Learning Technology Effectiveness

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1. Introduction

Student access to technology is no longer a privilege: it is a prerequisite for full participation in high-quality education opportunities. Increasingly, important learning resources used by students and teachers are digital, making access to the Internet as basic as access to a library. Technology access also enables students to find and enroll in educational opportunities, such as summer enrichment programs and college scholarship programs, and is increasingly fundamental for participation in college itself.

Modern technology tools that enable design, media production, self-expression, research, analysis, communication, collaboration, and computer programming are commonplace in various professions and disciplines, and facility with these tools is an essential part of becoming ready for college and careers. Interacting with digital learning environments that support the development of deeper learning skills such as problem solving, critical thinking, and inquiry is also crucial. Furthermore, goals for improved educational achievement and increased participation in science, technology, engineering, and mathematics (STEM) learning and careers will not be reached without the integral use of technology.

Certainly, students without access to technology-based environments and opportunities will be tremendously disadvantaged in efforts to organize and plan their intellectual pursuits and achieve in academic endeavors. Consequently, policy makers should not need experimental tests of the effects of broadband Internet access to be convinced it is important. Broadband access today is as integral to education as books and pencils have been in the past. It is part of the basic infrastructure and a prerequisite to full participation in public education.

While this fundamental right to technology access for learning is nonnegotiable, it is also just the first step to equitable learning opportunities. We must continue to ask questions about the effectiveness of technology-based learning systems and tools designed to promote academic learning in specific subjects. This brief suggests that the question "Does technology improve student learning?" is not the right one to ask, since learning technology effectiveness—like the effectiveness of many other classroom tools—depends on how a particular technology-supported intervention is designed and how it is implemented by teachers and students. Instead, we look at the types of learning technology uses that have been shown by research to tie to deeper student learning, the conditions under which these approaches can reach their educational potential, and how to identify those that are worth the investment.

2. What research tells us about learning

Any approach to improving learning—with or without technology—is more likely to succeed if it is informed by the decades of research in the learning sciences.[1,2] Therefore, to answer questions about the effectiveness of technology for learning, we begin with the characteristics of learning environments that support strong learning outcomes, whether on- or off-line. We then examine the ways that technology can be used to provide these features that support learning.

According to research, learning is enhanced when students are engaged in the following strategies.

Building on their prior understandings and actively driving their own learning. Traditional classroom instruction treats "learning" as a process of acquiring content, either from teachers or from textbooks. Learning research, on the other hand, demonstrates that learning is an active process of integration, with new information interpreted through the lens of prior experiences and conceptions.[3,4,5] The ideas that students bring with them into the classroom are often based on students' interpretations of their experiences in the everyday world, which may or may not be consistent with the normative disciplinary content they are asked to learn in school. For example, very young children understand that animals are living things, while objects such as rocks are not. Because of this understanding, they expect the insides of an animal to have an organization while the inside of a rock will be random.[6] But many young children also believe that all living organisms are capable of self-initiated movement, since this is an easily observable difference between dogs and rocks. As a consequence, they often do not recognize plants as part of the category of living things.[7] Intuitive but incorrect ideas such as these can make it more difficult for students to understand and retain scientific descriptions and explanations.

Effective learning environments elicit students' intuitive ideas and related experiences while providing new experiences that cause them to question those ideas, helping them to understand that there may be common situations they aren't yet able to explain. This can set the stage for students to use new knowledge to reorganize and modify their existing ideas, creating increasingly productive mental models.[8,9,10]

Technology can support this process by asking students to reason about many different situations and using each student's responses to diagnose the set of ideas that a student holds.[11] Technology can then provide students with counterexamples and contrasting arguments for naive ideas that do not correspond to experts' understanding of the concept.[12,13]

In addition to providing tailored examples or hints, technology-based learning systems can support the personalization of the student learning experience by analyzing students' performance on recent tasks and suggesting learning activities, resources, or approaches matched to each student's profile of skills and competencies. Appropriately executed, this tailoring process has been shown to lead to increases in student learning.[14]

In addition to adapting instruction to the particular academic progress of each student, technology can also support differing student capacities, opening learning opportunities to students with disabilities and others who have traditionally been excluded. For example, technology is particularly adept at providing the range of representations, means of engagement, and opportunities for expression that are essential to universal designs for learning,[15] enabling designs that are more flexible and effective for all students.

Developing connected knowledge, not just learning isolated facts. In today's fast-paced and competitive economy, workplaces demand that individuals and teams are able to apply their knowledge to new situations,[16,17] solving complex problems involving rapidly emerging topics and communicating the nature and logic of their work. Learning sciences research suggests that for these purposes, strictly factual knowledge is not sufficient. Instead, application of knowledge to novel problems relies on conceptual understanding in the form of higher-level principles and recognized patterns that can be transferred to new situations.[18] For example, if a student memorizes the names and locations of the biggest cities in the United States, he or she might do well on a test that requires filling the names in on a map, yet not be able to make inferences about the relationship between bodies of water and population centers or to reason about the likely location of population centers in other parts of the world. This latter task would require higher-level conceptual understanding—for example, why people tend to settle near large bodies of water.[19]

The process of building this rich conceptual understanding is often called "deeper learning" or "learning with understanding." Pedagogical approaches that promote this type of learning include:

- The use of multiple representations that help students to consider complex ideas in multiple ways and see the connections among them.[20,21]
- Instruction that provides opportunities to learn "big ideas" in depth rather than presenting a series of disconnected facts.[22,23,24]
- Project-based approaches that allow students to investigate ideas in the context of real-world problems or challenges that have meaning to them.[25,26,27]

Technology can support deeper learning in multiple ways. The vast array of resources on the Internet can support students' construction of rich and connected knowledge if, rather than simply looking up facts, they use Internet searches to find multiple resources that they can compare, contrast, and integrate. The Internet also offers access to a much broader assortment of materials and resources, including access to experts locally or around the world, to support understanding of complex ideas. Specific learning technologies and authentic scientific tools are designed to support simulation, visualization, modeling, and representation in particular topic areas, allowing students to explore complex relationships in a phenomenon or data set, including phenomena that may be too large, too small, or too abstract to experience directly in a classroom environment. The emerging field of game-based learning is also beginning to demonstrate promise in supporting deeper learning when designers follow principles such as a focus on clear learning goals, with environments, graphics, and storylines well-aligned to these goals; thoughtful scaffolding; and embedded feedback.[28,29] Finally, the Internet provides students with a forum for getting their ideas and the products they create to a much larger audience. Web 2.0 capabilities allow students to be producers as well as consumers of online technology.

Leveraging social interactions to build knowledge together. In traditional classrooms, learning is seen as an individual task, and a student who looks at someone else's paper might be accused of cheating. In contrast, learning research demonstrates the value of students working together to build deep knowledge.[30,31] In a learning community, students collaborate to advance their collective knowledge on a topic in a way that helps each student learn.[32,33] When students collaborate to build something together or debate a topic, they must articulate their own ideas and evaluate, question, sharpen, or build on the ideas of others. In well-designed learning activities, these processes deepen both students' individual and their collective conceptual understanding.[34]

Students learn better when they explain their emerging understanding to peers and have peer responses to their questions, but it can be hard to implement effective peer dialogue in typical classrooms or lecture halls where seating arrangements are not conducive to discussions among students. Online learning environments can be designed to support a variety of productive peer interactions, such as students' presentation of their ideas with peer discussion and feedback, the collaborative construction of documents and presentations online, and online homework help, study groups, and challenge-based learning teams. Platforms for online social interactions can also support organized and focused student collaborations and community building across geographic distances and even national borders.

Online social environments for learning can also augment teacher capacity. Although teachers do not need technology to work with students in small groups, they can only visit one group at a time. A host of new technologies have emerged, ranging from simple "clickers" to elaborate supports for a varied set of interactive roles within immersive virtual environments, that can support small-group collaboration within classrooms and keep students productively engaged in learning while the teacher is rotating among the groups.

Appropriate use of these technologies relies on a host of complementary supports. For example, Peer Instruction is a pedagogy that has transformed many physics lecture halls[35] and shown substantial benefits.[36] Effective implementation of Peer Instruction, however, requires a coordinated system of changes: in the way the space is used, the course materials, the roles that the students and instructor play, and how instructors are trained. Similarly, a handheld technology for collaborative work with fractions produced stronger student learning when content was carefully defined, behavioral training was provided to students, and teachers received training and ongoing support around both the math content and the new pedagogy.[37]

Monitoring their own learning and responding to ample, useful feedback. Developing students' ability to effectively learn independently is an important goal for preK-12 education. Independent learning requires a set of "self-regulation" skills, including students' abilities to monitor their own understanding and progress, make decisions about their own learning (for example, recognizing the need to review topics they do not yet fully understand), and control their own activities.[38] Students who are self-regulating take on tasks at appropriate levels of challenges, practice to proficiency, develop deep understandings, and use their study time wisely.

Feedback is important to self-regulation. Research has demonstrated that learning is enhanced when learners receive substantive feedback about their performance that helps them to see next steps on the path to their learning goals.[39,40] Many integrated technology systems are carefully designed to provide feedback to students as they use the system. These capabilities can supplement teachers' capacity to provide timely and customized feedback to each student in a class, even with large class sizes or with diverse student abilities within a class. In turn, these systems can support faster feedback loops by generating the information needed to decide on the best next steps for both students' learning and teachers' instruction.[41]

For effective use of the kind of feedback that technology-based systems can provide, both students and teachers need support. Students must learn to use the feedback to regulate their own learning process, and teachers must learn to take the feedback on students' understanding into account as they make instructional decisions. In one example of an integrated program, investigators used wirelessly connected graphing calculators to give students and teachers more feedback in an Algebra course, and also provided professional development for teachers (both in a week-long summer institute and follow-up opportunities during the year) with an emphasis on pedagogy and data-informed instructional decisions as well as use of the technology itself. A randomized controlled trial with 68 teachers and 1,128 students showed that this was an effective combination of technology-provided feedback and supports for pedagogical use of the feedback to improve teaching and learning.[42]

Formative assessment is the practice of assessing students' current knowledge state and proficiency for the purpose of deciding what future learning opportunities should be offered (in contrast to assessments to certify what has been learned).[43,44] The assessment items most commonly used in school focus on right or wrong answers, and a technology-based assessment can be designed to give immediate simple feedback (right or wrong) for such items. But technology can move well beyond these basics in providing feedback: technology-based feedback can include providing worked examples, modeling how to solve a problem, and guiding a student through the steps of problem solution. Other innovative types of assessments look at how students' thinking within a given content domain is organized and identify patterns of responses that may suggest a particular misconception or lack of a prerequisite skill.[45] In turn, technology-based learning systems with these kinds of formative assessment can offer customized instruction, guiding the student's construction of knowledge as well as making progress visible. Together, these features can further the type of deep conceptual learning of complex ideas, as described above. ASSISTments is an example of a computer-based system that uses a bank of standards-aligned math problems to analyze the patterns in students' responses, providing timely feedback and appropriate scaffolding tailored to each student. In addition, the system provides analytics for the teacher that describe individual student progress and common conceptual challenges, supporting teacher decisions about coaching for individual students and about the class discussion topics that will be most productive for the most students.[46]

In these descriptions of environments that support deep student learning, technology can play a key role in answering the call with which this paper began: the need to make this type of learning possible for all students, not just those in contexts of privilege.

3. Examples of learning technologies that can improve learning

Learning environments with the characteristics described in section 2 can be found in the classrooms of many motivated and talented teachers across the country. But the vast majority of American learners do not yet have sufficient opportunities for deeper and more productive learning. The effective use of today's learning technologies can help a greater proportion of teachers to provide these supportive conditions for learning for each and every student—something that would be difficult or impossible to do without technology.

The examples in this section describe a range of technology-supported applications for learning. Each of these illustrates the unique affordances for powerful learning that well-designed learning technologies can offer, and reviews results of rigorous research that demonstrate these effects.

Effect Size

Outcomes in these examples are presented in terms of *effect size*. Effect size is a standard way to represent the difference between two groups on a given outcome measure. It is defined as the difference in means between the treatment and control groups, divided by the pooled standard deviation. By convention, .10 standard deviation is considered to be the minimal noteworthy effect; an effect size of .25 is considered a moderate effect, and an effect size of .50 standard deviation in realistic conditions is considered both rare and important. Effect size interpretations may vary, however, based on other conditions. For example, a small positive effect that is obtained reliably across a great number of students can be important in the aggregate. There are also cases where finding no effect (either positive or negative) on learning outcomes can be desirable if the intervention saves time or money.

For each of these examples we provide results in terms of effect size (described in the sidebar). While effect size is a standard way to describe the quantitative outcomes of an intervention, we caution against its use as the sole basis of judgments of the value of a tool. Measured outcomes of an intervention can vary drastically based on a host of contextual factors. For example, how different are the treatment and control conditions in terms of pedagogy, rigor, and time on task? If the student learning experience is held constant with the exception of the insertion of technology, most experiments will show little or no effect, as the value of the technology often rests in the transformation of the learning experience that it might enable: factors which too often are not described in the research.[47] Conversely, a strong effect might be the result of conditions that are different in ways that could also be accomplished without the technology. Furthermore, in large experiments with randomized designs that seek to control for predicted or unpredicted differences in context, there is typically large variation in outcomes across the different participating settings: what design or implementation factors explain this variation?

These questions are essential to our ability to learn about the effectiveness of learning technologies and the conditions that can support their most powerful use. For this reason, the examples of proven learning technologies that follow describe not only effect size but also the key elements of design that are likely to support their success, through the lens of the ingredients for strong learning environments discussed in section 2.

SimCalc: Increased Learning of Advanced Mathematics

Developed at the University of Massachusetts, Dartmouth, with support from the National Science Foundation and the Institute for Educational Sciences, SimCalc (http://www.kaputcenter.umassd.edu/projects/simcalc) aims to "democratize access to advanced mathematical concepts" by allowing more students to learn the foundational concepts underlying Algebra and Calculus earlier and more deeply.

Evidence of Outcomes: In a randomized controlled trial across the diverse population of Texas and involving 95 teachers and 1,621 students, seventh-grade students in classrooms using SimCalc significantly outperformed students in classrooms using existing materials on a measure aligned both to Texas standards and to national and international achievement measures (ES = 0.63). This effect was replicated in two further studies, involving an additional 538 seventh-grade (ES = 0.50) and 825 eighth-grade students (ES = 0.56).[48] Similar gains were later found in Florida and the United Kingdom.

The Program: The SimCalc program integrates technology-based multiple representations, physical workbooks, and teacher professional development in instructional modules that replace conventional resources for key mathematics topics. Students investigate how mathematical symbols relate to numerical data, graphs, simulated motions, and stories about motions. Building on this experience, teachers lead discussions focused on big ideas in mathematics, such as the connection between slope and rate.

Support for Learning: SimCalc anchors student learning in familiar experiences of motion and engages students in activities in which they must use mathematics to analyze and control motions. The technology makes it possible for students to model more realistic motions using piecewise linear functions, a type of mathematic function that is commonly used in engineering but not typically introduced before college. The curriculum emphasizes connected understanding of big ideas of rate, proportionality, and function across multiple representations. Pedagogy engages students in a cycle of prediction, investigation, explanation, and reflection.

***For Example**:* In a 10- to15-day module called "Managing the soccer team," students investigate rate and proportionality in the contexts of both motion and money. To learn how the slope in a graph relates to distance, rate, and time, they make simulated races among soccer players. To win a race, a soccer player must have a graph with a steeper slope (faster speed), less time, and the same position. The module addresses classic misconceptions, such as students' belief that the shape of a graph reflects the shape of the terrain. For example, students make "road trips" for a school bus using piecewise linear functions to indicate changes in speed and direction, which helps them to realize that a downward slope is not a steep hill but rather signifies going backwards.

Technology-Enhanced Learning in Science (TELS)

Developed at the University of California, Berkeley, with support from the National Science Foundation, Technology-Enhanced Learning in Science (TELS) (http://telscenter.org/) is designed to support students' development of deep understanding of core principles in the middle and high school science curriculum.

Evidence of Outcomes: In a study of 26 teachers and 4,328 students using a time-delayed design, TELS students significantly outperformed their counterparts using traditional curricula in a measure of students' integrated understanding of scientific phenomena (ES = 0.32).[49]

The Program: TELS modules offer interactive visualizations of scientific phenomena that are often impossible to observe directly (such as chemical reactions). Students explore these phenomena through the lens of current scientific issues (such as treatment options for cancer). Through the software, students are guided to generate and test predictions, explain their understandings, and engage in discussions with peers.

Support for Learning: Interacting with visualizations, articulating explanations, and applying what they've learned to new situations give students the opportunity to develop richly connected knowledge. Scaffolding of the process and embedded formative assessments help students monitor their own learning process.

For Example: In a 5-day unit called *Chemical Reactions,*[50] students conduct a series of activities about chemical processes related to the greenhouse effect. For example, they work with an interactive visualization of hydrocarbon combustion reactions, manipulating variables to look at the relationship between ratios of reactant molecules and products, and they consider implications for carbon dioxide levels in the air. Students are prompted to conduct investigations and explain their understanding of related scientific processes. They use what they learn to write a letter to their congressperson about climate change and alternative fuels.

Intelligent Tutoring of the Structure Strategy (ITSS): Increasing Access to Successful Reading Strategies

Pennsylvania State University's Intelligent Tutoring of the Structure Strategy (ITSS) program (http://itss.psu.edu/) was designed to support students' reading comprehension and recall of expository text. While research on teacher-led instruction of the structure strategy had shown promise,[51] the in-depth teacher training that had been used in successful implementations was a barrier to wide-scale adoption. A computer-based online intelligent tutoring agent allowed the research team to expand access to the structure-strategy approach to greater numbers of classrooms.

Evidence of Outcomes: A multisite cluster randomized trial was used to compare the once-weekly use of ITSS as a partial curriculum replacement against the traditional language arts curriculum in 24 rural and suburban schools.[52] A total of 131 fourth-grade classrooms were randomly assigned to treatment or control conditions within schools. Students in ITSS classrooms significantly outperformed the control students on the GRST (Gray Silent Reading Test, a standardized test of reading comprehension, ES = 0.10) and on researcher-developed measures of signaling, main idea quality, and overall content recall (with effect sizes ranging from 0.11 for total recall to 0.49 for main idea quality).

The Program: ITSS helps students make the transition from reading narrative text to reading expository, content-rich text by learning to parse the structure of the text—for example, by learning to recognize signaling words that indicate that the writer is introducing an argument or comparison and using that structure to help organize more efficient mental representations of the text. The computer-based ITSS models this process and provides tailored feedback and scaffolding based on students' responses.

Support for Learning: The intelligent tutor gives each student immediate feedback and adjusts scaffolding to student progress, helping to guide students' cognitive paths. The computer program is designed according to research-based principles for multimedia learning tools, such as coherence between the interface and intended learning goals. Teachers receive regular reports of student progress to support their formative use of data for instructional decisions.

For Example: On individual computers in the lab, students read and listen to a text that describes the differences between crocodiles and alligators. With modeling from "IT" (a computed-based intelligent tutor with a human voice), students are prompted in a variety of ways to identify "signaling words" such as "in contrast" that suggest the text will have a comparative structure, and to leverage that structure to organize and summarize main ideas from the text. They get immediate feedback from ITSS, which also gives them progressive scaffolding and additional practice tasks if needed before they are ready to move on.

Student Outcomes of Technology Investments

Research has also demonstrated the value of students' use of technology on broader measures of student achievement. For example:

- Writing assessment results from National Assessment of Educational Progress (NAEP) 2011 show a positive relationship between use of technology for writing and student performance. Eighth-grade students' scores on NAEP were positively correlated with their teachers' self-reports of the frequency with which they asked their students to use a computer for drafting and revising writing assignments. Twelfth-grade students' self-reports of the frequency with which they used a computer to make changes to writing assignments were also positively correlated with scores on NAEP.[53]

- An analysis of the international results from the Programme for International Student Assessment (PISA) 2006 science assessment demonstrates a positive relationship between frequency of student computer use and scores on the science exam, and recommends policy attention to supports for student competencies for responsible and critical technology use as factors that correlate with increased effect.[54]

4. Technology Is Effective When Integrated into Systems

Questions about the effectiveness of technology for learning often implicitly assume a medical analogy: we know that some drugs can improve health, and want to know if some technologies can improve learning. However, whereas drugs can directly cause specific biochemical changes in bodies to halt a disease process, computers do not directly rewire the brain to fix a student's misconception. Instead, technology in education can best be seen as a platform or tool that can enable transformation of the learning activities among teachers, students, and resources in a classroom; when students engage in better activities, they can learn more.

However, the factors involved in changing the activities in classrooms involves more than inserting technology. Considering the medical analogy more deeply, this should not be surprising. Improving health in hospitals also requires more than drugs and x-ray machines: treatment regimes must be defined, professionals must be trained, best practices must be implemented, and in most cases patient behavior must change to see sustained improvement.

The effectiveness of the technology tools described above rests not only in their affordances for learning but also in how they are used in practice. Both students and teachers need guidance in order to use the Internet, for example, in ways that support deeper inquiry rather than simply finding facts. As demonstrated in the examples above, elements such as curriculum, pedagogy, teacher professional development, and assessment must be designed to fit together in a way that guides effective use of technology tools.

Technology can enable better learning when (a) it provides a unique, new capability that supports human learning processes and (b) interventions are designed to embed that capability within an integrated system that provides the supports students and their teachers need to enact the learning within the curriculum.

A complete learning system includes factors such as the following, in addition to the technology itself:

- Physical arrangements of the environment as well as the students to allow a mix of individual, small group, and large group work.
- Curriculum and specification of learning progressions.
- Pedagogy appropriate for the content to be learned.
- Professional development, coaching, and mentoring around pedagogy and content knowledge for teaching.
- Aligned assessments and ways to use them to adapt instruction.
- School leadership and professional culture.

Attention to all of these parts of the system will enable the most successful use of technology to support teaching and learning.

Meta-analyses of Learning Technology Outcomes

Meta-analysis is an analytic technique that allows researchers to look across multiple studies to compute an estimate of the size of the average effect, even if the individual studies look at different interventions that are implemented in different system contexts and use different outcome measures. Because meta-analysis is based on the existing body of research, meta-analyses of learning technology studies necessarily draw on studies of less current learning technology applications, in systems that do not always include aligned assessments and supports for teachers. Nevertheless, most meta-analyses of studies measuring the effects of technology-based learning in comparison to conventional educational practice have found that on average technologies enhance learning, albeit less dramatically than in the newer studies of carefully implemented technologies highlighted above. For example:

- A meta-analysis of educational technology applications for mathematics that included 74 qualifying studies and a total of 56,886 students found a small but positive overall effect (ES = 0.16) of mathematics technologies on measures of math achievement.[55]
- A meta-analysis of middle- and high-school reading programs, including programs that did and did not incorporate technology and those that did and did not focus on changes to the teachers' instructional process (such as professional development toward cooperative learning), found that the mean effect across 9 studies of programs that incorporated both technology and support for instructional change (ES = 0.22) was greater than the mean effect of programs that focused on either technology or instructional change alone.[56]
- A second-order meta-analysis of studies of a variety of types of learning technologies, including 25 meta-analyses that encompassed 1,055 primary studies, found a strong overall positive effect (ES = 0.33) for classrooms that used technology compared to their face-to-face counterparts.[57]

- As part of a larger synthesis of over 800 meta-analyses related to a variety of teaching methods and student achievement outcomes, 76 meta-analyses of computer-assisted instruction (including 4,498 primary studies) yielded an average effect size of 0.37.[58] Across these studies, program characteristics that produced the strongest effects were consistent with those highlighted in this report, including the provision of training for teachers in the uses of computers for teaching and learning, scaffolding for peer learning, and opportunities for student self-directed learning.

5. Conclusion

Technology is not a silver bullet and cannot—by itself—produce the benefits we seek in learning, but without technology, schools have little chance of rising to 21st-century expectations. Syntheses of best available evidence consistently indicate the potential for positive effects when technology is a key ingredient in well-designed learning systems. Smart policy will both ensure equality of access to technology and also encourage uses of that technology that focus on specific connections to learning processes and address all the factors in complete learning systems. Smart research and development investment will be in learning systems that include technology applications as well as the conditions that support students and teachers to use them effectively toward strong learning.

Notes

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