Educational Psychology Review (2021) 33:1583–1630
https://doi.org/10.1007/s10648-020-09592-4

REVIEW ARTICLE

A Comprehensive Review of Educational Technology on Objective Learning Outcomes in Academic Contexts

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Accepted: 28 December 2020 / Published online: 5 April 2021
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Abstract

Rapid advances in technology during the last few decades have provided a multitude of new options for teaching and learning. Although technology is being widely adopted in education, there is a shortage of research on the effects that this technology might have on student learning, and why those effects occur. We conducted a comprehensive review of the literature on various uses of digital technology in educational settings, and the effects of that technology on students' objective learning outcomes. We interpret these effects within the context of empirical research on effective principles of learning, and the extent to which the affordances of technology permit opportunities for increased engagement with the material, retrieval practice, and spacing. Results revealed that technology is neither beneficial nor harmful for learning when used primarily as a means of presenting information (e.g., information viewed on a computer screen vs. on paper), but can be beneficial when it involves unique affordances that leverage effective learning principles. We discues these findings in light of the ever-increasing availability of technology in education, and the importance of evidence-guided criteria in decisions about adoption and implementation.

Keywords Technology · Learning · Classroom · Cognitive Science · Effective Learning Principles

Advances in technology have revolutionalized the way that we live, work, and communicate. In the past few decades, the increasing availability of digital devices has made the acquisition and transmission of information faster and easier. Given the particular enhancements that

This material is based upon work supported by the James S. McDonnell Foundation 21st Century Science Initiative in Understanding Human Cognition, Collaborative Grant No. 220020483. We thank Sierra Lauber, Luke Huber, and Kyle St. Hilaire for their help in locating articles.

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technology affords for rapid communication to large groups of people, it is perhaps no surprise that a myriad of emerging technologies are implemented within education to improve the efficiency of teaching and learning.

Technology has long been incorporated into instruction. Even in the early 20th century, teachers made use of radio and film to supplement classroom lessons (Cuban 1986). Computers became increasingly available in classrooms in the 1980s and 1990s, and in the decades following even more sophisticated forms of technology have been developed specifically for classroom use. According to the National Center for Education Statistics, the most recent survey on teachers' use of technology reports that 97% of U.S. public school teachers have daily access to computers in their classrooms (Gray et al. 2010). Nearly half of the teachers surveyed also reported having daily access to LCD projectors, and over 20% reported having access to videoconferencing, interactive whiteboards, and wireless classroom response systems to enable "clickers" and other mobile devices.

The widespread adoption of technology in schools suggests the (at least implicit) belief that this technology is benefitting the educational experience. Indeed, the common use of the term *technology-enhanced learning* implies that technology is improving or increasing student learning in some way. As noted in a recent review by Kirkwood and Price (2014), however, specific and consistent descriptions of what is "enhanced" by technology, and the evidence to support it, have been elusive.

Further research shows that the decisions to adopt technology in education are not always driven by evidence-based rationale. In a survey about the sources of college instructors' learning about educational technology (Price and Kirkwood 2014), conversations with colleagues and personal experiences were the most common learning sources, whereas the reading of journal articles was one of the least common. Other reports have shown that the use of technology in education is driven more often by questions about what the technology can do, rather than how it might enable students to learn more effectively (Kirkwood and Price 2013). Given that technology can be adopted without any prerequisite for understanding what effects it might have, there is a need for rigorous research that evaluates the effects of educational technology, and can help guide the important (sometimes expensive) decisions about adoption and implementation.

Technology is best conceptualized as a tool. As with any tool, in order to determine whether it is effective we first have to ask the question, *effective for what*? The reasons for the use of any technological tool depend on a particular goal. For example, students may take courses online to accommodate schedules, or institutions may adopt computerized assessments to save on printing costs. In the current review, we focus on the effects of educational technology on students' objective learning outcomes, measured through students' performance on a test or assessment over the material that they have learned. The focus on objective learning outcomes is important for at least three reasons.

First, there has not yet been a systematic and comprehensive literature review of the effects of educational technology on students' objective learning in real academic settings. Some reviews can be found on the use of a particular type of technology or in a particular subject area such as anatomy (Clunie et al. 2018), biology (Lee and Tsai 2013), mathematics (Li and Ma 2010; Rosen and Salomon 2007), and foreign language learning (Golonka et al. 2014; Grgurović et al. 2013). The outcome measures reported in previous research have varied considerably, including some quantitative, some qualitative, and some self-reported measures (see Kirkwood and Price 2014; Nora and Snyder 2008). The current review is based on a broad search unrestricted to technology type, subject matter, or educational level, and thus provides a new systematic investigation into the effects of a wide range of technology on objective learning.

Second, focusing on objective learning outcomes permits an assessment of how well the technology aligns with evidence-based principles about how people learn. Objective learning has been the focus of over 100 years of rigorous scientific research, which has revealed a number of learning principles that are reliable and effective. As a given pedagogical approach will enhance learning only to the extent that it engages effective learning principles, the propensity of any technology to improve learning hinges on the degree to which that technology engages those principles. Examining learning as a function of the principles afforded by the technology therefore provides a reliable means of understanding—and *predicting*—the effectiveness of that technology for learning. Predictive power is especially important in the age of ever-increasing new technologies that are continually being developed. As the "packaging" of technology easily changes, having a principled and stable basis on which to evaluate its effectiveness is crucial to guiding important decisions about adoption and implementation.

Finally, objective learning is a common metric used to evaluate academic success. Exam scores, grades earned in courses, and GPA are often used as indicators of achievement and can be important factors in selecting individuals for academic programs, scholarships, awards, and jobs. Such metrics may not capture the variety of qualitative factors that are also reflective of academic success, however they continue to be relied upon for these important purposes. Understanding the role that technology might play in improving objective achievement is therefore of critical importance in weighing the costs and benefits of the adoption of technology, and can also help guide efforts to deliberately utilize technology in ways that are intended to enhance academic performance.

The effects of technology on learning are best understood by considering the affordances of that technology, and whether those affordances leverage effective ways of learning. For example, a video-recorded lecture that is made available to students affords a higher degree of user control—the ability to view the lecture multiple times, or pause and rewind for concepts that are difficult to understand—than a live lecture. In this case, the technology affords multiple opportunities to re-visit learning material, which aligns with the general principle of *repetition* in that learning benefits from additional opportunities to engage with the learning material. Video-recorded lectures may therefore be expected to enhance learning to the extent that students utilize the additional opportunities that they provide for engagement with the material.

In this review, we focus on general learning principles that are widely applicable across a variety of learning situations. One of the most fundamental principles is what we refer to here as *repetition*. As described above, more frequent engagement with learning material generally produces better learning. Although this "practice makes perfect" idea is quite intuitive, empirical research has confirmed significant learning benefits as a result of more time spent, or more frequent engagement with, the learning material (Rawson and Dunlosky 2011).

Proper scheduling of repetitions can make them even more effective for learning. A large number of studies show that repetitions that are spaced—i.e., spread out or distributed across time—are far more effective than repetitions that occur immediately in close succession. The *spacing effect* (also called the *distributed practice effect*) was first demonstrated by Ebbinghaus (1885) and has become one of the most reliable and widely-demonstrated principles in the science of learning (for recent reviews, see Carpenter et al. 2012; Carpenter 2014, 2017, 2020; Cepeda et al. 2006; Delaney et al. 2010; Gerbier and Toppino 2015; Kuepper-Tetzel 2014; Rohrer 2015). Thus, beyond the effects of mere repetition, a given technology would be expected to benefit learning to the extent that it affords spaced repetition of the learning material.

A third principle is *retrieval practice*, wherein the act of retrieving information from memory significantly enhances learning. The positive effects of retrieval practice have been demonstrated in a large number of studies and apply to a variety of learning situations (for recent reviews, see Karpicke 2017; Kornell and Vaughn 2016). The act of retrieval itself can strengthen memory, (Carpenter 2009, 2011; Roediger III and Karpicke 2006; Roediger III and Butler 2011), and retrieval can also serve as a metacognitive check of one's knowledge that improves the efficiency of subsequent study (Fernandez and Jamet 2017; Little and McDaniel 2015). For various reasons, therefore, technology-based components that incorporate opportunities for retrieval practice would be expected to benefit learning.

These general learning principles provide a guiding framework for interpreting the effects of technology on learning. As with any tool, technology would be expected to produce desirable effects on learning only to the extent that its affordances leverage the principles that produce those effects. However, studies exploring the effects of technology on learning are not typically guided by empirical principles of learning, which makes it difficult to interpret the effects of that technology and even more difficult to predict when technology will benefit learning. In light of the increasing availability of technology options in education, knowing when and how to use it to accomplish particular learning goals can be facilitated by understanding the alignment between technology affordances and effective learning principles. Thus, the current review contributes a critical new perspective by merging the ever-growing literature on educational technology with that of effective learning principles, to better understand when and why technology enhances learning. The broad nature of our review—unrestricted to a particular technology, subject matter, or educational level—reveals the consistency of these principles across a range of situations.

The goal of the current paper is to review the published literature on the effects of educational technology on students' objective learning outcomes in academic contexts. In the interests of external validity, we focused on studies conducted in real courses. Our aim was to gain a broad understanding of the types of technology being utilized in educational settings, across all grade levels and subject matters, and the measurable effects that this technology has on student learning. We interpret these effects within the context of the affordances of the technology, and the degree to which those affordances align with the learning principles described above.

Method

A broad literature search of article titles was conducted using the following keywords (no date range specified), from databases Education Source, ERIC, and PsycINFO, on March 28, 2017: (achiev* OR assess* OR education* OR effect* OR exam* OR grade* OR instruct* OR Learn* OR outcome* OR scor* OR teach*) AND (benefit* OR enhanc* OR impact* OR improv* OR influenc* OR compar*) AND (animat* OR app* OR artificial intelligence OR -based OR computer* OR digital OR e-learning OR face-to-face OR gam* OR graph* OR hybrid* OR in-person OR interact* OR internet OR iPad* OR media* OR mobile OR multimedia* OR multi-media* OR online OR phone* OR remot* OR simulat* OR smart OR smartphone* OR tablet* OR technology OR virtual OR web OR whiteboard OR traditional).

This title search resulted in 16,342 articles. Of these, 4463 duplicates were removed, resulting in 11,879 articles. Two coders independently read the titles of these articles and rated each one as relevant, not relevant, or potentially relevant according to the following criteria:

1. The article reported empirical research on the effects of technology on objective learning. Survey studies, reviews, and commentaries were not included.
2. The research was conducted in an academic setting with students as participants. We focused on studies conducted in authentic courses that provide direct evidence of the effects of technology in real academic environments, which are often the settings for which decisions about technology adoption and implementation need to be made. Laboratory-based studies were not included, nor were studies conducted outside of traditional academic settings (e.g., driver's education or flight simulation).
3. The research involved an experimental (or quasi-experimental) design comparing an experimental group that learned course material via a particular technology, versus a control group that learned the same material without using that technology.
4. The research included an objective measure of student learning, via a test or grade in the course, that was the same across experimental and control groups.

Title Selection

Across the 11,879 titles coded, interrater agreement between the two coders (via Chronbach's alpha) was 0.95. A total of 10,178 articles were independently coded as not relevant by both coders and removed from selection. A total of 1356 articles were independently coded as relevant or potentially relevant by both coders and retained. The remaining 345 articles were coded as relevant or potentially relevant by one coder, and not relevant by the second coder. For these 345 articles, both coders reexamined their ratings and resolved discrepancies through discussion, resulting in 246 articles that were coded as relevant or potentially relevant by one or both coders. Thus, a total of 1602 articles were retained on the basis of their titles.

Abstract Selection

The abstracts for these 1602 articles were searched. Four articles could not be located despite extensive searching efforts. For the remaining 1598 articles, abstracts were included in 1424 of the articles. For these articles, both coders independently read the abstracts and applied the same four criteria as above to determine whether an article was relevant, not relevant, or potentially relevant. Inter-rater agreement between the two coders (via Chronbach's alpha) was 0.91. A total of 687 abstracts were independently coded as not relevant by both coders and removed from selection. A total of 613 abstracts were coded as relevant or potentially relevant by both coders and retained. The remaining 124 abstracts were coded as relevant or potentially relevant by one coder, and not relevant by the second coder. For these 124 abstracts, both coders reexamined their ratings and resolved discrepancies through discussion, resulting in 29 abstracts that were coded as relevant or potentially relevant by both coders.

For the remaining 174 articles, there was either no abstract available or the abstract was too brief to be informative for classifying the relevance of the article. In these cases, the full articles were examined. These articles tended to be brief reports or non-empirical editorials or commentaries. Based on a brief examination of the full articles, 83 were coded as potentially relevant by both coders, and the remaining 91 articles were removed from selection. A total of 725 articles were thus retained on the basis of their abstracts or a brief examination of the article.

Full Article Selection

The full text versions of these 725 articles were obtained and read in their entirety. Articles were evaluated for the degree to which they met the four criteria above, in addition to quality of methodology. This entailed verifying that designs were free from identifiable confounds—for example, an experimental section of a course incorporated computer-assisted technology in addition to team-based learning, whereas the control section involved neither computer-assisted technology nor team-based learning—and included the use of appropriate statistical analyses to test for significant effects (not merely descriptive statistics) of the key comparisons. A total of 423 articles were excluded for failing to meet the four criteria (or in cases where it was uncertain whether the criteria were met), for having identifiable confounds, or for lacking the appropriate quantitative information needed to calculate effect sizes.

Additional methodological criteria were applied during this stage. It was verified that the experimental and control groups were taught by the same instructor, learned the same course material, and were given the same objective criterial assessment to measure their learning. These criteria were applied in order to control for the potential influences of factors unrelated to the technology that could influence student learning.[1] Some studies involved multiple assessments (for example, a test given after the course ended followed by a repeated administration of the same test at a later time). Because it cannot be verified whether and how often students in different groups may have engaged with the material in-between the two tests, and research on retrieval practice indicates that a first test is likely to influence performance on a second test, in the studies that involved multiple administrations of the same test we report the results of the first one. For studies involving non-random assignment of students to groups—for example, those studies where students self-enrolled in an online versus face-to-face section of a course—baseline measures of course knowledge or academic aptitude were required to ensure that students across different groups did not differ in their preexisting potential to learn the material. Articles were excluded if these baseline measures revealed significant or marginally significant differences between groups that were not controlled through statistical analyses, such as entering preexisting knowledge as a covariate. Altogether, 237 articles were excluded for not meeting one or more of these criteria, or in cases where it was unclear whether or not the criteria were met. This resulted in a total of 65 articles included. Figure 1 shows a flowchart of this process.

To include any articles published since the time of the original database search and the drafting of the manuscript, the search was performed again using the same databases and keywords, for any articles published between March 28, 2017 and February 16, 2020. The same selection criteria were applied, and given the high interrater agreement that was observed for the original selection process, the process was carried out by only one coder. Based on the 3359 articles that resulted from the search, 695 articles were retained based on their titles, 261 based on their abstracts, and 26 based on the full article. These 26 articles were combined with the 65 previously selected, for a total of 91 articles included in the review.

[1] Even with the same instructor across all conditions, there is a possibility that some instructor-related factors could change across conditions or across time (e.g., instructors could improve their teaching effectiveness from one term to the next, or have difficulty implementing a new technology). Notwithstanding these possibilities, instructor-related factors that could influence student learning are likely to be greater when there are different instructors across the conditions (e.g., bringing differences in teaching style, personality, grading practices, or experience), such that the potential influence of these factors was minimized by ensuring that the same instructor taught all students.

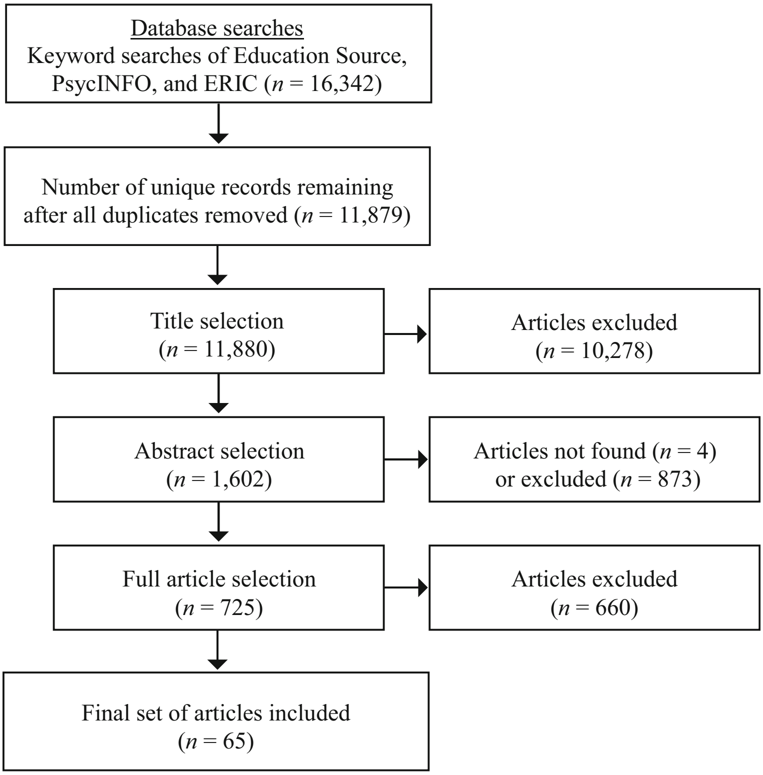

Fig. 1 Flowchart depicting the search and selection process

Results and Discussion

The 91 articles were classified according to the way in which technology was utilized in the study. These included (1) video-based instruction, (2) online courses, (3) computer-assisted instruction, (4) mobile devices, (5) simulations, (6) animations, (7) games, and (8) flipped classrooms. These categories do not necessarily represent different types of technology (e.g., animation components can be part of computer-assisted instruction, and digital content can be delivered via a computer or a mobile device). Rather, our classification scheme was based on common and identifiable ways that technology has been incorporated into education and could influence decisions about implementation. For example, should an instructor recommend that her students attend a live lecture from an expert visiting scholar, or would students learn just as well from viewing the lecture via livestream or video? Universities looking to offer classes to more students may want to know whether students learn better from face-to-face courses compared to online courses. Given the increasing popularity of mobile devices in everyday life, educators may wonder whether these devices can be used for educational purposes so that students can engage in learning even when not in school.

Using these eight categories as a general organizing scheme, we review the studies emerging from our search. We include a description of the basic design of each study, how technology was incorporated, and how the advantages afforded (or not afforded) by that technology align with the learning principles described earlier. We also describe the characteristics of the students and subject matter, the way in which learning was measured, and the effect sizes (expressed in Cohen's d, calculated using the formulas provided by Thalheimer and Cook 2019) associated with the effects of the technology. Positive effect size values indicate a learning advantage of the technology, and negative values indicate a disadvantage.

Video-Based Instruction

This section includes comparisons of student learning from face-to-face presentation by an instructor, versus the same instructor delivering the information through a video presentation. Both groups of students (face-to-face vs. video) were taught the same information and received the same criterial test to measure their learning. In cases where students were not randomly assigned to groups, baseline assessments (e.g., achievement or pretest scores, prior GPA, or grades in prerequisite courses) verified that the groups did not differ in their preexisting knowledge or academic aptitude. The results are shown in Table 1.

Starting with the oldest study to emerge from our search, Anderson and Vander Meer (1954) taught high school mathematics students a series of lessons over the slide rule. Six weekly 30-min lessons were taught by the same instructor and delivered to one group of students face-to-face in a classroom, and to a different group of students by television in the same classroom on the same days. The groups were matched ahead of time on mathematics achievement test scores. Tests over the content given after each lesson revealed no significant difference in performance between the face-to-face group ($M = 42.41$, $SD = 19.23$) versus the television group ($M = 43.34$, $SD = 19.61$), $d = .05$. Thus, when the content, instructor, and learning environment are controlled, it does not appear to matter whether students receive the instruction face-to-face or via a television screen.

Indeed, other studies observed nonsignificant (though slightly negative) effects of video-based lectures under conditions in which the amount of information was controlled and the primary difference was the medium of delivery—televised versus face-to-face. MacLaughlin et al. (2004) found that final grades across three of four graduate-level pharmacy courses were slightly (and nonsignificantly) lower when the students viewed the lectures via live videoconference compared to the same lectures in person. Hollerbach and Mims (2007) observed (nonsignificant) negative effects of video-based versus face-to-face instruction over radio concepts in three sections of an undergraduate communications course (although the sample sizes in this study were small, ranging from 4 to 13 students per group).

Importantly, in none of the above studies did students control the pace of the televised lectures by having the ability to pause, rewind, or view the lecture multiple times. Effects on learning may be different when students have more control over the lectures. In an introductory biology course, Lents and Cifuentes (2009) also observed a small and nonsignificant advantage of face-to-face lectures over video-recorded lectures on exam scores covering the content from those lectures. This time, however, students had access to the video-recorded lectures outside of class and could pause, rewind, or view the lectures multiple times. Based on students' feedback, the effectiveness of the video-recorded lectures depended upon how students utilized them. Whereas some students reported having problems staying engaged or focused with the video-recorded lectures, other students felt the video-recorded lectures were advantageous (relative to face-to-face lectures) because they had the option to pause, rewind, or watch them again if they needed to. Performance in the video group was also highly variable, which might reflect different degrees of leaning resulting from the differences in how students utilized the video lectures. Though it cannot be verified directly as conditionalized

Table 1 Comparison of video versus face-to-face instruction on student learning outcomes

	Comparison	Subject	Students	Assignment method	Televised components	Baseline measure	Learning measure	Effect size
Anderson and Vander Meer (1954)	Face-to-face (n = 41) vs. televised lectures (n = 41)	Slide rule skills	High school mathematics	Matched pairs based on mathematics achievement pre-test scores	Televised lectures	Mathematics achievement pre-test	Test over content learned	d = .05
MacLaughlin et al. (2004)	Face-to-face (n = 32) vs. video lectures (n = 46)	4 Pharmacy courses: Integumentary (ITG), Bone and joint disorders (BJD), Neurosensory (NS), Psychiatry (P)	Graduate pharmacy students	Different course sections within a term	Live video-conference lectures	GPA prior to study	Final course grades	d_{ITG} = -.36 d_{BJD} = -.18 d_{NS} = -.25 d_{P} = .04
Hollerbach and Mims (2007)	Face-to-face (ns = 4-13) vs. video lectures (ns = 6-13) vs. online tutorial (ns = 5-13)	Radio concepts across three course sections	Undergraduate mass communication students	Random by student	Video lectures and online tutorials	10-item pretest	Identical 10- item posttest	Face-to-face vs. video: $d_{section1}$ = -.59 $d_{section2}$ = -.51 $d_{section3}$ = -1.32 Face-to-face vs. online: $d_{section1}$ = -1.58 $d_{section2}$ = -.72 $d_{section3}$ = -.65
Lents and Cifuentes (2009)	Face-to-face (n = 59) vs. video lectures (n = 24)	Biology	Undergraduate forensic science majors	Different course sections within a term	Video-recorded lectures	Grade in prerequisite biology course	Exam 1 scores for content in video	d = -.24

exam scores were not reported, students' feedback indicated that their ability to control the pace of the video-recorded lectures was beneficial to their learning. The user control afforded by video-recorded lectures may thus be beneficial when students utilize that control to engage in extra opportunities for learning.

Online Courses

This section includes comparisons of student learning from conventional classes that meet face-to-face, versus the same class offered either fully or partially online (i.e., "hybrid" courses, Swenson and Evans 2003). Both groups of students (face-to-face vs. online) were taught the same material, by the same instructor, and received the same criterial test to measure their learning. In cases where students were not randomly assigned to groups (face-to-face vs. online), baseline assessments (e.g., pretest scores, prior GPA) verified that the groups did not differ in their preexisting knowledge or academic aptitude. The results are shown in Table 2.

Online instruction appears to have no significant effect on learning when it is used primarily as a method of information delivery, with no identifiable affordances over and beyond face-to-face instruction. Indeed, no significant learning differences were observed in a study comparing face-to-face versus online instruction under conditions involving a higher-than-usual degree of methodological control. Edwards et al. (2013) had two groups of sixth grade math students learn each of 10 topics (e.g., decimals, statistics, probability, algebra) by alternating between face-to-face and online instruction. For face-to-face instruction the teacher taught each lesson in a classroom using an interactive lecture format where students could ask questions during the lesson, followed by an assignment pertaining to the lesson that students worked on while the teacher monitored and provided help as needed. For online instruction, students used the same classroom but worked from laptop computers to access the lesson materials, and then completed the same assignment as in the face-to-face instruction. When students had questions, they posted these to an online chat window and received responses from the instructor. Thus, this study controlled for a number of factors, including the physical environment in which students learned the information, and the opportunities to engage and ask questions. The lack of significant differences in posttest performance indicates that, after controlling for these factors, the method of delivery itself (face-to-face vs. online) does not have a direct effect on learning.

Other studies show similar findings when online instruction is used primarily as a method of delivery. Francescucci and Rohani (2019) compared final exam scores in introductory marketing from a face-to-face section versus a synchronous online section that students logged into at scheduled dates and times. The online section involved the same instructor-led presentations as the face-to-face section, along with audio and video for each student and the same interactive features that would be present in a physical classroom (e.g., chat function, hand raising). With a large sample of students aggregated across multiple academic terms, there were no differences in final exam scores between the face-to-face and online sections. Using the same synchronous online delivery but with students alternating between online and face-to-face class sessions, Francescucci and Foster (2013) observed no significant differences in final exam scores between a pure face-to-face class compared to the alternating online/face-to-face class. Johnson et al. (2000) similarly observed no significant differences in final project grades between students enrolled in a face-to-face graduate course on instructional design, compared to a synchronous online course with identical content. When the course contents were identical but delivered asynchronously in an online section of a special education course,

Table 2 Comparison of online versus face-to-face courses on student learning outcomes

	Comparison	Subject	Students	Assignment method	Online components	Baseline measure	Learning measure	Effect size
Edwards et al. (2013)	Face-to-face (*ns* = 22-24) vs. online course (*ns* = 22-24)	10 topics in Mathematics	6th grade students	Different course sections within a term	All course materials online	10-item pretest over content to be learned from each topic	Identical posttest over content learned	$d_{decimals}$ = .23 $d_{statistics}$ = -.25 $d_{probablity}$ = -.04 $d_{algebra}$ = .08 $d_{measurement}$ = .24 $d_{symmetry}$ = -.01 $d_{geometry}$ = -.18 $d_{polygons}$ = .17 $d_{perimeter}$ = .55 d_{area} = -.31
Francescucci and Rohani (2019)	Face-to-face (*n* = 376) vs. online course (*n* = 322)	Introductory marketing	Undergraduate students	Random by student	All course materials online	None	Final exam	*d* = .01
Francescucci and Foster (2013)	Face-to-face (*n* = 44) vs. hybrid course (*n* = 36)	Marketing	Undergraduate students	Random by student	Alternate face-to-face and virtual classroom meetings	None	Final exam	*d* = -.24
Johnson et al. (2000)	Face-to-face (*n* = 13) vs. online course (*n* = 17)	Instructional design	Graduate human resource development students	Different course sections within a term	All course materials online	GPA prior to study	Final project grades	*d* = -.12
Steinweg et al. (2005)	Face-to-face (*n* = 26) vs. online course (*n* = 28)	Special education	Undergraduate education students	Different course sections within a term	All course materials online	44-item pretest over course content	Identical 44-item posttest	*d* = .51
Johnson et al. (2002)	Face-to-face (*n* = 25) vs. online course (*n* = 13)	Consumer economics	Undergraduate students	Different course sections within a term	All course materials online	70-item multiple-choice pretest over content to be learned	Identical 70-item posttest over content learned	*d* = .78 (adjusted for pretest scores)
Schoenfeld-Tacher et al. (2001)	Face-to-face (*n* = 22) vs. online course (*n* = 6)	Histology	Undergraduate students	Different course sections within a term	All course materials online, post-lecture quizzes	25-item multiple-choice pretest over content learned	32-item multiple-choice post-test over content learned	*d* = 1.16 (adjusted for pretest scores)

Table 2 (continued)

	Comparison	Subject	Students	Assignment method	Online components	Baseline measure	Learning measure	Effect size
Arias et al. (2018)	Face-to-face (n = 17) vs. online course (n = 15)	Macro-economics	Undergraduate students	Random by student	Mini lectures, videos, discussion boards	30-item multiple choice pretest over content to be learned	Course exams	d = -.66

For learning measures, Edwards et al. (2013) report both posttest scores and gain scores (i.e., posttest minus pretest) across the 10 topics. Effect size estimates for both measures are consistent in direction and magnitude, so we report only effect sizes for the posttest to achieve greater consistency in how the effect sizes are reported for the other studies

Steinweg et al. (2005) observed a slight (nonsignificant) advantage of the online over the face-to-face section.

When online instruction involves unique affordances for learning beyond just a method of delivery, however, it can be beneficial. In the studies showing significant benefits of online courses over face-to-face courses, additional evidence suggests that students in the online courses were more likely to engage with effective learning principles. In Johnson et al.'s (2002) study, a survey administered at the end of the semester indicated that students in the online section of a consumer economics course reported spending more hours per week on the course, compared to students in the face-to-face section. Schoenfeld-Tacher et al. (2001) found that students in the online section of a histology course were more likely than students in the face-to-face section to initiate interactive discussions and ask high-level questions. The online section also incorporated practice quizzes after viewing online lectures, so some of the learning advantage could have been due to retrieval practice. Although Arias et al. (2018) included discussion boards as part of the online course, the frequency and quality of students' interactions in discussions was not reported (and the authors note that attendance was higher than usual in the face-to-face section, which could reflect motivational factors that contributed to the learning advantage of the face-to-face section). Thus, when the online platform affords activities that align with effective learning principles—such as retrieval practice, or repetition through revisiting course material more often or engaging more in discussions—online instruction can be beneficial for learning.

Computer-Assisted Instruction

This section includes comparisons of student learning from conventional face-to-face classroom instruction versus computerized instruction. Both groups of students (conventional instruction vs. computerized instruction) were taught the same information and received the same criterial test to measure their learning. In cases where students were not randomly assigned to groups, baseline assessments (e.g., pretest scores, GPA) verified that the groups did not differ in their preexisting knowledge of the content or academic aptitude.

One broad theme that emerged from our search was whether the computer-based instruction was implemented on its own or in conjunction with conventional instruction. Thus, we organize this literature into two sections: (1) studies that compared conventional classroom instruction versus computerized instruction with no intermixing of the two, and (2) studies that compared conventional classroom instruction only, versus conventional classroom instruction supplemented with computerized instruction.

Conventional Classroom Instruction Versus Computerized Instruction Table 3 contains studies that compared learning of the same material via conventional classroom instruction versus computerized instruction. Consistent with the literature reviewed so far, the effects of computerized instruction on learning seem to depend on the affordances it provides, and whether those affordances align with effective learning principles.

In cases where computerized instruction served primarily as a method of delivering information without any further identifiable affordances for learning, no significant benefits emerged on student learning outcomes. In some of these cases, both computerized and conventional approaches provided opportunities for retrieval practice. For example, Campbell et al. (1987) compared paper-based versus computer-based drills over math problems in third grade children. Time spent on classroom instruction was the same, and students

Table 3 Comparison of computer-based instruction versus conventional instruction on student learning outcomes

	Comparison	Subject	Students	Assignment method	Computer components	Baseline measure	Learning measure	Effect size
Campbell et al. (1987)	Paper-based (n = 24) vs. computer-based math drills (n = 24)	Mathematics	Third grade students	Matched pairs based on 50-item pretest over division problems	Division math drills with feedback	50-item pre-test over division problems	Identical 50-item posttest over division problems	d = -.39
Olkun (2003)	Physical (n = 31) vs. computer-based puzzles (n = 31)	Geometry	4th and 5th grade students	Matched pairs based on pretest score	Computerized puzzles	24-item pretest over content to be learned	Identical 24- item posttest	d = .14
Cakir and Simsek (2010)	Paper-based vs. computer-based math problems, either personalized (ns = 18-22) or non-personalized (ns = 23-27)	Mathematics	7th grade students	Different course sections within a term	Computerized practice problems with feedback	17-item pretest over content to be learned	17-item posttest over content learned	$d_{Personalized}$ = .09 $d_{Non\text{-}personalized}$ = -.66
Wang and Sleeman (1993)	Conventional lecture instruction with paper-based review (n = 25) vs. computerized review (n = 25)	Operations management	Undergraduate business students	Random by students	Computerized review involving drill and practice	SAT scores	Proficiency exam over operations management	d = .093 (adjusted for SAT scores)
Oglesbee et al. (1988)	Paper-based (n = 57) vs. computer-based case problems (n = 51)	Accounting	Undergraduate business students	Different course sections within a term	Computerized case study problems	10-item pretest over content to be learned	34-item common final exam questions	d = .32 (adjusted for GPA and prerequisite grades)
Hahn et al. (2013)	Paper-based (n = 17) vs. Online Homework (OHM, n = 33) vs. Intelligent Tutor System (ITS, n = 20)	Accounting	Undergraduate business students	Different course sections within a term	Practice problems, feedback, explanations	8-item pretest over content to be learned	6 exam questions relevant to content learned	d_{OHM} = .29 d_{ITS} = -.53

Table 3 (continued)

	Comparison	Subject	Students	Assignment method	Computer components	Baseline measure	Learning measure	Effect size
Yildirim et al. (2001)	Conventional instruction (n = 12) vs. web-based lessons (n = 15)	Circulatory and excretory systems	High school biology students	Matched pairs based on biology achievement test scores	Presentation of content with pictures, graphics, and videos	81-item pretest over content to be learned: Declarative, Conditional, Procedural knowledge	Identical posttest over content learned	$d_{Declarative}$ = .21 $d_{Conditional}$ = .53 $d_{Procedural}$ = .28
Nguyen and Paschal (2002)	Conventional instruction (n = 22) vs. web-based tutorial (n = 21)	Ultrasound recordings	Undergraduate medical imaging students	Matched pairs based on mid-semester grades	Presentation of content, graphics, animations, simulations	Mid-semester grades and 5-item pretest over content to be learned	Exam scores over content learned	d = -.34
Tilidetzke (1992)	Lecture instruction (n = 21) vs. computer-based instruction (n = 21)	Algebra	Undergraduate students from two course sections (taught by instructor A or B)	Different course sections within a term	Computerized lessons	Pretest over content to be learned	Posttest over content learned	$d_{InstructorA}$ = -.30 $d_{InstructorB}$ = .22
Lee et al. (1997)	Instructor-led workshops (n = 45) vs. computerized lessons (n = 37)	Acid-based problem solving	2nd year medical students	Random by student	Computerized lessons with animations, graphics, and case studies	Medical school admissions exam	25-item posttest measuring recall and problem-solving of content learned	d_{Recall} = -.21 $d_{Problem\ solving}$ = -.50
Delafuente et al. (1998)	Lecture-based instruction (n = 54) vs. computer-based instruction (n = 53)	Pharmacy calculations	Undergraduate pharmacy students	Random by students	Examples and practice problems with feedback	Exam 1 scores prior to group assignment	Exam 2 scores following group assignment	d = -.38
Vichitvejpaisal et al. (2001)	Textbook-based (n = 40) vs. computer-based instruction (n = 40)	Arterial blood gas interpretation	3rd year medical students	Stratified and random by students	Presentation of content, graphics, animations, videos	30-item multiple choice pretest over content to be learned	Identical 30-item posttest over content learned	d = -.72

Table 3 (continued)

	Comparison	Subject	Students	Assignment method	Computer components	Baseline measure	Learning measure	Effect size
Harrington (1999)	Conventional instruction (n = 61) vs. computer-based instruction (n = 33)	Statistics	Graduate students in social work	Different course sections across terms	Videos, simulations, exercises, self-quizzes; feedback via e-mail	GPA	Final course grade	d = -.50
Arús et al. (2017)	Conventional instruction (n = 15) vs. computer-based instruction (n = 14)	Anatomy of temporo-mandibular joint	Dentistry students	Random by student	Computerized lessons involving text, pictures, animations, and videos	10-item multiple-choice pretest over content to be learned	Posttest over content learned	d = -1.24
McDonough and Marks (2002)	Conventional instruction (n = 18) vs. computer-based instruction (n = 19)	Behavior therapy	3rd year medical students	Random by students	Case study examples of diagnosis and treatment	15-item multiple-choice test over content to be learned	Identical 15-item multiple-choice test over content learned	d = -.67
Pei et al. (2020)	Conventional instruction (n = 57) vs. computer-based instruction (n = 68)	Photosynthesis	Middle school students	Different course sections within a term	Computerized lessons involving demonstration, questions, writing exercises	Multiple choice and short answer pretest over content to be learned	Identical posttest over content learned	d = -.56
Kunnath and Kriek (2018)	Lecture instruction (n = 10) vs. guided computerized (n = 10) vs. autonomous computerized instruction (n = 10)	Physical science	High school students	Random by student	Computerized simulations of photo-electric effect	Pretest over content to be learned	Identical posttest	d_{guided} = 2.91 $d_{autonomous}$ = -1.29

Table 3 (continued)

	Comparison	Subject	Students	Assignment method	Computer components	Baseline measure	Learning measure	Effect size
Chang (2000)	Lecture instruction (n = 72) vs. computer-based instruction (n = 79)	Earth science	High school students	Not specified	Videos, questions, and exercises over geologic hazards	30-item pretest over content to be learned	Identical 30-item posttest over content learned	d = .36 (adjusted for pretest scores)
Fajardo-Lira and Heiss (2006)	Lecture (n = 12) vs. web-based tutorial (n = 19)	Food safety	Undergraduate food science students	Random by students	Computerized lessons, graphics, and interactive case studies	50-item pretest over content to be learned	Identical 50-item posttest	d = 1.35
Jeffries (2001)	Lecture instruction (n = 19) vs. computer-based instruction (n = 23)	Medication administration	Nursing students	Random by students	Computerized self-paced lessons with practice and application	40-item pretest over content to be learned	Identical 40-item posttest over content learned	d = .77
Liu et al. (2010)	Conventional instruction (n = 36) vs. computerized practice problems (n = 36)	Statistics	High school students	Different course sections within a term	Practice problems with feedback, graphics and examples	10-item pretest over content to be learned	Identical 10-item posttest over content learned	d = .52 (adjusted for pretest scores)
McLaughlin and Rhoney (2015)	Paper-based (n = 59) vs. interactive web-based module (n = 57)	Seizure disorders	Graduate pharmacology students	Random by students	Animations, pop-up definitions and assessment questions	None	Final exam	d = .37
Spichtig et al. (2019)	Conventional instruction (n = 213) vs. computerized instruction (n = 213)	Reading proficiency	4th and 5th grade students	Matched pairs based on reading comprehension scores	Computerized reading exercises with comprehension questions	Pretest over reading comprehension and vocabulary	Identical posttest	d = .14
Ebadi and Rahimi (2017)	Face-to-face (n = 10) vs. online peer editing (n = 10)	English as a foreign language	Adult learners at private language school	Different course sections within a term	Online editing of peer writing assignments	Pretest over English writing skills	Posttest over English writing skills	d = 1.46

Table 3 (continued)

	Comparison	Subject	Students	Assignment method	Computer components	Baseline measure	Learning measure	Effect size
Nguyen and Kulm (2005)	Paper-based (n = 49) vs. computer-based math homework (n = 46)	Mathematics	Middle school students	Random by students	Fraction math homework problems with feedback	Pretest over content to be learned	Identical posttest over content learned	d = .55
Huang (2014)	Paper-based (n = 25) vs. online computer-based (n = 32) reading exercises	English reading skills	English as a Foreign Language (EFL) students	Random by students	Computer-based reading exercises	TOEIC scores prior to study	Written free recall	d = .70
Englert et al. (2005) Study 2	Paper-based (n = 12) vs. computerized word exercises (n = 12)	Reading skills	1st grade students at risk for learning disabilities	Within-subjects, counter-balanced design	Word assembly and fill in the blank exercises	None	Reading accuracy of words learned	d = 1.34
Zaini and Mazdayasna (2015)	Paper-based (n = 24) vs. computer-based writing (n = 20)	English language skills	Undergraduate English writing students	Random by students	Computer-based writing exercises with feedback	Pretest writing exercise	Identical posttest writing exercise	d = 1.90
Boblick (1972)	Lecture instruction (n = 29) vs. computer-based instruction (n = 27)	Chemical compounds and formulas	High school chemistry students	Random by students	Computer-based, self-paced lessons	8-item pretest over content to be learned	8-item posttest over content learned	d = .54
Kiliçkaya (2015)	Lecture-based (n = 15) vs. computer-based (n = 18) vs. mixed grammar lessons (n = 17)	English language grammar	English as a Foreign Language (EFL) students	Matched by pretest scores	Computer-based grammar exercises	50-item pretest over content to be learned	Identical 50-item posttest	$d_{Computer}$ = .91 d_{Mixed} = 1.64

were given the same amount of time in class to complete either the paper-based or computer-based drills while their performance was monitored and evaluated (by instructors or by the computer, respectively). No significant differences in math achievement occurred as a result of whether the drills took place on paper or on computer. Along similar lines, Olkun (2003) found that fourth and fifth grade students' learning of geometry principles did not differ significantly after spending the same amount of class time working on creating geometrical patterns to match a visual model provided, either by moving and assembling pieces of wood that were cut into different shapes, or by using the computer to assemble the shapes into patterns on the computer screen. In both cases, students could determine their accuracy by visually comparing their created patterns with those of the models provided. Cakir and Simsek (2010) found that seventh grade students demonstrated no significant differences in mathematics achievement after working through story problems on paper versus on the computer (with corrective feedback provided by the instructor or the computer, respectively). Similarly, Wang and Sleeman (1993) found no significant differences in business students' learning of operations management as a function of whether they spent 20 min completing postlecture review questions after each class on the computer versus on paper (with the option to request help from the computer or instructor, respectively, if they did not know the answers). Similar results were found for university students completing homework on accounting case problems using computers versus paper (Oglesbee et al. 1988), and university students completing extra credit problems in accounting via paper and pencil (with instructor feedback) versus online or via an intelligent tutoring system (with computerized feedback) (Hahn et al. 2013). In all of these studies, students received traditional classroom instruction as part of their courses, and worked on the practice problems as part of their course activities where they had opportunities to receive feedback on their performance. Thus, both methods (computerized vs. noncomputerized problems) provided practice at learning the course material such that one method did not afford any learning advantages over the other.

Other studies involved similar affordances in information delivery between computerized and conventional approaches (i.e., both approaches provided comparable amounts of access to, and practice with, the learning materials), and observed no significant learning advantages either way. Yildirim et al. (2001) compared ninth grade students' learning of biology information delivered via conventional classroom instruction versus computerized modules. Following an introductory lecture over the topics, students either learned the topics through conventional lecture and laboratory assignments, or they learned the topics in the computer lab by completing computerized modules consisting of text links and videos over the information. Both groups spent the same amount of time learning the material (5 hours per week over 3 weeks). Although the group that completed the computerized modules showed a slight advantage on an achievement test assessing declarative knowledge (e.g., facts and terms), conditional knowledge (e.g., processes and relationships), and procedural knowledge (e.g., application of knowledge for problem solving or evaluation), these differences were not significant. Nguyen and Paschal (2002) found that biomedical engineering students' learning of ultrasound concepts was not significantly different whether they received conventional classroom instruction over 2 weeks, or spent the same amount of time in a computer lab completing a computerized module (consisting of text, links, and videos) over the same information. Tilidetzke (1992) found that undergraduate students' learning of college algebra concepts did not differ whether they learned these concepts over two class periods via classroom instruction versus the same two class periods using a computerized program in a computer lab. Lee et al. (1997) found that medical students' knowledge of acid-based problem solving did not differ significantly following a 2.5-h face-to-face workshop involving coverage of acid-based physiology and solving of case studies, compared to the same time spent on the same activities delivered via a computerized program. Although recall of factual knowledge did not differ between the two groups, the face-to-face group actually showed a small but significant advantage in problem solving application assessed through vignettes.

In other studies, the conventional instruction involved learning advantages that the computerized instruction did not. In these studies, computerized instruction resulted in negative effects on learning. In some of these studies, the conventional instruction involved more opportunities to engage with the learning material. Delafuente et al. (1998) compared students' learning of pharmacy calculations from examples provided during conventional lecture-based instruction, versus example problems worked via computer. Lecture-based instruction was scheduled, whereas students in the computer-based group could access the problems on their own computers or from a computer lab anytime during normal business hours. The scheduling flexibility provided to students in the computer-based group appeared to be a disadvantage, however, as some of the students in this group reported spending little time on the computer-based problems, and others reported skipping some of the problems or delaying working on them until shortly before exams. Along similar lines, Vichitvejpaisal et al. (2001) found that medical students' learning of arterial blood gases was significantly better after reading the textbook and working on assignments over the material, compared to working on the assignments using computerized instruction that involved text and videos. Relative to the textbook, the computerized components ended up taking more time to view, which led to fewer completed assignments due to time constraints in the computerized instruction group. Harrington (1999) found that students who completed a conventional face-to-face statistics course earned higher final grades than students who learned the same material through computerized instruction that involved videos, exercises, and quizzes. Both groups received the same quizzes and homework assignments. The learning advantage for the face-to-face course appeared to be driven partly by the extra time spent discussing homework assignments in class, which was not possible for students using the computerized instruction.

Computerized instruction may sometimes hinder opportunities to engage with the learning material when students do not have access to the instructor for assistance or questions. In some studies, students completed the computerized instruction in a lab without access to an instructor, and showed learning detriments relative to the group of students who received face-to-face instruction. Arús et al. (2017) compared dental students' learning of the temporomandibular joint as a function of examining and interpreting MRI images of the joint in a conventional classroom, versus computerized modules completed in a computer lab involving text, images, and videos over the same information. Although both groups completed quizzes and exercises over the material and spent the same amount of time (15 hours distributed over four sessions) learning the material, students in the computer lab did not have access to the instructor for assistance. Similarly, McDonough and Marks (2002) found that medical students' learning of phobia diagnosis and treatment was better following 90 min of working through four case study questions in a face-to-face classroom with an instructor, versus 90 min of working through the same four questions via a computerized program in a computer lab with no access to the instructor. Pei et al. (2020) found that sixth grade students' learning of photosynthesis over three class periods was better following conventional classroom instruction versus computerized instruction carried out in a computer lab involving text, images and animations. In these studies, students receiving computerized instruction were responsible for monitoring and regulating their own understanding of the material, which may have been less effective without an instructor present who could answer questions and clarify concepts. Indeed, the lack of a live instructor may be detrimental particularly for lower-performing students, as Harrington (1999) found that the advantage of the face-to-face instruction over the computerized instruction was stronger for students with lower GPAs than for students with higher GPAs. Some evidence for the benefits of *guided* computerized instruction may be provided by Kunnath and Kriek (2018), who found that high school students' learning of the photoelectric effect was better following instructor-led lessons on the blackboard in the classroom, versus students' independent use of a computerized program to demonstrate the concepts. Learning was best, however, when the instructor operated the computerized demonstrations to explain the concepts.

The studies reviewed so far show that computerized instruction does not benefit learning when it does not involve unique affordances for learning, and that computerized instruction can actually be detrimental to learning if it *lacks* the affordances involved in conventional instruction. When computerized instruction does involve unique affordances for learning; however, it can produce benefits on learning. In some studies, the computerized instruction afforded opportunities for retrieval practice. For example, Chang (2000) found that high school students' learning of earth science concepts was better following computerized instruction that involved videos of a geologic hazard (e.g., debris flow) followed by questions about the hazard and use of resources (e.g., textbooks, maps) to answer the questions, compared to lecture-based instruction in which the same information was simply provided by the instructor. Fajardo-Lira and Heiss (2006) found that food science students learned information about food safety better if they completed a computerized lesson involving practice quizzes and case studies, compared to the same information delivered via lecture. Jeffries (2001) found that nursing students' knowledge of medication administration was better following a computerized lesson involving links to the information, along with practice quizzes and feedback, compared to a lecture over the information. Liu, Lin, and Kinshuk (2010) examined high school students' learning of statistics by targeting specific misconceptions about correlation. Students received material and worked through practice exercises on correlation either on the computer or via lecture from the instructor, each for about 80 min. The computerized task also involved an initial test to expose students misconceptions about correlation (whereas the lecture approach did not), and produced significant enhancements in students' understanding of correlation. Along similar lines, McLaughlin and Rhoney (2015) found that students' learning about seizure disorders was significantly enhanced by completing an online preclass activity involving interactive links and assessment questions, compared to a paper handout of the information. Finally, Spichtig et al. (2019) found that fourth and fifth grade students' reading achievement was significantly enhanced by using a computerized program that provided reading exercises and comprehension questions with feedback, compared to the same amount of time receiving instructor-led reading lessons. The instruction (computerized vs. conventional) took place at least four times per week during the duration of the academic year, so some of the advantages of the computerized exercises could have been further attributed to spaced retrieval practice over time.

In other cases, computerized instruction afforded more time spent on the learning activities and resulted in learning benefits. Ebadi and Rahimi (2017) found that the writing skills of students taking English as a foreign language (EFL) were significantly improved as a function of practicing to edit their classmates' writing via an asynchronous online editing program that they could access at any time, compared to editing during class time in small groups. Class time for editing was limited, but students using the online program reported that the accessibility of the program provided more time to reflect on their edits and engage in reviewing and revision.

Finally, in some studies computerized instruction was given the same amount of time as conventional instruction, but the computerized instruction afforded more effective use of that time. Nguyen and Kulm (2005) compared middle school students' math achievement after completing 4.5 h of homework practice problems (30 min a day, 3 days per week, over 3 weeks) either on the computer, or in class using paper and pencil. Although the homework problems and overall time spent were the same, computerized practice provided immediate feedback over the correctness of students' answers (whereas students using paper and pencil had to wait for the instructor to grade and return their work the following day), and this resulted in a greater number of practice problems completed on the computer versus paper and pencil, and an ultimate advantage for the computer group on a posttest over the concepts learned. Huang (2014) compared university EFL students' learning of English via a 4-h activity that involved reading an English text with access to dictionaries either on the computer (i.e., reading on the screen with link to an electronic dictionary) or on paper (i.e., reading a hard copy and using a paper dictionary). Even though both groups spent the same amount of time on the reading activity, the computerized version of the task produced significant enhancements in reading comprehension. Qualitative comments from students indicated that the electronic dictionary links provided easy and efficient access to word meanings, which they needed for comprehending the text. Similar results were found by Englert et al. (2005), who observed significant enhancements in first graders' reading skills after completing reading exercises on the computer versus on paper. Although the exercises were identical between computer and paper (e.g., unscrambling words and fill-in-the-blank activities), and students spent the same amount of time on each, they received immediate feedback on their performance with the computerized task but had to wait for feedback from the instructor with the paper-and-pencil task. Zaini and Mazdayasna (2015) as well found that EFL students enhanced their writing skills to a greater degree by practicing writing tasks on the computer (where they received immediate feedback about mistakes) versus the same tasks on paper (where they had to wait for instructor feedback until the next class).[2] Boblick (1972) observed significant enhancements in chemistry students' understanding of chemical formulas after completing computerized lessons and practice exercises (e.g., writing the chemical formula when given the compound) compared to a lesson and practice exercises led by the instructor. Although both groups engaged with retrieval practice, the computerized lesson delivered practice exercises according to students' performance and allowed more practice at the things they had not yet learned.

In summary, replacing conventional instruction with computerized instruction does not always result in learning advantages. Computerized instruction can be advantageous when it affords opportunities for retrieval practice, extra time spent learning the material, or more efficient feedback that makes more effective use of instructional time. However, computerized

[2] In these studies it cannot be determined whether the immediacy of the feedback per se was responsible for the learning gains. Some studies have directly explored the timing of feedback and have found that feedback can be more beneficial for learning some types of materials—particularly those involving non-overlapping materials—when it is delayed rather than provided immediately (Carpenter and Vul 2011; Corral et al. in press). In the studies reviewed here, however, the answer to any one item (such as a math problem or grammatical rule) could have informed students' answers to subsequent problems of the same type. Beyond the timing of feedback per se, therefore, the immediacy of the correct answers could have changed the way that students approached subsequent questions of the same type, increasing the likelihood that they would apply the correct answer.

instruction can actually be less effective when it allows students to spend less time on the learning materials or reduces opportunities for instructor interaction and feedback. Instructor involvement could be important in situations where students need additional explanation and assistance that cannot be achieved via the computer alone. Indeed, Kiliçkaya (2015) found that EFL students' learning of English grammar skills was better following computerized instruction versus conventional classroom instruction, but the best learning occurred when students received a combination of conventional and computer-based instruction (see also Kunnath and Kriek 2018). Instead of exploring computerized instruction in lieu of conventional instruction, therefore, some studies have explored the effects of computerized instruction used as a *supplement* to conventional instruction. We review those studies next.

Conventional Classroom Instruction Versus Conventional Instruction Supplemented with Computerized Instruction Table 4 contains studies that compared the use of computer-based instruction combined with conventional instruction. These studies involved students from the same courses who received conventional instruction only, versus the same conventional instruction combined with computerized learning activities over the course material. In these cases the effects of the computerized learning activities were generally positive.

A likely contributor to these positive effects is that the computerized activities afforded additional opportunities to engage with the learning material. Sometimes these additional learning opportunities were in the form of online videos to reinforce the concepts learned in classes over marketing (Lancellotti et al. 2016) and pharmacy (Baumann-Birkbeck et al. 2015; Karaksha et al. 2014). Further, Bryner et al. (2008) found that medical students' learning of anatomy was enhanced (although not significantly) by utilizing, in addition to their regular course materials, web-based modules that provided videos and links to additional information. Ebadi and Rahimi (2018) found that supplementing conventional classroom instruction with online videos and links to additional resources significantly enhanced students' learning of English writing and critical thinking skills (although sample sizes were small in this study). Consistent with the idea that extra opportunities to engage with the material enhance learning, Karaksha et al. (2014) found that the frequency with which students accessed the online videos correlated significantly and positively with their exam scores on questions over that content.

In other studies, the computerized components provided extra learning opportunities in the form of interactive activities. Verdugo and Belmonte (2007) found that primary school children learned English language skills better from classroom instruction combined with online digital stories that involved illustrated narratives and simple tasks to be completed via audio instructions (e.g., click on the apple), compared to classroom instruction alone. Liu et al. (2018) found that middle school students' English skills were significantly enhanced, over and beyond classroom instruction, when the students created their own narrated digital stories using the vocabulary and grammatical skills that they were learning in class.

In other studies the computerized activities provided opportunities for retrieval practice. Ebadi and Ghuchi (2018) observed significant enhancements in students' English vocabulary as a result of conventional instruction combined with an online program that provided vocabulary quizzes, compared to conventional instruction alone. González et al. (2010) observed significant benefits on students' statistical knowledge by incorporating into conventional instruction access to web-based practice problems by giving half of the class (group A) access to these problems early in the course, and the other half (group B) access to the problems later in the course. Zubas et al. (2006) found that conventional instruction supplemented with web-based practice

Table 4 Comparison of supplemental computer-based instruction versus conventional instruction on student learning outcomes

	Comparison	Subject	Students	Assignment method	Computer components	Baseline measure	Learning measure	Effect size
Lancellotti et al. (2016)	Conventional instruction (n = 232) vs. incorporation of web-based videos (n = 247)	Marketing	Undergraduate students	Different course sections across terms	Short online videos over concepts from lecture	Exam 1 scores (prior to video access)	Exam 2 scores	d = .671
Baumann-Birkbeck et al. (2015)	Conventional instruction (n = 53) vs. incorporation of web-based animated videos (n = 23)	Mechanisms of action for pharmacological drugs	Undergraduate pharmacology students	Different course sections across terms	Animated and narrated videos	GPA prior to study	Short-answer exam over content learned	d = .46
Karaksha et al. (2014)	Conventional instruction (ns = 52-53) vs. incorporation of web-based animated videos (ns = 23-25)	Mechanisms of action for pharmacological drugs	Undergraduate pharmacology students across two semesters	Different course sections across terms	Animated and narrated videos over mechanisms of drug action	GPA prior to study	Exam scores over content learned	$d_{Semester1}$ = .20 $d_{Semester2}$ = .46
Bryner et al. (2008)	Conventional instruction (n = 34) vs. incorporation of interactive computerized modules (n = 42)	Anatomy and system-related topics	1st and 2nd year medical students	Random by students	Illustrations, animations, narrations, self--assessment	None	Multiple-choice quiz over concepts learned	d = .24
Ebadi and Rahimi (2018)	Conventional instruction (n = 10) vs. incorporation of web-based activities (n = 10)	English as a foreign language	Adult learners at private language school	Different course sections within a term	Online videos and resources	Pretest over critical thinking (CT) and writing skills in English	Identical posttest	d_{CT} = 1.35 $d_{writing}$ = 1.55
Verdugo and Belmonte (2007)	Conventional textbook instruction (n = 103) vs. incorporation of digital stories (n = 105)	English as a foreign language	6-year-old primary school children	Different course sections within a term	Internet-based interactive digital stories with questions and prompts	Pretest over basic English proficiency	3-part posttest over more advanced English proficiency	d_{Part1} = .49 d_{Part2} = .30 d_{Part3} = .88

Table 4 (continued)

	Comparison	Subject	Students	Assignment method	Computer components	Baseline measure	Learning measure	Effect size
Liu et al. (2018)	Conventional instruction (n = 32) vs. incorporation of digital story telling (n = 32)	English as a foreign language	Middle school students	Different course sections within a term	Creation of online stories with text and illustration	Course grades from previous semester	Achievement test over fluency, translation, and listening comprehension	$d_{fluency}$ = .68 $d_{translation}$ = .35 $d_{listening}$ = .00
Ebadi and Ghuchi (2018)	Conventional instruction (n = 20) vs. incorporation of web-based app (n = 20)	English as a foreign language	Undergraduate and masters students	Random by student	Web-based vocabulary exercises	40-item multiple-choice pretest over vocabulary knowledge	Identical posttest	d = .71
González et al. (2010)	Conventional instruction (n = 101) vs. incorporation of computerized practice problems (n = 101)	Statistics	Dentistry students	Within-subjects, practice problems over some topics from the course (A) vs. other topics (B)	Practice problems with feedback	None	Final course exam over topics practiced vs. not practiced	d_A = .44 d_B = .06
Zubas et al. (2006)	Conventional instruction (n = 12) vs. incorporation of web-based tutorial (n = 10)	Diabetes	Undergraduate nutrition students	Random by students	Case studies and practice questions	50-item pretest over content to be learned	Identical 50-item posttest over content learned	d = 1.03
Cerra et al. (2014)	Conventional instruction (n = 64) vs. incorporation of web-based drawing tools (n = 57)	Industrial engineering	Undergraduate students	Random by students	Graphical drawing exercises with feedback	Pretest over knowledge of technical drawing	Posttest over new drawing exercises	d = .44
Botezatu et al. (2010)	Conventional instruction (n = 24) vs. incorporation of virtual case studies (n = 25)	Haematology and cardiology	Medical students	Random by student	Computer-based virtual case studies with diagnosis and treatment exercises	None	Computer and paper-based posttests over diagnosis and treatment	Computer: $d_{Haematology}$ = 1.96 $d_{Cardiology}$ = 2.11 Paper: $d_{Haematology}$ = 1.41 $d_{Cardiology}$ = 1.12

Table 4 (continued)

	Comparison	Subject	Students	Assignment method	Computer components	Baseline measure	Learning measure	Effect size
Bortnik et al. (2017)	Face-to-face chemistry lab ($n = 25$) vs. incorporation of pre-class virtual experiments ($n = 25$)	Chemistry	Undergraduate students	Random by student	Videos, animations, simulated procedures	Pretest over content learned	Posttest over content learned, lab reports over 10 criteria	$d_{posttest} = .86$ $d_1 = 1.56$ $d_2 = .45$ $d_3 = 1.42$ $d_4 = .37$ $d_5 = .88$ $d_6 = .64$ $d_7 = .22$ $d_8 = .98$ $d_9 = 1.03$ $d_{10} = 1.11$
Du et al. (2011)	Face-to-face ($n = 88$) vs. hybrid course ($n = 40$)	Accounting	Undergraduate students	Different course sections across terms	Pre-class quizzes, post-class, discussion	GPA prior to study	66-item multiple-choice final exam	$d = .08$

quizzes and case studies significantly enhanced nutrition students' knowledge of diabetes. Cerra et al. (2014) found that problem solving practice via computer-based drawing exercises that were made available alongside conventional instruction significantly enhanced students' learning of industrial engineering concepts. Botezatu et al. (2010) found that medical students' learning of hematology and cardiology was significantly enhanced by supplementing conventional instruction with virtual case studies in which students practiced diagnosis and treatment. Bortnik et al. (2017) found that undergraduate students' learning of chemistry was significantly enhanced by completing preclass virtual experiments prior to in-class lab activities, compared to the in-class lab activities without the preclass virtual experiments.

An exception to these positive effects was observed by Du (2011), who found no significant difference in final exam scores between a face-to-face accounting course, versus the same course supplemented with online preclass quizzes. Although preclass quizzes might be expected to benefit learning by engaging a form of retrieval practice, these potential benefits might have been overshadowed by the fact that both sections of the course also completed online post-class quizzes as well. Indeed, there is evidence that postclass quizzes can be more effective than preclass quizzes (McDaniel et al. 2011), and that adding preclass quizzes does little to boost these benefits (Carpenter et al. 2018; Geller et al. 2017). As such, when postclass quizzes are already incorporated as part of the course, the online preclass quizzes may not have provided sufficient affordances for learning above and beyond the retrieval practice provided by the post-class quizzes.

Mobile Devices

Some studies in our search included the use of a portable mobile device—e.g., smartphone or tablet—that students could use during class or take with them to another location. This section includes comparisons of learning with the mobile devices, versus learning of the same information without the use of those devices. Both groups of students (mobile device vs. control) were taught the same information by the same instructor, and received the same criterial test to measure their learning. In cases where students were not randomly assigned to groups, baseline assessments (pretest, GPA) verified that the groups did not differ in their pre-existing knowledge of the content or academic aptitude. The results are shown in Table 5.

In most of these studies, mobile devices afforded additional opportunities for engaging with course material. Learning benefits occurred when students used mobile devices to engage with apps and computerized programs that were designed to provide extra practice with the material via experiments and visual models in undergraduate biology courses (Chang and Yu 2018), visual graphics of geomorphology processes in undergraduate geography courses (Turan et al. 2018), and feedback on rhythm and pitch as students learned a new song in primary school music classes (Debevc et al. 2020). Similar benefits were observed by Siciliano et al. (2011), who found that students learned more information about English gardens if they listened to audio podcast narratives about the gardens while exploring them, compared to students who did not listen to the podcast narratives. In all of these studies, students from the same classes used their regular course materials and either used the mobile devices as an additional resource or did not, so the benefit of the mobile devices was likely attributable to the additional opportunities they afforded for engaging with the course material.

Table 5 Comparison of mobile devices versus conventional instruction on student learning outcomes

	Comparison	Subject	Students	Assignment method	Mobile device components	Baseline measure	Learning measure	Effect size
Chang and Yu (2018)	Lab experiments using lab manual (n = 46) vs. incorporation of mobile-based app (n = 47)	Biology	Undergraduate students	Different course sections within a term	Mobile-based app with text, images, 3-D graphics, and dissection procedures	Midterm exam scores	Final exam scores over 5 experimental skills	$d_{inquiries}$ = .36 $d_{hypothesis}$ = .39 $d_{procedures}$ = .69 $d_{collaborations}$ = .15 $d_{reflections}$ = .39
Turan et al. (2018)	Conventional instruction (n = 55) vs. mobile-based app (n = 40)	Geomorphology	Undergraduate geography students	Different course sections within a term	Mobile-based app with text, images, and 3-D graphics	Pretest over content to be learned	Posttest over content learned	d = 3.58
Debevc et al. (2020)	Conventional instruction (n = 21) vs. mobile-based app (n = 21)	Learning a new song	Primary school music students	Random by student	Mobile-based app with practice over pitch, rhythm, visual notes	5-item multiple-choice factual pretest	Posttest over singing ability	d = .21
Siciliano et al. (2011)	Site visits to English gardens with audio podcasts (n = 11) vs. without (n = 11)	History and design of English gardens	Undergraduate horticulture and landscape architecture students	Random by student	Audio podcasts delivered via iPod or MP3 player	None	Written quiz and oral interview over content learned in 3 gardens	Written quiz: $d_{Garden1}$ = 1.39 $d_{Garden2}$ = .17 $d_{Garden3}$ = .50 Oral interview: $d_{Garden1}$ = .08 $d_{Garden2}$ = .96 $d_{Garden3}$ = 1.25
Nikou and Economides (2018)	Paper-based (n = 54) vs. mobile app-based homework (n = 54)	Electric fields and currents	High school science students	Random by student	Mobile app-based homework	Pretest over content to be learned	Posttest over content learned	d = .54 (adjusted for pretest scores)
Diliberto-Macaluso and Hughes (2016)	Textbook (n = 28) vs. mobile app (n = 26)	Brain structure and function	Undergraduate psychology students	Different course sections within a term	Use of smartphone to access 3D brain anatomy, damage, disorders, case studies	Pretest over content to be learned	Posttest over content learned	d = .80
Li and Tong (2019)	Paper-based (n = 50) vs. mobile app-based flashcards (n = 50)	Chinese as a foreign language	4th and 5th grade students	Random by student	Digital flashcards over Chinese vocabulary on iPad	Pretest over words to be learned	Posttest over reading and listening of words learned	$d_{reading}$ = 1.44 $d_{listening}$ = 4.60

Table 5 (continued)

	Comparison	Subject	Students	Assignment method	Mobile device components	Baseline measure	Learning measure	Effect size
Shadiev et al. (2018)	Conventional instruction (n = 27) vs. tablet PC (n = 26)	English as a foreign language	Middle school students	Different course sections within a term	Tablet PC-based grammar and vocabulary exercises	Pretest over content to be learned	Posttest over content learned	d = 1.52 (adjusted for pretest scores)
Yarahmadzehi and Goodarzi (2020)	Paper-based (n = 20) vs. mobile app-based quizzes (n = 20)	English as a foreign language	Undergraduate students	Different course sections within a term	Mobile app-based vocabulary quizzes	50-item multiple-choice pretest over vocabulary knowledge	20-item multiple-choice posttest over vocabulary learned	d = .68
Chang et al. (2016)	Tablet PC (n = 31) vs. paper-based activities (n = 27)	Geometry	High school students	Different course sections within a term	Tablet PC with 3-D graphics and practice problems	25-item pretest over content to be learned	Identical 25-item posttest over content learned	d = .76 (adjusted for pretest scores)
Chen et al. (2008)	Personal digital assistants (PDAs, ns = 16-19) vs. physical flashcards (ns = 16-19)	Statics	Undergraduate engineering students	Within-subjects; students alternated use of PDAs vs. flashcards	Use of PDA to submit answers to concept questions during class	Prerequisite course grades and GPA	Quizzes over concepts in homework	d = .36 (adjusted for prerequisite grades and GPA)
Nouri et al. (2014)	Field trips with smartphones (n = 15) vs. without smartphones (n = 15)	Science of plants and trees	5th grade students	Random by students	Use of smartphones to scan QR code to learn about plant/tree species and take photos	10-item test over content to be learned	Identical 10-item posttest over content learned	d = .29 (adjusted for pretest scores)
Su and Cheng (2014)	Conventional lecture (n = 34) vs. mobile app (n = 34)	Ecology of insects	4th grade students	Different course sections within a term	Smartphone-based app with learning activities	Pretest over knowledge of insects	Posttest over information learned	d = .10

In other studies, learning activities via mobile devices were compared to learning activities delivered via other means, such as traditional classroom instruction or paper-based activities. In these cases, even though the amount of instruction was comparable, the mobile devices afforded additional learning opportunities above and beyond the traditional activities, and resulted in better learning. For example, Nikou and Economides (2018) compared high school students' learning of science concepts through paper-based homework followed by in-person discussions, compared to the same homework completed via smartphones or tablets followed by online discussions. Although both groups completed homework assignments over the same concepts, the in-person discussions proved to be difficult to schedule and did not always occur, lending an advantage to the mobile device group in the form of additional discussions of the homework. Diliberto-Macaluso and Hughes (2016) observed learning advantages in introductory psychology as a result of using a mobile app, compared to the course text, to complete an in-class worksheet on the brain and central nervous system. Though the course text and app covered the same basic information, the app contained additional features to demonstrate the learning material, including rotated 3D images of brain structures and case studies. Li and Tong (2019) found that vocabulary knowledge and listening comprehension of new Chinese words was better when students used iPads to study from electronic flashcards that provided practice at both vocabulary and audio pronunciations, compared to paper flashcards that only provided vocabulary practice. Shadiev et al. (2018) found that students' learning of English language skills was superior following use of a mobile app–based program on tablet PCs that they could access and use at any time, compared to learning activities completed in paper workbooks that students could only access during class. Thus, a clear affordance of mobile devices is that they allow extra opportunities to engage with learning material, sometimes outside of scheduled classes.

In other studies, mobile devices provided opportunities for retrieval practice. These studies observed significant benefits of practice quizzes completed on mobile devices compared to paper-and-pencil quizzes for undergraduate students learning English vocabulary (Yarahmadzehi and Goodarzi 2020), and high school students learning geometry (Chang et al. 2016). Although students in both groups (mobile app vs. paper) completed multiple practice quizzes, the mobile devices provided immediate feedback about their accuracy after each quiz, whereas the paper-based quizzes had to be graded by an instructor and were sometimes returned at a later time. The immediate knowledge of results afforded by the mobile apps likely benefited learning by allowing students to identify and correct mistakes as they progressed.

When mobile devices do not afford any identifiable advantages for learning, they produce no observable benefits on learning. Chen et al. (2008) found that the effects of in-class practice quizzes on statistics learning did not differ significantly whether students provided answers via digital response devices or paper flashcards. In both cases, the instructor could view students' responses and provide corrective feedback and discussion related to the concepts in real time, so one method of delivery (digital vs. paper) did not afford any particular advantages over the other with respect to opportunities for retrieval practice and feedback.

Along similar lines, in Nouri et al.'s (2014) study, fifth grade students showed no significant differences in learning about plant and tree species following an outdoor field activity in which they either used smartphones to scan the QR codes attached to the different species and read about them, or were guided through each of the species by a teacher. In Su and Cheng's (2014) study, fourth grade students learned basic information about insects in their class before using a smartphone-based app to explore and learn further information about insects in an outdoor insect ecology area, versus learning the information through classroom instruction presented by the teacher, and demonstrated similar achievement test scores over the material. In both of these studies, students in both groups (smartphone vs. teacher-led presentation) received information about the learning material, and the smartphones acted primarily as a means of delivering the information without providing any identifiable affordances that were not also available from the teacher's presentation.

Simulations

This section includes comparisons of learning using live activities versus computer simulations. In these studies, students learned a particular process or procedure via a hands-on physical task (e.g., using physical equipment to carry out an experiment) compared to a simulated version of the task delivered via computer. The results thus reveal effects of learning using the "real thing" compared to a digital version designed to simulate it. Both groups of students (live vs. simulation) were taught the same information by the same instructor, and received the same criterial test to measure their learning. In cases where students were not randomly assigned to groups, baseline assessments (pretests, GPA) verified that the groups did not differ in their preexisting knowledge of the content or academic aptitude. The results are shown in Table 6.

When the same basic procedures can be delivered through live versus simulated methods and simulated methods do not afford any identifiable learning advantages, it appears there are no consistent benefits or costs to simulations. Dewhurst et al. (1994) observed a slight (nonsignificant) advantage in students' learning of principles of intestinal absorption when the students carried out experiments via computer simulations compared to laboratory-based experiments on a real rat. Wiesner and Lan (2004) observed slight (nonsignificant) negative effects on learning in two of three chemical engineering topics as a result of students carrying out simulated experiments with interfaces designed to resemble physical lab equipment, versus using the physical lab equipment. Although the sample sizes were small in both of these studies, neither showed reliable effects on learning as a function of the computerized simulations under conditions in which those simulations did not afford advantages for learning.

Along similar lines, William et al. (2016) found that nursing students' phlebotomy skills were slightly (but not significantly) enhanced when they practiced with a virtual computerized simulation of a patient's arm, compared to a physical model of the arm. Further, Lewis (2015) found that students' learning of classical and operant conditioning principles was not significantly different after students in the class practiced to condition a behavioral response on a classmate, versus each student using computer software to condition a response on a virtual rat. Finally, Gibbons et al. (2004) found no significant benefits or detriments of computerized simulations over physical activities in students' learning of chromosome analysis (i.e., when students completed karyotyping exercises with computerized images, versus using scissors and glue to paste chromosome images on paper).

When the simulations afforded identifiable advantages that the physical tasks did not, however, they resulted in significant learning benefits. A large positive effect was observed by Liu and Su (2011), who explored high school students' learning of electric wiring procedures via interactions with physical equipment versus computerized simulations. Over a 5-week period, students carried out electrical wiring procedures using either physical devices or computer simulations of those same

Table 6 Comparison of computerized simulations vs. live demonstrations on student learning outcomes

	Comparison	Subject	Students	Assignment method	Simulation components	Baseline measure	Learning measure	Effect size
Dewhurst et al. (1994)	Live experiments (n = 8) vs. computerized simulations (n = 6)	Physiology	Undergraduate students	Not specified	Computer simulations of interactive experiments	50-item short-answer pretest over course concepts	Identical 50-item short-answer posttest	d = .26
Wiesner and Lan (2004)	Physical experiments (n = 16) vs. computerized simulations (n = 8)	Unit operations	Undergraduate chemical engineering students	Random by student	Computer simulations of heat transfer, gas absorption, humidification	None	Exam questions over heat transfer, gas absorption, humidification	d_{heat} = .08 d_{gas} = -.87 d_{humid} = -.59
William et al. (2016)	Plastic physical model (n = 33) vs. computerized simulation (n = 29)	Phlebotomy	Nursing students	Random by student	Computer simulations of blood drawing	None	Competence checklist over 5 phlebotomy skills	d_{pain} = .10 $d_{duration}$ = .41 $d_{hematoma}$ = .24 $d_{reinsert}$ = .02 d_{time} = .42
Lewis (2015)	Live human (ns = 37-38) vs. computerized demonstrations (ns = 37-38)	Classical and operant conditioning principles	Undergraduate psychology students	Random by students	Computer-based classical/operant conditioning demonstrations	None	Exam over concepts learned	$d_{Classical}$ = .09 $d_{Operant}$ = .36
Gibbons et al. (2004), Study 1	Physical tools (n = 24) vs. computerized simulations (n = 23)	Chromosome analysis	Undergraduate biology students	Random by students	Simulated karyotyping exercises	None	Exercises over procedure learned	d = .31
Liu and Su (2011)	Live demonstrations (n = 83) vs. computerized simulations (n = 86)	Electrical wiring	High school students	Different course sections within a term	Computer simulations of wiring procedures	Pretest over electricity concepts	30-item multiple-choice test over learned content	d = 1.53
Hsiao et al. (2019)	Physical tools (n = 63) vs. 3D modeling software (n = 33)	Physics	High school students	Different course sections within a term	Creation of windmill generator	20-item multiple-choice pretest over scientific concepts	Identical posttest	d = .34
Mathiowetz et al. (2016)	Live demonstrations (n = 32) vs. computerized 3D models (n = 53)	Anatomy	Graduate occupational therapy students	Different course sections within a term	Computerized 3-D model of anatomical structures	GPA in prerequisite courses	Final exam scores and final course grade	d_{exam} = -.40 d_{grade} = -.52

procedures. Students who worked with physical devices approached the instructor when they made errors or had questions and sometimes had to wait for assistance, whereas students who worked with the computerized simulations received immediate feedback from the computer that allowed them to correct their mistakes quickly and repeat the procedure. Some of the advantage for the simulation group could therefore be driven by extra time spent practicing the procedures. In addition, students practiced the procedures in a spaced fashion, once per week over the course of 5 weeks, so some of the learning advantage of the simulated procedures could be due to a greater amount of spaced practice.

Similar factors could have contributed to the findings observed by Hsiao et al. (2019), who compared high school students' learning of concepts related to wind power generation after students learned to create windmill generators by using physical tools (e.g., drills and saws) versus 3D printers. Both groups learned how to use either the physical tools or 3D printers across eight weeks (with 100 min of class per week), and both groups received lectures over the to-be-learned concepts and active supervision from the instructor.[3] The 3D printers were available for each student, whereas only a few of the physical tools were available and had to be shared, limiting the time that each student could spend using these tools. Similar to the findings of Liu and Su (2011), therefore, the advantage of the 3D printers could have been due to more time spent on the learning activities that was spaced across a number of weeks.

In other studies, there is evidence that the simulations may have *hindered* students' tendencies to engage in extra practice or space out their learning. In the study by Mathiowetz et al. (2016), occupational therapy graduate students enrolled in a functional anatomy and kinesiology course completed either a live or online gross anatomy lab involving demonstrations with physical versus computerized cadavers, respectively. The live lab involved students viewing instructor-led dissections and demonstrations, whereas the computerized simulations involved students interacting with 3D models of anatomical layers and structures. Although both groups (live vs. online lab) used the same lab manual and learned through interactive quizzes, the group attending the live anatomy lab earned higher final exam and final course grades. Importantly, a survey administered at the end of the course revealed that students in the live anatomy lab (which was scheduled at specific times) reported spending more consistent time on the lab activities throughout the module, whereas students in the online lab (which was self-paced) tended to spend little time on the lab activities until shortly before exams. Thus, although computerized simulations may afford the opportunity for extra practice distributed over time, learning does not benefit if those affordances are not utilized and students instead engage in the all-too-common practice of "cramming" before exams (e.g., Corral et al. 2020).

Animations

This section includes comparisons of computerized animations versus the same information learned through a visual still image. Both groups of students (animation vs. still image) were taught the same information by the same instructor, and received the same criterial test to measure their learning. In cases where students were not randomly assigned to groups (which happened in only two studies), a baseline pretest verified that the groups did not differ in their preexisting knowledge of the content. The results are shown in Table 7.

[3] A third group was included that used 3-D printers but did not receive the same type of lecture-based guidance from the instructor. Due to the difference in instructional procedures, this "experiential learning" group is not included in the comparisons.

Table 7 Comparison of animations versus still images on student learning outcomes

	Comparison	Subject	Students	Assignment method	Multimedia components	Baseline measure	Learning measure	Effect size
McClean et al. (2005)	Still images presented in overheads (n = 12) vs. animation (n = 14)	Protein translation	Undergraduate biology students	Random by students	In-class presentation using 3-D animation	4-item multiple-choice pretest over content to be learned	Identical 4-item posttest over content learned	d = .74
Daly et al. (2016)	Still images (ns = 13-14) vs. animation (ns = 13-14)	Physiology and Pharmacology	Undergraduate life science majors	Random by students	In-class presentation using 3-D animation	None	Essay-style question over the content taught	d = .22
Perry et al. (2011)	Still images and text (n = 20) vs. still images, text, and animations (n = 20)	Surgical procedures for cleft palate	Undergraduate students in communication sciences and disorders	Random by students	Computerized presentation using 3-D video animation	None	10-item multiple-choice test over content learned	d = 1.41
Mešić et al. (2015)	Static diagrams (D, n = 19) vs. animations (A, n = 17) vs. animation frames (AF, n = 16)	Kinematics	High school physics students	Different course sections within a term	In-class lesson and activities using diagrams from text, animations, or still frames from animations	15-item multiple-choice test over content to be learned	Identical 15-item posttest	d_A = .71 d_{AF} = .75
Kühl and Münzer (2019)	Static pictures vs. animations with either more information (ns = 48-49) or less information (ns = 50-52)	Physics	High school students	Random by student	Computerized animations of Kepler's Law	None	Factual knowledge test (over dynamic and non-dynamic components) and transfer test	More information: $d_{dynamic}$ = .50 $d_{non\text{-}dynamic}$ = .03 $d_{transfer}$ = .45 Less information: $d_{dynamic}$ = .59 $d_{non\text{-}dynamic}$ = .05 $d_{transfer}$ = .22

McClean et al. (2005) included four conditions that varied in their type of exposure to the material before, during, and after the lesson. The groups either (A) Received the lecture with animations and then studied the animations on their own, (B) Studied text material on their own and then received the lecture with animations, (C) Received the lecture with overhead transparencies and then studied the animations on their own, or (D) Studied the text material on their own and then received the lecture with overhead transparencies. To compare the effects of animation while controlling for other types of exposure to the material, our comparison includes only Groups B and D

In two of these studies, animations were compared with static images as a way of presenting the material to be learned. McClean et al. (2005) supplemented an in-class biology lesson with computerized animations versus still images (shown on overhead transparencies) of protein translation, and found that the lecture supplemented with animations produced an advantage (although not significant) on a later posttest over the information learned (although sample sizes were small). Daly et al. (2016) also observed a slight (but nonsignificant) advantage of animations over still images on students' learning of sympathetic neurotransmission via a short in-class demonstration and an immediate test afterward.

In other studies, animations were incorporated into conventional instruction in a way that afforded identifiable learning advantages. In one study, the animations were added to existing lesson contents and could have benefited learning through affording additional opportunities to engage with the material. For example, Perry et al. (2011) observed a benefit of animations in students' learning of a surgical procedure that included still images and a reading text, compared to the same images and text combined with animations. In this case, the animations were included as an additional feature of the learning materials and could have enhanced learning through providing extra information that illustrated the procedure to be learned.

In other studies, animations appear to enhance the effectiveness of retrieval practice. Mešić et al. (2015) introduced the concepts of kinematics via a standard lecture, then provided high school physics students with either animations to illustrate the principles (e.g., two trucks traveling at different speeds), frames of the animations in the form of still images, or static diagrams of the still images that were drawn by the instructor on the chalkboard. One of these methods was incorporated into class discussions and problem solving exercises (e.g., calculating the point at which one truck passes the other). The animations and animation frames were about equally effective, and both produced better learning than the static diagrams on a later posttest over the principles of kinematics. Although not as seemless as the fully animated demonstration, the animation frames were presented sequentially and thus could have illustrated the key principles of motion that were needed to understand the concepts enough to engage effectively with the problem-solving exercises.

Although animations can afford advantages for learning by leveraging general learning principles such as retrieval practice and additional opportunities to engage with the material, animations can also benefit learning by visually illustrating a dynamic process that is hard to capture with still images (e.g., see Mayer and Moreno 2002). Indeed, Kühl and Münzer (2019) presented high school physics students with a lesson on Kepler's laws that included reading material combined with either a static image or an animation demonstrating the changes in a planet's velocity during elliptical orbit. On a later essay-style test over the information, the group that received the animation performed better at recalling content related to dynamic features (i.e., which was illustrated specifically by the animation but not the still image), whereas the two groups performed about equally well at recalling the non-dynamic information (i.e., the fact that the orbit is elliptical, which was illustrated by both the still image and animation).

Games

This section includes comparisons of learning via digital games versus learning of the same information without digital games. Both groups of students (game vs. no game) were taught the same information by the same instructor, and received the same criterial test to measure their learning. In cases where students were not randomly assigned to groups, baseline assessments (pretest, GPA) verified that the groups did not differ in their preexisting knowledge of the content or academic aptitude. The results are shown in Table 8.

Table 8 Comparison of game-based versus conventional instruction on student learning outcomes

	Comparison	Subject	Students	Assignment method	Game-based components	Baseline measure	Learning measure	Effect size
Ellinger and Frankland (1976)	Conventional lecture (n = 52) vs. computerized game (n = 40)	Spatial competition	Undergraduate economic geography students	Random by students	Computerized game to illustrate best location for a business	13-item pretest over content to be learned	Similar 13-item posttest	d = .10
Wiebe and Martin (1994)	Conventional instruction (n = 56) vs. computer-based game (n = 53)	Geography	5th and 6th grade students	Random by students	Computerized game to illustrate geography facts	None	10 multiple-choice and 2 short answer questions over content learned	d = -.01
Dorji et al. (2015)	Conventional lecture with textbook (n = 52) vs. incorporation of computer-based game (n = 69)	Energy consumption and conservation	10th grade physics students	Different course sections within a term	Computerized game simulating energy consumption by household appliances	20-item multiple-choice test over content to be learned	20-item multiple-choice test over content learned	d = .53
Wu (2018)	Conventional lecture (n = 30) vs. computerized game (n = 32)	English as a foreign language	Undergraduate students	Different course sections within a term	Mobile-based game on vocabulary practice	Midterm exam grades prior to study	Final exam grades	d = .79
Su and Cheng (2014)	Conventional lecture (n = 34) vs. game-based app (n = 34)	Ecology of insects	4th grade students	Different course sections within a term	Smartphone-based game with learning activities	Pretest over knowledge of insects	Posttest over information learned	d = .87

Su and Cheng (2014) is duplicated from the previous section on mobile devices

Computerized games appear to be most effective when they afford advantages for learning that conventional instruction does not. When used primarily as a way to deliver the learning material, there appears to be neither benefit nor harm. Ellinger and Frankland (1976), for example, found that economics students who learned about the optimal location to maximize profits for a new business showed no differences in learning as a function of whether they learned via a computerized game (in which they chose different locations for a business and received feedback about profits) or learned the information via conventional lecture. Wiebe and Martin (1994) also observed no benefits of a computerized geography game, relative to noncomputerized classroom activities, on fifth and sixth graders' learning of geography facts. However, the noncomputerized activities involved active manipulation of the information, such as looking up locations of countries and cities, utilizing information on geography fact sheets, and engaging in quizzes over the information being learned. Thus, although the computerized game may have provided practice with the learning material, the noncomputerized learning activities appeared to do so as well.

In other studies, the computerized games afforded advantages for learning and produced significant benefits on learning. In some cases, the games provided opportunities for retrieval practice. For example, Dorji et al. (2015) explored high school students' learning of physics concepts through conventional instruction supplemented with a computerized game that simulated energy consumption by household appliances, versus conventional instruction supplemented with textbooks. The computerized game included demonstrations in which students could explore and test the effects of different factors (e.g., wattage, time duration) on energy consumption, along with concept questions to check their understanding, which were not available in the conventional instruction group. Along similar lines, Wu (2018) found that EFL students' vocabulary learning was enhanced when they reviewed vocabulary using a game-based mobile app that provided practice at word identification, spelling, and listening comprehension, compared to reviewing the same vocabulary through lecture-based instruction.

The study by Su and Cheng (2014) is reproduced from the earlier section on mobile devices. This study showed that the benefits of smartphone-based apps for learning about the ecology of insects only occurred when the app was in the form of an interactive game (involving maps identifying the locations of learning activities, "quests" that notified students of learning objectives, learning material about ecology of insects, badges for achievement, and leaderboards), rather than simply providing information about the insects. One advantage of the game-based app could be in the extra time it afforded for engaging with the learning material. As compared to classroom instruction, the game-based app that was utilized in the insect ecology area took students more time to complete.

Flipped Classrooms

The final section includes comparisons of learning via conventional lecture versus flipped classrooms. Both groups of students (conventional and flipped classrooms) were taught the same information by the same instructor, and received the same criterial test to measure their learning. In cases where students were not randomly assigned to groups, baseline assessments (pretest, GPA) verified that the groups did not differ in their preexisting knowledge of the content or academic aptitude. The results are shown in Table 9.

In all of these studies, the conventional approach involved an instructor delivering information via face-to-face lecture to the class during scheduled times. The flipped classrooms involved students viewing the same lecture content before class in the form of online pre-

Table 9 Comparison of flipped classrooms versus conventional instruction on student learning outcomes

	Comparison	Subject	Students	Assignment method	Flipped components	Baseline measure	Learning measure	Effect size
Anderson et al. (2017)	Conventional lecture (n = 32) vs. flipped classroom (n = 38)	Pharmacy calculations	First-year pharmacy students	Random by student	Pre-class video-recorded lectures, reading, in-class quizzes, discussion, case studies, simulations, problem-solving	Prerequisite GPA	Posttest over content learned	d = .58
Goh and Ong (2019)	Conventional lecture (n = 74) vs. flipped classroom (n = 63)	Dosage form	Second year pharmacy students	Different course sections across terms	Pre-class video-recorded lectures, quizzes, post-class online learning activities	Grades in prerequisite course	Final exam scores	d = .63 (adjusted for prerequisite grades)
Lin (2019)	Conventional lecture with some active learning (n = 15) vs. flipped classroom (n = 19)	Software engineering	Undergraduate students	Different course sections within a term	Pre-class videos, quizzes, in-class case studies, discussion	Pretest over content to be learned	Posttest over content learned	d = .78 (adjusted for pretest scores)
Blázquez et al. (2019)	Conventional lecture (n = 43) vs. flipped classroom (n = 58)	Social work	Undergraduate students	Different course sections within a term	Pre-class videos and quizzes, in-class feedback and discussion	University entrance exams	Course exam over content learned	d = .64
Lucchetti et al. (2018)	Conventional lecture (n = 83) vs. flipped classroom (n = 83)	Gerontology	Third year medical students	Different course sections across terms	Pre-class videos, in-class discussion and case studies	Pretest over geriatric knowledge	Identical posttest over geriatric knowledge	d = .24

recorded video lectures, in addition to a number of other preclass activities and active learning components during class. In Anderson et al.'s (2017) study, pharmacy students in the flipped classroom viewed prerecorded online lectures and completed reading assignments before each class, so that class time was spent answering quiz questions (at the beginning of class), and participating in group discussions, along with case studies, guided note-taking, problem sets, simulations, and think-pair-shares. Goh and Ong (2019) used a similar approach in that pharmacy students in the flipped classroom viewed online prerecorded lectures and videos and completed quizzes prior to each class, so that class time was spent discussing and applying concepts. Compared to the conventional approach, the flipped classroom also involved online post-class learning activities (e.g., flashcards) designed to provide additional practice.

In Lin's (2019) study, software engineering students in the flipped classroom viewed online pre-recorded videos and completed questions over the content prior to class, so that class time was spent engaging in discussions, case studies, and other practice assessments. The conventional class did not involve the preclass activities, but did involve some active learning in that the instructor presented the software engineering concepts via lecture slides in class, along with discussions, case studies, and practice exercises. In the study by Blázquez et al. (2019), social work students in the flipped classroom viewed online videos and answered questions about the content prior to class, so that class time was spent discussing the answers to the questions. Finally, in Lucchetti et al.'s (2018) study, medical students in the flipped classroom viewed online prerecorded video lectures over gerontology concepts prior to class, so that class time was spent on discussion of case studies, group activities, and application of the concepts.

Based on these fairly recent studies, flipped classrooms appear to produce positive effects on learning. Although the learning contents and precise approaches vary across these studies, one consistent feature of flipped classrooms is frequent quizzes or practice assessments over the learning contents. These are often delivered online prior to class, and/or incorporated into class. These activities afford the opportunity for retrieval practice, as well as the important metacognitive "reality check" that gives students a chance to check their understanding of the material before engaging in focused learning activities that can be targeted toward the concepts that they may need more practice with. Furthermore, flipped classrooms often involve preclass online videos and other preparatory work prior to class, which can afford extra time spent engaging with the materials. While active learning during class has been shown to benefit learning (e.g., see Deslauriers et al. 2019) and could be contributing to some of the positive effects seen here, the technology-enabled affordances of flipped classrooms involve opportunities to engage the effective learning principles of retrieval practice and additional time with the learning material.

General Discussion

In this review we have discussed a number of studies exploring the effects of educational technology on students' objective learning. We placed no restrictions on the particular technology, subject matter, or educational level, but focused our search to studies that were conducted in actual educational environments and considered scientifically rigorous in that the effects of the technology were evaluated by comparing learning of the same material, taught by the same instructor, with versus without the use of the technology.

Results of our search revealed empirical investigations of the effects of video-based instruction, online courses, computer-assisted instruction, mobile devices, simulations, animations, digital games, and flipped classrooms on student learning. Across these categories, consistent themes emerged in that positive effects of technology on student learning occurred when the technology involved affordances that leveraged effective learning principles of repetition, retrieval practice, or spacing. In some cases the technology afforded more opportunities to engage with the learning material that were not available through conventional instruction, such as videos and other instructional content that could be accessed outside of class on computers (e.g., Baumann-Birkbeck et al. 2015; Karaksha et al. 2014; Lancellotti et al. 2016) or mobile devices (e.g., Shadiev et al. 2018; Siciliano et al. 2011; Turan et al. 2018). The time-saving aspects of some technology also afforded more time available to spend on learning activities within a given instructional period, such as in the case of computerized simulations that provide feedback and additional practice without the need to wait for an instructor's feedback or set up physical equipment (e.g., Chang et al. 2016; Yarahmadzehi and Goodarzi 2020). Technology that afforded opportunities for retrieval practice also produced positive effects on learning in the form of online practice questions (e.g., Ebadi and Ghuchi 2018; Zubas et al. 2006), pre-class quizzes (e.g., Anderson et al. 2017; Goh and Ong 2019; Lin 2019), and problem-solving activities (e.g., Cerra et al. 2014). Technology-based components that afforded extra engagement with the material and retrieval practice appeared to be particularly effective when they provided multiple opportunities for learning that were distributed over time (e.g., Hsiao et al. 2019; Liu and Su 2011).

In other cases, technology actually hindered extra opportunities to engage with the learning material (for example, by lacking the opportunity to discuss coursework with classmates or consult an instructor for assistance) and produced negative effects on learning (e.g., Harrington 1999; McDonough and Marks 2002). Other negative effects occurred in studies where, although technology increased the accessibility of the course material, students tended to delay accessing the material until shortly before exams, which forfeited opportunities to benefit from additional engagement with the material or distributing their learning over time (e.g., Delafuente et al. 1998; Mathiowetz et al. 2016). Thus, simply incorporating technology as part of a course does not itself increase the likelihood of successful learning. Even if that technology involves particular affordances that have the potential to promote learning (e.g., increased access to material), the ultimate effects of that technology on learning depend upon the degree to which students utilize those affordances to engage effective learning principles.

Thus, this review provides important new data showing that the effects of technology on learning depend critically on how the affordances of that technology align with effective learning principles. Such principles are not typically utilized (or even referred to) as a guiding framework for interpreting and predicting the effects of technology on learning. A greater reliance on these principles in designing and interpreting studies of technology on learning is of critical importance, however, as they provide the key to understanding when, how, and why a particular technology enhances (or does not enhance) learning.

Importantly, these learning principles are not inherently linked with a particular technology. As this broad literature review shows, extra engagement with the material, retrieval practice, or spacing can be accomplished through a variety of technology components, and it is the learning principles that can be leveraged through the technology (rather than the technology per se) that promote learning. Over and beyond the particular technology, therefore (e.g., online courses, mobile devices), the most effective approach to utilizing technology to enhance learning is to consider the ways in which that technology affords opportunities to engage with effective learning principles. That is, instead of asking whether online courses are effective for learning, we should ask what affordances come with online courses, and how those affordances can be leveraged to engage effective learning principles.

The results of this review suggest that additional considerations must be involved to ensure that those affordances are properly leveraged and utilized, however. Simply making course information available online does not guarantee that students will access it or utilize it in a way that best promotes their learning. Indeed, some studies have tracked students' use of optional online resources such as review questions and practice problems, and have found that few students tend to use these resources, and they tend to delay using them until shortly before exams (Corral et al. 2020; Lui et al. 2019). To make the most of such technology resources, students' natural tendencies toward procrastination may need to be offset by providing incentives (e.g., course points or a schedule to follow) that promote engagement with extra learning opportunities in a way that is distributed over time.

Although we focus on direct learning outcomes in this review, it is important to note that technology can be beneficial to learning in ways that do not always produce direct effects on learning. For example, the increased availability of online platforms makes it possible to offer courses to a greater number of students who may not have access to those courses through traditional face-to-face means. Computerized simulations can also provide students with practice at carrying out a particular task (e.g., a medical procedure or chemistry experiment) under conditions that allow greater safety than real situations. Studies from this review show that when technology is used primarily as a method of information delivery, it produces neither consistent beneficial nor harmful direct effects on learning. Given similar learning outcomes between technology-based and conventional approaches, in cases like these technology can afford clear advantages in accessibility and safety that are not possible through conventional approaches.

The Importance of Evidence-Guided Decisions

The question of how to use technology to improve learning is not new. Nor is the tenet that such technology must be based on what we know about human learning. As early as the 1920s, devices were being developed to automatically assess students' knowledge in a number of school subjects (Pressey 1926, 1927). These "teaching machines" were designed to test students' knowledge, deliver timely feedback, and track each student's progress so that the testing could be individually adapted to each student's knowledge level (see Benjamin 1988; Skinner 1958). The earliest known efforts for the design of technology-enhanced instruction were thus based on the principle of learner-adapted testing, which was not possible via traditional classroom instruction.

Indeed, the selective use of technology to accomplish particular learning objectives that are unobtainable by other means is the most efficient, cost-effective, and responsible way to use these tools. The "teaching machines" of today have increased dramatically in number and in the level of technological sophistication. In the absence of an awareness of concrete learning principles afforded by the technology, however, the decisions about whether to adopt a given technology, how to use it, and its ultimate effects on student learning are rendered uncertain.

More than 20 years ago, Schacter and Fagnano (1999) reviewed the emerging evidence from computerized instruction and concluded that "computer technologies, when designed according to sound learning theory and pedagogy, have and can substantially improve student learning" (p. 330). The same rings true today. In order to make the most of the resources invested in educational technology to increase student achievement, technology must be carefully considered according to the learning principles that it affords. When approached in this way, all of the stakeholders—teachers, students, parents, administrators, and policymakers—can play an informed role in the selection and implementation of the appropriate types of technologies that will positively impact student learning.

Limitations and Directions for Future Research

We have focused this review on studies conducted in real courses. In the interests of ecological validity, precise experimental control is not possible over factors such as students' motivation and amount of studying of the course material. Classroom data collection is also inevitably limited to the number of students enrolled, which means that some of the studies had relatively small sample sizes. Such factors might influence precise estimates of effect sizes, and future research is encouraged that can contribute additional data on the effects of technology in multiple classes with large numbers of students. A worthwhile consideration for future research is to track individual differences in relevant student characteristics, such as their course performance and information about how and when they are utilizing the technology. A general limitation of many studies is that they do not always describe how students are using the technology. Although the affordances of the technology may be apparent (e.g., practice questions, user control), the ultimate effectiveness of that technology depends upon how students are making use of those affordances, which is not always reported. Such data would provide valuable insights into the ways in which students are engaging with the technology and whether it is being utilized in the ways that most effectively leverage its potential to enhance learning.

Although we had good reasons for using objective learning as our outcome measure, it is also worth investigating the effects of technology on other academic outcomes. Student motivation, course satisfaction, and interest in the subject matter could be important indirect contributors to learning, and investigating these factors and their potential mediating effects could reveal additional potential ways that technology promotes learning.

Finally, we encourage future research that explores the deliberate use of technology to enhance learning by designing the use of educational technology with effective learning principles in mind. Technology can be developed for various reasons and has been effective at increasing the number of students who can access educational opportunities. As we have seen that technology can be particularly beneficial for student learning when it affords engagement with effective learning principles, designing the technology with this specific goal in mind increases the potential for educational technology to more effectively and efficiently enhance students' academic success.

Declarations

Conflict of Interest Shana Carpenter has received grants from the National Science Foundation (DUE 1504480) and the James S. McDonnell Foundation (220020483).

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