available from the authors upon request.
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hand. The scarcity of research on the effects of photo-taking in learning contexts provides an impetus to fill this lacuna, particularly in light of the educational implications at stake. In the following sections, we outline current literature on longhand note-taking and photo-taking, and discuss potential theoretical mechanisms underlying their consequences for learning.

Note-Taking: To Write or Photograph?

Two accounts have been proposed for the learning benefits of note-taking: the *external storage function* and *encoding function* of note-taking (Di Vesta & Gray, 1972; Kiewra, 1989; for a meta-analysis, see Kobayashi, 2006). According to the external storage hypothesis, notes can serve as a helpful resource or record for learners' later study and reference. Indeed, reviewing notes is a study technique that students frequently use when preparing for exams (Blasiman et al., 2017; Gurung, 2005), and is their predominant motivation for note-taking (Morehead, Dunlosky, Rawson, Blasiman, & Hollis, 2019; see also Hartley & Davies, 1978). Whereas the slower and more cumbersome process of longhand inherently limits students in capturing only a fraction of the lecture content, photo-taking enables students to easily capture virtually all visually presented information. If learners' subsequent test performance is predicted by the sheer quantity of externally stored content that is available to them during review (e.g., Fisher & Harris, 1973; Peverly & Sumowski, 2012), then one might expect photo-taking to be more useful than longhand note-taking.

However, the benefits of note-taking for learning also derive from its encoding effect—during note-taking, students engage in deeper processing when comprehending the lecture material, identifying key points, linking the material to their prior knowledge, paraphrasing or summarizing, and transforming the content to written form (Jansen et al., 2017). Thus, even without a review opportunity, the act of note-taking itself may aid learners' recall of the material (Di Vesta & Gray, 1972; Kiewra, 1985). Some evidence for this account has been offered in a widely cited study by Mueller and Oppenheimer (2014), which found that learners who took longhand notes while watching Technology, Entertainment, Design (TED) Talk lectures subsequently performed better on a conceptual application test without review, relative to their peers who had typed their notes on laptops (cf., Morehead, Dunlosky, & Rawson, 2019; Urry et al., 2021). This longhand-superiority effect was striking because it occurred even when learners' handwritten notes consistently contained significantly fewer words than their typed notes, in line with the observation that students often write slower than they type (Brown, 1988). Presumably, the slower process of longhand note-taking encourages deeper encoding when learners are compelled to selectively and meaningfully reframe the material in their own words, whereas learners who use laptops for note-taking tend to transcribe the lectures verbatim and thus engage in shallower processing (Luo et al., 2018; Mueller & Oppenheimer, 2014). Moreover, the superiority of longhand note-taking over typing persisted even when learners were given an opportunity to review their notes after a week's delay before being tested. This suggests that the deeper encoding associated with longhand note-taking may, in some situations, offset any benefits of gaining access to more content per se during review.

Mind-Wandering

Attentional processes may be a key mechanism that determines the consequences of note-taking versus photo-taking for memory. Specifically, learners may be less likely to mind-wander when studying a lecture via longhand note-taking than photo-taking, thereby boosting their test performance. Mind-wandering involves a shift in executive control away from a primary task to task-irrelevant goals (McMillan et al., 2013; Smallwood & Schooler, 2006). Although mind-wandering is a pervasive phenomenon (Killingsworth & Gilbert, 2010) and successful learning often hinges on learners' ability to maintain executive control, mind-wandering has, only until recently, been regarded as an "under-recognized" influence in educational settings (Smallwood et al., 2007).

With the exception of some learning outcomes such as creativity (Baird et al., 2012), substantive research has shown that mind-wandering during lectures is often negatively associated with learning performance (e.g., Lindquist & McLean, 2011; Risko et al., 2012; Wammes et al., 2016; for a meta-analysis, see Randall et al., 2014). When learners mind-wander, their attention is decoupled from the task at hand, producing a breakdown in their ability to attend to and successfully integrate information from the external environment with their own internal representations (Smallwood et al., 2007). Consequently, the encoding of information is impaired and learning suffers.

Crucially, photo-taking may lead to mind-wandering and attentional disengagement. Photo-taking has been found to produce poorer memory of the photographed objects than simply observing them—the *photo-taking impairment effect* (Henkel, 2014), unless participants pay additional attention to the object by zooming in onto a specific part of it when taking photos. In a study by Henkel (2014), participants were led on a museum tour, and were asked to photograph some objects (either as a whole or by zooming in on a specific part of the object) and to observe other objects without taking a photo. When later tested on their memory of the objects, participants demonstrated significantly poorer recognition accuracy for photographed than observed objects. Of note, this impairment extended to objects that had been photographed as a whole, but not those that had been zoomed in on. Moreover, for the latter objects, there was no difference in participants' memory for features on which were versus were not zoomed in, suggesting that the mnemonic benefit stemmed from additional attentional processes through the focused activity of zooming in on the object, rather than from paying additional visual attention only to the features being zoomed in on. That is, the photo-taking impairment effect may occur because participants often fail to fully attend to objects that they photograph—when their attentional focus is drawn more acutely to the object, the photo-taking impairment effect dissipates.

Further support for this attentional account has been shored up by Soares and Storm's (2018) finding that the photo-taking impairment effect persists even when participants are given additional unimpeded time to view the objects after photographing them. Thus, participants' subsequent poorer memory for those objects cannot be simply attributed to reduced encoding time while using the camera (e.g., time spent angling the shot, focusing the camera lens, etc.). Furthermore, the impairment manifested even when participants did not expect to have subsequent access to their photos, either because they had used the ephemeral photo application Snapchat or manually deleted their photos immediately after taking them. Hence, the negative effects of photo-taking for memory cannot be fully explained by cognitive offloading in which participants rely on their camera's "prosthetic memory" instead of their own organic memories, such that the offloaded information is less likely to be recalled in the future (e.g., Sparrow et al., 2011; for a review, see Risko & Gilbert, 2016). Rather, these results are consistent with the account that taking photos causes one's attention to be limited or disengaged when encoding an object or experience, thus impairing memory for it. In addition, this attentional disengagement persists even after taking a photo, whereby participants continue to encode the photographed objects more poorly than if they had simply observed them (Soares & Storm, 2018).

Taken together, the extant findings suggest that: In the absence of additional measures that strongly direct attention to particular aspects of the object or experience—either through explicit instructions to zoom in (Henkel, 2014) or by having participants take photos volitionally and thus intentionally select some items to capture (Barasch et al., 2017)—photo-taking may, by default, encourage mind-wandering whereby attention drifts away from the task at hand. Surprisingly, however, the potential mediating role of mind-wandering in the effects of photo-taking on memory has yet to be directly interrogated in current research.

In contrast, longhand note-taking may enable learners to focus and maintain their attention more effectively. For instance, subjective reports of note-taking have been associated with reduced task-unrelated thoughts in an ecologically valid lecture environment (Lindquist & McLean, 2011). This relationship has also been extended to actual note-taking behaviors in experimental settings. In a study by Kane et al. (2017), learners watched a video lecture on introductory statistics either while taking longhand notes or not, and were further probed on their thought content at random points during the lecture before they were tested on the material. The authors found that mind-wandering, as assessed via the frequency of learners' self-reported task-unrelated thoughts, negatively predicted test performance. Crucially, note-taking reduced mind-wandering, particularly for learners who had low prior knowledge of the lecture content. This suggests that note-taking may be a study technique that enables learners with less background knowledge to sustain their attention during lectures. Accordingly, we hypothesized that mind-wandering is a key mechanism through which note-taking and photo-taking affect learning, and directly tested this prediction in the present research.

The Present Study

We conducted two experiments that compared the effects of three learning methods on students' recall performance: *longhand note-taking* versus *photo-taking* versus *control* (no note-taking). The learning material comprised of lectures that were presented via a Microsoft PowerPoint slideshow with audio narration, similar to how lectures are commonly delivered in educational contexts. To control for cognitive offloading when learners rely on external stores of information to reduce cognitive demand (Risko & Gilbert, 2016), all learners were similarly informed of and provided with a review opportunity after studying, during which they were given physical access to the lecture information—note-taking participants reviewed their own longhand notes, photo-taking participants reviewed their photos, and control participants received verbatim printouts of the lecture slides (e.g., Fisher & Harris, 1973).

In Experiment 1, we tested and found support for the hypothesis that longhand note-taking produces superior memory than both photo-taking and a no-note-taking control. Experiment 2 aimed to replicate and extend this finding in two ways: (a) expanding the range of lecture topics for greater generalizability and (b) directly probing the role of mind-wandering in mediating the relationship between learning method and recall performance. Across both experiments, we further investigated the extent that learners were able to accurately predict which learning methods worked best for them. Extant research has suggested that learners tend to be unaware of how they learn and remember knowledge, thereby compromising their own learning (e.g., Bjork et al., 2013). From an applied standpoint, illuminating such a problem, if any, is vital for enhancing real-world educational processes and outcomes.

Experiment 1

Method

Participants

The participants were 105 students (74 were female) between the ages of 18 and 32 ($M = 21.06$, $SD = 2.37$) from the National University of Singapore. In both experiments reported here, the target sample size was determined based on the estimated note-taking effect size of $d = 0.77$ reported in Kobayashi's (2006) meta-analysis for the comparison between note-taking-with-reviewing over note-reviewing-only (i.e., no-note-taking) based on 34 independent samples from 18 studies. A power analysis (G*Power; Faul et al., 2007) indicated that at least 28 participants per condition would afford 80% power to detect a between-subjects note-taking effect in the present study using an alpha (α) of .05. Outcomes reported below are based on data from 100 participants; five participants who failed to conform to the studying instructions during the experiment were excluded from analyses. In both experiments, participants received either course credit or monetary reimbursement for their participation. This research was conducted with the appropriate ethics-review-board approval by the National University of Singapore, and all participants provided their written informed consent.

Design

The primary between-subjects factor of interest was learning method, whereby participants were randomly assigned to either the *control*, *photo-taking*, or *note-taking* condition. We also included lecture topic ("bats" vs. "bread") as a second within-subjects factor for control purposes to ensure that effects, if any, generalized across educational content. The dependent variable was participants' retention of the lecture material, as assessed via the number of idea units that they correctly recalled on a test.

Materials

Lecture Materials. We created two 9-min lectures corresponding to two prose passages adapted from Butler (2010) on "bats" (1,074 words) versus "bread" (1,093 words), respectively. The prose passages are available in the Supplemental Materials. Both lectures were presented via Microsoft PowerPoint, and comprised of 10 slides each. The lecture slides were designed to closely resemble those typically used in educational contexts, with each slide formatted to include a heading and information about the topic presented in point form. In addition, an audio file containing verbal narration of the presented content was embedded in each lecture slide. The narrated content overlapped closely with the information presented visually on the slides—this procedure ensured that participants in the photo-taking and control conditions would not be unfairly disadvantaged during the review opportunity because their photos and verbatim printouts of the lecture slides would necessarily contain only the onscreen information. Similar to how lectures are often delivered, each slide contained three words or phrases that were animated to appear only when they were mentioned verbally during the narration. To simulate the way that lecturers naturally pause during their speech and to allow students time to process the material, a brief 15-s pause was inserted after each lecture slide while its content remained onscreen, before the lecture automatically transitioned to the next slide.

For scoring purposes, we identified 78 idea units in each of the two prose passages. We ascertained that both lectures did not significantly differ in the mean number of idea units that were presented onscreen and verbally per slide, all $ps > .05$.

Postlearning Questionnaire. A five-item postlearning questionnaire was administered after participants had viewed both lectures. Specifically, participants rated on a 7-point Likert scale the extent that the lectures were *interesting* and *understandable* (1 = *not at all*; 7 = *extremely*), as well as their prior knowledge of the lectures in terms of *how much information they knew* (1 = *not very much*; 7 = *very much*) and *how well they knew the material* before viewing the lectures (1 = *not at all*; 7 = *very well*). Participants also made a *judgment of learning* (JOL) by predicting how well they would later be able to remember the lecture content (1 = *not at all*; 7 = *very well*).

Procedure

Upon their arrival at the laboratory, participants were seated at individual computers with headphones, and were told that they would be viewing two lectures before they would be tested on the lecture content. Participants in the *note-taking* condition were instructed to write down their notes using pen and paper while they viewed the lectures. Those in the *photo-taking* condition were similarly instructed to take notes while viewing the lectures, but through taking photos using their camera phone. Across both the note-taking and photo-taking conditions, participants were informed that they would later be allowed to review their handwritten notes or photos, respectively, before the test. Participants in the *control* condition did not take any notes, but were told that they would later be provided with handouts of the lecture slides to review before being tested on the material. All participants then used their randomly assigned learning method to study the "bats" and "bread" lectures. The order in which participants experienced both lectures was counterbalanced. After viewing the first lecture, participants were allowed to take a brief self-paced break before proceeding to the second lecture.

When they had completed both lectures, participants responded to the postlearning questionnaire. Then, they completed a 30-s distractor task in which they counted backward in 3s from 547. Following which, all participants were given 3 min to review the lecture content—note-taking participants reviewed their handwritten notes, photo-taking participants reviewed the photos they had taken, and control participants reviewed printouts of the lecture slides that the experimenter provided.

After the 3-min review period, participants were asked to put aside their notes (or photos). Then, they completed a free-recall test for each of the two lectures in the same order that they had earlier been studied, during which participants typed out as much information as they could remember from each lecture. This procedure ensured that all participants completed the test using a medium that was different from the one that they had earlier engaged in during study. Thus, any observed differences in test performance across learning conditions could not be attributed to any advantage arising from a match in encoding and retrieval contexts for some participants (e.g., a pen-and-paper test may unfairly favor note-taking participants who have similarly studied the lectures by writing down their notes, relative to their counterparts in the photo-taking and control conditions). Finally, participants' handwritten notes and photos were collected for analyses, and they were debriefed and thanked.

Results

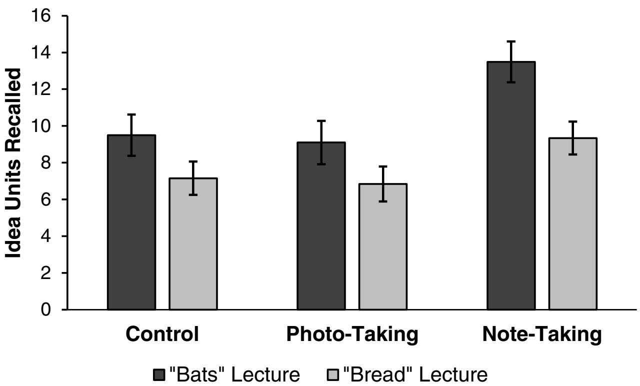
Scoring

Participants' test responses were scored by awarding one point for each idea unit that they correctly recalled from the lectures. For instance, a sample idea unit from the "Bats" lecture was as follows: "Bats are the only mammals that can fly." Two raters who were blind to the experimental conditions independently coded 20 out of 100 of the test scripts. Interrater reliability was high, absolute agreement intraclass correlation (ICC) = .99, 95% CI [.973, .996] based on a two-way random-effects model. Discrepancies were reviewed and resolved through discussion to reach 100% agreement. Given the high interrater reliability, the remaining scripts were scored by one rater.

Recall Test Performance

A 3 (learning method: control vs. photo-taking vs. note-taking) × 2 (lecture topic: "bats" vs. "bread") repeated-measures ANOVA revealed a significant main effect of learning method on participants' recall test performance, $F(2, 97) = 4.07$, $p = .02$, $\eta_p^2 = .08$. As predicted, note-taking ($M = 11.41$, $SD = 7.21$) produced superior retention than the photo-taking ($M = 7.97$, $SD = 4.30$) and control ($M = 8.32$, $SD = 4.21$) conditions, $p = .012$ and $.021$, $d = 0.58$ and 0.52, respectively. The photo-taking and control groups did not differ in their recall performance, $p = .79$. $d = 0.08$. There was also a significant main effect of lecture topic, $F(1, 97) = 38.03$, $p < .001$, $\eta_p^2 = .28$, whereby participants tended to recall more idea units from the "bats" ($M = 10.77$, $SD = 6.80$) than "bread" ($M = 7.82$, $SD = 5.36$) lecture. Importantly, however, there was no interaction between learning method and lecture topic, $F(2, 97) = 1.72$, $p = .19$, $\eta_p^2 = .03$, indicating that the recall advantage of note-taking over the photo-taking and control conditions persisted across both lectures. Figure 1 shows participants' recall test performance across conditions.

Figure 1
Recall Test Performance Across Learning Methods and Lecture Topics (Experiment 1)



Note. Error bars represent standard errors.

Content Analysis of Longhand Notes Versus Photos

To test the extent that qualitative differences in participants' notes or photos predicted their recall test performance, we analyzed the number of idea units in participants' longhand notes and the number of photos that they took. The notes or photos from four participants were missing due to experimenter error. Note-taking participants' longhand notes contained an average of 80.72 idea units (51.74%; $SD = 23.57$) from both lectures. The number of idea units in participants' notes did not significantly correlate with their recall test performance, $r(30) = .27$, $p = .13$. Photo-taking participants took an average of 18.07 photos ($SD = 3.68$) of the lecture slides. Likewise, there was no correlation between the number of photos that participants took and their recall test performance, $r(28) = .02$, $p = .91$. Given these findings, we did not analyze the content of participants' notes and photos any further in the subsequent experiment.

Metacognitive Judgments

Analyzing participants' postlearning questionnaire responses, we found that the three learning groups did not differ in their ratings on all the questionnaire items—how interesting they perceived the lectures to be, $F(2, 97) = 0.94$, $p = .39$, $\eta_p^2 = .02$, how understandable they perceived the lectures to be, $F(2, 97) = 0.15$, $p = .86$, $\eta_p^2 = .003$, how much information from the lectures they knew before the experiment, $F(2, 97) = 0.23$, $p = .79$, $\eta_p^2 = .01$, and how well they knew the lecture content prior to the experiment, $F(2, 97) = 0.39$, $p = .68$, $\eta_p^2 = .01$. Of particular interest, participants' JOLs did not significantly differ across learning conditions, $F(2, 97) = 0.38$, $p = .69$, $\eta_p^2 = .01$. That is, participants inaccurately predicted that the three learning methods would be equally (in)effective for their test performance, when note-taking actually benefited them more. Table 1 shows the mean values and standard deviations of participants' postlearning questionnaire ratings. Moreover, participants' JOLs did not significantly correlate with their actual recall performance in the note-taking, $r(33) = .20$, $p = .26$, photo-taking, $r(29) = .08$, $p = .68$, and control condition, $r(32) = -.11$, $p = .55$.

Discussion

As predicted, learners who took longhand notes displayed superior retention of the lecture material, as compared to their counterparts who had engaged in photo-taking or had not taken any notes. Yet, learners were largely unaware that longhand note-taking had been more helpful for their test performance. Instead, they inaccurately predicted that all three learning methods were similarly (in) effective.

The longhand-superiority effect observed here cannot be attributed to cognitive offloading—reliance on the prosthetic memory of an external source (Risko & Gilbert, 2016; Soares & Storm, 2018)—since all participants were similarly informed of and provided with an opportunity to review the lecture content via their handwritten notes, photos, or printouts of the lecture slides. Furthermore, it is worth noting that the benefits of longhand note-taking emerged even though photo-taking and control participants had access to the full lecture content during review, whereas longhand note-takers were presumably disadvantaged during review because the slow process of longhand meant that their handwritten notes would inevitably contain only a fraction of the lecture content. Indeed, although longhand note-takers only managed to capture 51% of the lecture idea units in their notes, they still performed better than photo-takers and control participants who would have readily captured up to 100% of the on-screen idea units in their photos or received an exact copy of the full lecture slides for review. Thus, the sheer amount of externally stored content that learners access during review alone is insufficient to predict their test performance—if this were the case, then one would have expected better recall in the photo-taking and control conditions. Yet, we found the reverse.

These findings point to the possibility that there are crucial differences between longhand note-taking and photo-taking during the encoding of information, which may subsequently impact learners' test performance. Specifically, longhand note-taking may enhance learners' encoding and retention of the material by sustaining their attention to the lectures, whereas learners may be more likely to report mind-wandering when taking photos or not taking any notes (as detailed in the Introduction). Accordingly, we conducted Experiment 2 to test this attentional account of the longhand-superiority effect.

Table 1
Mean Values and Standard Deviations of Participants' Responses on Postlearning Questionnaire (Experiment 1)

Variables	Control		Photo-taking		Note-taking	
	M	*SD*	*M*	*SD*	*M*	*SD*
Lecture interestingness	4.76	1.42	4.29	1.32	4.57	1.44
Lecture understandability	5.41	1.50	5.29	1.44	5.49	1.42
Prior knowledge quantity	2.29	1.19	2.35	1.11	2.49	1.27
Prior knowledge quality	2.26	1.26	2.55	1.36	2.43	1.27
Judgment of learning (JOL)	3.62	1.10	3.48	1.36	3.77	1.54

Note. $N = 100$. All ratings were made on a 7-point Likert scale.

Experiment 2

Experiment 2 was designed to accomplish three objectives. First, we aimed to replicate Experiment 1's finding that longhand note-taking was more beneficial for learners' test performance than both a photo-taking and a no-note-taking control condition. Second, to increase the generalizability of the effects observed, we expanded the lecture topics in Experiment 2 to include a third lecture on "vaccines." Third and most importantly, we interrogated the role of mind-wandering in mediating the effects of learning method on participants' recall test performance. To do so, we directly probed learners' mind-wandering tendencies during the lectures using the widely adopted *probe-caught* method (e.g., Smallwood & Schooler, 2006; Szpunar et al., 2013; Weinstein, 2018), which involves briefly stopping participants during a task and asking them to indicate whether they had been mind-wandering just before the probe's onset. This procedure has been established as a nonreactive method that captures participants' mind-wandering without fundamentally altering their performance on cognitive tasks (Wiemers & Redick, 2019). As mind-wandering has been found to increase with time on task when students watch video-recorded lectures (Farley et al., 2013; Risko et al., 2012), we assessed participants' mind-wandering at multiple points during the lectures. To the extent that longhand note-taking encourages less mind-wandering than the photo-taking and control conditions, such attentional differences may account for its benefits for knowledge retention.

Method

Participants

The participants were 105 students (75 were female) between the ages of 19 and 33 ($M = 22.00$, $SD = 2.45$) from the National University of Singapore who did not take part in Experiment 1. Outcomes reported below are based on data from 100 participants; five participants who failed to conform to the experimental instructions were excluded from analyses. A power analysis (G*Power; Faul et al., 2007) indicated that this sample size afforded sufficient sensitivity to detect moderate between-subjects effects ($d \geq 0.70$) for two-tailed pairwise comparisons at 80% power and $\alpha = .05$.

Design

As in Experiment 1, the primary between-subjects factor of interest was learning method: *control* versus *photo-taking* versus *note-taking*. Lecture topic ("bats" vs. "bread" vs. "vaccines") was also included as a second within-subjects factor for control purposes to ensure that effects, if any, generalized across educational content. The dependent variables were as follows: (a) participants' retention of the lecture material, as assessed via the number of idea units that they correctly recalled in a test and (b) the proportion of mind-wandering that occurred while participants engaged in the lectures.

Materials

Lecture Materials. We adopted the same lectures on "bats" and "bread" that had been used in Experiment 1, and added a third lecture on "vaccines," which was based on a 1,006-word prose passage similarly adapted from Butler (2010). All prose passages are available in the Supplemental Materials. The "vaccines" lecture was created in the same way as the "bats" and "bread" lectures—it consisted of 10 lecture slides in Microsoft PowerPoint that were each formatted with a heading and information presented in point form, included audio narration of each slide's content, and had three words or phrases on each slide that were animated to appear only when they were mentioned during the verbal narration. All three lectures lasted approximately 9 min each. For scoring purposes, we identified 66 idea units in the "vaccines" passage, and further ascertained that all three lectures were comparable in the mean number of idea units that were presented onscreen and verbally per slide, all $ps > .05$.

Postlearning Questionnaire. The same five-item postlearning questionnaire used in Experiment 1 was administered to measure participants' perceptions of how interesting and understandable the lectures were, the quantity and quality of their prior knowledge of the lecture content, and their JOLs in predicting how well they would later be able to remember the lecture content. All ratings were made on a 7-point Likert scale.

Procedure

The procedure was identical to that in Experiment 1, with three exceptions. First, participants studied three, instead of two, lectures. The order in which participants experienced the three lectures was fully counterbalanced.

Second, we included two mind-wandering probes in each lecture (i.e., six mind-wandering probes in total). At two specific points during each lecture, a bell ring was played and the question "Are you mind-wandering?" was presented briefly onscreen for 2 s, upon which participants were to quickly write down a yes/no response on a blank sheet of paper provided without pausing the lecture (e.g., Szpunar et al., 2013). For each lecture, the first mind-wandering probe occurred at least 30 s into the lecture, while the second probe occurred at least 30 s before the end of the lecture. Of note, no probes were presented during lecture slide transitions when participants in the photo-taking group were likely to be taking photos momentarily. To ensure that participants knew what was required of them, they were familiarized with this direct-probing approach via a practice trial at the start of the experiment. Participants were told that "mind-wandering occurs when your attention drifts and you are no longer fully concentrating on the task at hand," and they were encouraged to respond honestly to the probes. Specifically, participants were instructed to report "no" so long as they were focused on and following the lecture content and activities, and "yes" under all other circumstances. Participants were not given any indication of how many mind-wandering probes to expect. Mind-wandering was taken as the proportion of "yes" responses over the six time points at which they were prompted.

Third, after completing the lectures, postlearning questionnaire, and distractor task, participants were given 4.5 min to review the content of the three lectures. This duration was proportionate to the 3-min period allocated for participants to review the content of two lectures in Experiment 1. As in Experiment 1, note-taking participants reviewed their longhand notes, photo-taking participants reviewed the photos they had taken on their camera phone, and control participants reviewed printed handouts of the lecture slides that the experimenter provided. After the review phase, all participants then completed a free recall test in which they typed out as much information as they could remember from each of the three lectures. Participants were tested on each of the three lectures in the same order that they had earlier been studied.

Results

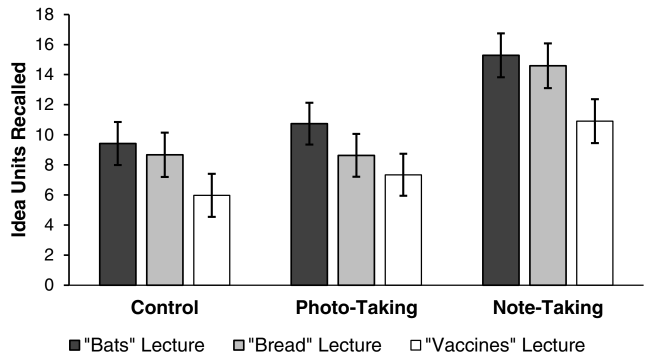
Scoring

Similar to Experiment 1, participants' test responses were scored by awarding one point for each idea unit that they correctly recalled from the lectures. Two raters who were blind to the experimental conditions independently coded 20 out of 100 of the test scripts. Interrater reliability was high, absolute agreement ICC = .99, 95% CI [.977, .996] based on a two-way random-effects model. Discrepancies were reviewed and resolved through discussion to reach 100% agreement. Given the high interrater reliability, the remaining scripts were scored by one rater.

Recall Test Performance

A 3 (learning method: control vs. photo-taking vs. note-taking) × 3 (lecture topic: "bats" vs. "bread" vs. "vaccines") repeated-measures ANOVA revealed a significant main effect of learning method on participants' recall test performance, $F(2, 97) = 5.06$, $p = .008$, $\eta_p^2 = .09$. Replicating our earlier findings in Experiment 1, note-taking ($M = 13.59$, $SD = 8.25$) participants outperformed those in the photo-taking ($M = 8.90$, $SD = 7.13$) and control ($M = 8.02$, $SD = 7.39$) conditions, $p = .013$ and .004, $d = 0.61$ and 0.71, respectively. The photo-taking and control groups did not differ in their recall performance, $p = .63$, $d = 0.12$. There was a significant main effect of lecture topic, $F(2, 194) = 21.38$, $p < .001$, $\eta_p^2 = .18$, whereby participants tended to recall more idea units from the "bats" ($M = 11.76$, $SD = 8.53$) and "bread" ($M = 10.55$, $SD = 8.81$) lectures than the "vaccines" ($M = 8.03$, $SD = 8.41$) lecture, both $ps < .001$, $d = 0.66$ and 0.41, respectively, as well as more idea units from the "bats" than "bread" lecture, $p = .043$, $d = 0.21$. Importantly, however, there was no interaction between learning method and lecture topic, $F(4, 194) = 0.79$, $p = .53$, $\eta_p^2 = .02$, indicating that the recall advantage of note-taking over the photo-taking and control conditions persisted across all three lectures. Figure 2 shows participants' recall test performance across conditions.

Figure 2
Recall Test Performance Across Learning Methods and Lecture Topics (Experiment 2)



Note. Error bars represent standard errors.

Mind-Wandering

To examine participants' mind-wandering over the course of the learning task, we conducted a 3 (learning method) × 3 (lecture temporal position) × 2 (probe temporal position within each lecture) repeated-measures ANOVA with participants' responses to the mind-wandering probes as the dependent variable. Table 2 shows the mean values and standard deviations of the proportion of participants' mind-wandering during each lecture and probe across learning methods.

There was a significant main effect of learning method, $F(2, 97) = 5.96$, $p = .004$, $\eta_p^2 = .11$. As predicted, note-taking participants ($M = .17$, $SD = .16$) reported less mind-wandering on overall than photo-taking ($M = .32$, $SD = .21$) and control ($M = .34$, $SD = .27$) participants, $p = .005$ and .002, $d = 0.82$ and 0.76, respectively. The photo-taking and control groups did not differ in their overall mind-wandering rates, $p = .79$, $d = 0.06$. This pattern of mind-wandering parallels that of participants' recall test performance.

Analyzing the time course of participants' mind-wandering, we observed a significant main effect of lecture position, $F(2, 194) = 16.61$, $p < .001$, $\eta_p^2 = .15$, whereby mind-wandering increased from the first ($M = .16$, $SD = .25$) to second ($M = .28$, $SD = .34$) and third ($M = .41$, $SD = .41$) lectures, $p = .003$ and $p < .001$, $d = 0.30$ and 0.56, respectively. Mind-wandering was also greater in the third than second lecture, $p = .005$, $d = 0.28$. In addition, there was a significant main effect of probe position, $F(1, 97) = 45.11$, $p < .001$, $\eta_p^2 = .32$. Specifically, participants reported significantly more mind-wandering on the second probe ($M = .37$, $SD = .31$) of each lecture than the first probe ($M = .19$, $SD = .23$). All two-way and three-way interactions were nonsignificant, all $ps > .05$.

The Mediating Role of Mind-Wandering

Participants' mind-wandering rates negatively correlated with their overall recall test performance, $r(98) = -.40$, $p < .001$. Learners who reported mind-wandering more while studying the lectures tended to perform more poorly at test. To test the mediation effect of mind-wandering on the relationship between learning method and overall recall performance, we employed regression analysis using

Table 2
Mind-Wandering Proportion Across Time by Learning Method

	Control		Photo-taking		Note-taking	
Time	*M*	*SD*	*M*	*SD*	*M*	*SD*
Lecture 1						
Probe 1	.06	.24	.00	.00	.00	.00
Probe 2	.45	.51	.29	.46	.13	.34
Lecture 2						
Probe 1	.24	.44	.31	.47	.00	.00
Probe 2	.33	.48	.49	.51	.25	.44
Lecture 3						
Probe 1	.36	.49	.34	.48	.34	.48
Probe 2	.58	.50	.51	.51	.28	.46

Note. $N = 100$.

Model 4 of Hayes' (2013) PROCESS macro for SPSS with a percentile bootstrap estimation approach with 5,000 samples (Preacher & Hayes, 2004). The multicategorical predictor variable Learning Method was dummy coded with note-taking as the reference group. In mediation analyses with a multicategorical predictor, evidence that at least one relative indirect effect differs from zero supports the conclusion that a mediator variable mediates the effect of the predictor on the outcome (Hayes & Preacher, 2014). We found that the relative indirect effects of learning strategy on overall recall performance via mind-wandering were statistically significant for both note-taking relative to photo-taking, −5.28; 95% CI [−9.58, −1.77], and note-taking relative to the control group, −5.77; 95% CI [−11.57, −1.76]. Thus, learners' poorer recall performance in both the photo-taking and control conditions relative to the note-taking condition was mediated by greater mind-wandering.

Metacognitive Judgments

Analyzing participants' postlearning questionnaire responses, we found that the three learning conditions did not significantly differ on all the questionnaire items—how interesting the lectures were, $F(2, 97) = 2.04$, $p = .14$, $\eta_p^2 = .04$, how understandable the lectures were, $F(2, 97) = 2.08$, $p = .13$, $\eta_p^2 = .04$, the quantity of participants' prior knowledge of the lecture content, $F(2, 97) = 0.55$, $p = .58$, $\eta_p^2 = .01$, and the quality of their prior knowledge of the lecture content, $F(2, 97) = 2.34$, $p = .10$, $\eta_p^2 = .05$. Of particular interest, participants were largely unaware of the benefits of note-taking—as in Experiment 1, their JOLs did not significantly differ across learning conditions, $F(2, 97) = 2.86$, $p = .062$, $\eta_p^2 = .06$. Table 3 shows the mean values and standard deviations of participants' postlearning questionnaire ratings. Moreover, echoing Experiment 1's findings, participants' JOLs did not significantly correlate with their actual recall performance in the note-taking, $r(30) = .18$, $p = .33$, photo-taking, $r(33) = .25$, $p = .16$, and control condition, $r(31) = .23$, $p = .20$.

Discussion

Replicating Experiment 1's findings, we found that longhand note-taking produced superior retention than both photo-taking and a no-note-taking control condition. Importantly, these differences in recall performance were mediated by learners' mind-wandering during study—whereas longhand note-taking was more effective in sustaining attention during the lectures, learners reported mind-wandering more frequently in the photo-taking and control conditions, thereby impairing their test performance. Yet, as in Experiment 1, learners were largely unaware of the benefits of longhand note-taking, and instead misjudged all three learning methods to be equally effective.

Table 3
Mean Values and Standard Deviations of Participants' Responses on Postlearning Questionnaire (Experiment 2)

	Control		Photo-taking		Note-taking	
Variables	*M*	*SD*	*M*	*SD*	*M*	*SD*
Lecture interestingness	4.09	1.61	4.17	1.29	4.75	1.39
Lecture understandability	5.18	0.88	5.69	1.16	5.50	1.02
Prior knowledge quantity	2.30	1.10	2.57	1.01	2.38	1.19
Prior knowledge quality	2.30	1.08	2.86	1.33	2.31	1.20
Judgment of learning (JOL)	3.64	1.14	3.29	1.27	4.00	1.24

Note. $N = 100$. All ratings were made on a 7-point Likert scale.

General Discussion

Across two experiments, longhand note-taking enhanced learners' video-recorded lecture learning, relative to taking photos of the lecture materials or not taking any notes. Moreover, the longhand-superiority effect occurred even though all learners were similarly provided with a review opportunity immediately before being tested, during which photo-takers and control participants presumably gained the advantage of reviewing an exact transcript of the lecture slides via their photos or printouts, whereas longhand note-takers only had access to a fraction of this content because their handwritten notes were limited in capturing up to just half of the lecture material (Experiment 1). This suggests that the sheer quantity of externally stored and reviewed information is, in itself, inadequate to predict learning. Rather, we tested and found support for an attentional account of the benefits of longhand note-taking (Experiment 2). Specifically, taking notes by hand sustained learners' attention to the lectures more effectively and significantly reduced mind-wandering, relative to taking photos or not taking any notes at all. In turn, longhand note-takers' lower mind-wandering mediated their enhanced retention of the lecture content.

We also consistently found across both experiments that the photo-taking and control groups did not differ in their recall performance. This stands in apparent contrast to the photo-taking impairment effect that has been documented in some other studies, whereby memory for photographed objects has been found to be worse than that for observed objects (Henkel, 2014; Soares & Storm, 2018). To reconcile these seemingly conflicting findings, it is worth noting that: Whereas the photo-taking impairment effect has been attributed to attentional disengagement particularly when participants are not actively in control of deciding what to photograph (Soares & Storm, 2018), mind-wandering rates were similar across the photo-taking and control conditions in our study when participants took photos of the lecture materials volitionally. In other words, when learners' attention is more strongly directed to the task via intentionally selecting which items to photograph (e.g., Barasch et al., 2017), photo-taking may not harm, but also does not help, memory (Henkel, 2014). Moreover, whereas previous work demonstrating the photo-taking impairment effect did not include a review opportunity before learners were tested on their memory for the photographed items (Henkel, 2014; Soares & Storm, 2018), learners in our study were permitted to review their photos because students often take notes precisely so that they can revisit them later when preparing for examinations (Hartley & Davies, 1978; Morehead, Dunlosky, Rawson, Blasiman, & Hollis, 2019). To the extent that photos of the lecture materials served as image-based transcriptions comparable to verbatim printouts of the lecture slides, taking and reviewing photos of lecture content was just as ineffective as *not* taking any notes at all and simply reviewing instructor-provided printouts.

Educational Implications

Our data suggest that it is insufficient for students to review externally generated notes without having taken any notes themselves during lectures (e.g., Kiewra et al., 1991). Instead, actively documenting and reviewing to-be-learned knowledge facilitates retention (e.g., Kobayashi, 2006; Ladas, 1980). Crucially, *how* learners record lecture content matters. Technological advancement has equipped students with sophisticated and convenient means of note-taking beyond traditional longhand, such as using one's smartphone to take photos of lecture materials. In some other everyday settings such as tours or eating experiences, photo-taking may increase engagement and even enjoyment (Diehl et al., 2016). In educational settings, however, the present research has demonstrated that photo-taking does little to enhance knowledge retention, even while it is efficient in allowing students to rapidly and easily capture large amounts of information. Indeed, features or conditions that make encoding easier can produce poorer learning outcomes (for discussions, see Bjork, 1994; Mueller & Oppenheimer, 2016). Compounding this problem, volitional photo-taking has also been found to incur costs for participants' memory of auditory information when their attention is diverted to visual aspects of their experience (Barasch et al., 2017). Whereas the lecture content that was visually versus auditorily presented in our study was deliberately kept similar to avoid disadvantaging photo-takers, real-world lectures often include further verbal elaborations when teachers explain the information presented on their slides. Given our finding that photo-taking did not facilitate students' retention of onscreen content, there is reason to be even less optimistic about its benefits on memory for additional auditory information presented during lectures.

Rather, it would be prudent for students to adopt strategies that sustain their attention on the task at hand and preserve helpful cognitive processes that facilitate learning. Our data point to generating longhand notes as one such strategy to enhance students' attention to and retention of lecture content. Although self-taken photos must also be "generated" (at least, via the push of a button), this method of acquiring knowledge does not effectively reduce mind-wandering and improve performance, relative to longhand note-taking.

Yet, learners in our study were largely unaware that longhand note-taking was more beneficial for their test performance than photo-taking or not taking any notes. Instead, they incorrectly predicted that all three learning methods would produce comparable test performance. Such inaccurate metacognitive knowledge has similarly been observed in previous investigations of students' judgments of several other learning strategies (McCabe, 2011), with students only weakly endorsing generating their own study materials as opposed to receiving instructor-provided study materials. This is problematic because a lack of awareness of which strategies are actually more effective may lead students to adopt suboptimal ones, despite their understanding that mind-wandering can be detrimental for their video-recorded lecture learning performance (Was et al., 2019). Such metacognitive illusions can potentially be dispelled by providing students with targeted instruction on applied learning and memory topics (McCabe, 2011). To guide students' self-regulated learning, it may be worthwhile for educators to impart knowledge on not only what to learn, but also how best to learn.

Future Directions

Extending the longhand-superiority effect observed in the present study, it will be valuable for future research to investigate when and for whom longhand note-taking is more likely to be helpful. For instance, as note-taking is cognitively effortful (Piolat et al., 2005), the combined demands of having to mentally maintain, organize, and record information while comprehending lecture content may produce excessive cognitive load and interfere with learning in some situations, particularly when lectures are delivered at a rapid pace (Aiken et al., 1975; Ladas, 1980; Peters, 1972) or are highly complex (Sweller & Chandler, 1994). In a similar vein, note-taking may induce greater load for learners with lower cognitive and working memory abilities, who may then face greater difficulty taking effective notes, thereby impairing their retention of the lecture content (e.g., Kiewra & Benton, 1988; for reviews, see Bui & Myerson, 2014; Jansen et al., 2017). To better understand and contextualize the benefits of longhand note-taking, it will be crucial to explore its effects across a wider range of educational settings and learner characteristics.

At the same time, the effectiveness of longhand note-taking is closely related to the quality of students' notes (Fisher & Harris, 1973; Nye et al., 1984). To optimize their learning, it is vital that students engage in generative processes during note-taking, such as summarizing, paraphrasing, and organizing the material to integrate it with their prior knowledge (Wittrock, 1974), rather than simply transcribing the material verbatim. Hence, a useful avenue for future work is to develop interventions that teach learners how to take high-quality notes to amplify the benefits of this strategy (Kobayashi, 2006), particularly because it is a popular technique that students often use in their study routines (Miyatsu et al., 2018).

The role of mind-wandering demonstrated here is not mutually exclusive with other potential mechanisms underlying the longhand-superiority effect. For instance, generating longhand notes may prompt deeper elaborative processing (Peper & Mayer, 1978, 1986) than photo-taking, thereby improving learners' memory for the lecture material. In addition, there may be important differences in the utility of longhand notes versus photos as external storage material during review. Students have reported that they typically include content that they find personally meaningful and relevant in their notes (Van Meter et al., 1994). Such idiosyncratic features in personalized notes may be useful for cueing certain information or the use of particular retrieval strategies (for a discussion, see Carrier & Titus, 1979). Thus, although reviewing photos can offer helpful retrieval cues that aid later memory by prompting reinstatement or reactivation of the photographed events (Koutstaal et al., 1998, 1999), it is possible that longhand notes may provide relatively more potent cues during review despite holding less content, per se. This presents an intriguing avenue for future exploration of other potential mechanisms underlying the longhand-superiority effect.

It may also be useful for future work to distinguish between intentional versus unintentional mind-wandering in explaining the longhand-superiority effect. A growing body of work suggests that the two categories of mind-wandering are associated with distinct cognitive experiences, and can be influenced differentially by various experimental settings (see Seli et al., 2016 for a review). Intentional and unintentional mind-wandering correspond to current theories of volitional and reflexive attention, respectively—whereas intentional mind-wandering and endogenous control of attention both involve a voluntary shift to alternative content, unintentional mind-wandering and exogenous control of attention involve involuntary attentional capture, notwithstanding any top-down efforts to focus on the current task. Furthermore, individuals with higher working memory capacities have been found to be better able to tame intentional and unintentional mind-wandering tendencies (Soemer & Schiefele, 2020), which implicates learning in educational settings. Although it is not the case that researchers ought always to examine the intentionality of mind-wandering (Seli et al., 2016), making a distinction between intentional versus unintentional mind-wandering in future work may yield a fuller theoretical understanding of this mediating mechanism underlying the longhand-superiority effect and, potentially, more targeted interventions in the classroom.

Finally, in the present study, learners first studied the material and then made metacognitive judgments of their learning, while anticipating to review the material subsequently. It is possible that learners' inaccurate judgments of learning across conditions may have been influenced by their similar expectation to further review their study materials during the next phase. To what extent, then, might the current pattern of results persist if there were in fact no review period, such that learners made their metacognitive judgments after the lectures while expecting to be tested immediately? Assessing the influence of a review opportunity (or the expectation of being provided one) on learners' metacognitive awareness is an interesting prospect for future work.

Conclusion

As technology becomes more pervasive in the classroom, learners enjoy a wider range of note-taking tools at their disposal that allow them to swiftly and conveniently record more information than would be possible with traditional longhand. In particular, taking photos of lecture materials produces an exhaustive and faithful transcript that learners can later review when preparing for tests. However, as the present study demonstrates, using one's smartphone to take photos is not necessarily a smart way of learning—longhand note-takers outperformed photo-takers and control learners, even when all of them had equal opportunity to review their notes right before being tested, and photo-takers and control participants in fact reviewed an exact transcript of the lecture slides via their photos or printouts whereas longhand note-takers accessed only a fraction of the content as captured by their handwritten notes. These benefits of longhand note-taking for test performance were mediated by learners' mind-wandering tendencies, with photo-taking incurring attentional costs that were comparable to those of not taking any notes at all. Becoming cognizant of the benefits of longhand note-taking—the need to put one's smartphone (camera) away during learning—is vital.

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Received December 16, 2020
Revision received March 22, 2021
Accepted May 14, 2021 ■