The Learning Return On Our Educational Technology Investment

A Review of Findings from Research

Cathy Ringstaff
and Loretta Kelley

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WestEd RTEC
730 Harrison Street
San Francisco, CA 94107-1242

CONTENTS

First, I believe that instructional technology works. Instructional technology only works for some kids, in some topics, and under some conditions, but that is true of all pedagogy, all systems for teaching or learning. There is nothing that works for every purpose, for every learner and all the time.

— Dale Mann (1999)

INTRODUCTION

The overriding message that can be gleaned from most current research on the implementation of computer-based technology in K–12 education is that technology is a means, not an end; it is a tool for achieving instructional goals, not a goal in itself. And yet, many schools and districts have invested in computer-based technology before establishing clear plans for how to use this important tool.

In today's world, computer-based technology is not a frill, but an important component of any modern curriculum. During the last decade, technology expenditures tripled in K–12 schools in the United States; estimates suggest that over $6 billion was spent in 1999–2000 (Sivin-Kachala & Bialo, 2000). Since no one wants these funds to be wasted, educators need insight into how to maximize the positive impact of their technology. This paper is for educators and policymakers who want to learn from the research and experiences of others about how to make their technology investment a wise one.

To address this issue, we summarize major research findings related to technology use and, based on these findings, attempt to draw out implications for how to make the most of technology resources. This paper will focus on pedagogical and policy issues related to technology, not smaller issues such as what hardware configurations or software to use. This is not a "how to" paper, but rather a paper about the key policy issues to be addressed in order to make technology use the most effective.

Rather than attempting a comprehensive review of the literature, this paper draws on a selection of research studies. We tried to choose studies that were the most methodologically sound. We favored those that were longitudinal, examining change over time, such as Apple Classrooms of Tomorrow (ACOT), West Virginia's Basic Skills/Computer Education Program, and IBM's Reinventing Education program. Other sources include numerous papers and reports from such organizations as the Milken Family Foundation, RAND Corporation, Educational Testing Service, California Research Bureau, Institute for Research on Learning, and the North Central Regional Educational Laboratory. We have identified general lessons learned from this body of current literature — representing a wide range of attempts to implement technology in K–12 classrooms from 1993 to the present. We also chose studies with an eye toward illuminating the differences between "instruction" and "construction." We believe that, compared to more didactic approaches, constructivist or student-centered approaches are better suited to fully realizing the potential of computer-based technology. Our review of the research is guided by this perspective.

OVERVIEW

The term "technology" can be used to mean a very wide variety of things, from computers to pencils. In this paper, we use the term to refer broadly to computer-based tools — both hardware and software, the Internet, and computer-based multimedia.

In the early sections of the paper, we begin by describing research on the relation between technology and student learning — addressing the question of what kinds of impact technology has on education.

In order to understand the impact of technology on education, it is helpful to consider the purposes to which technology is applied. One distinction that we have found particularly helpful comes from Thomas Reeves (1998) who describes learning "from" computers as different than learning "with" computers. When students are learning "from" computers, the computers are essentially tutors. In this capacity, the technology primarily serves the goal of increasing students' basic skills and knowledge. In learning "with," by contrast, students use technology as a tool that can be applied to a variety of goals in the learning process, rather than serving simply as an instructional delivery system. Students use the technology as a resource to help them develop higher order thinking, creativity, research skills, and so on. Generally, more advanced technology is involved in learning "with." Because these are very different kinds of applications of computer-based technology, we discuss them in separate sections below.

After discussing research on each of these kinds of technology, we turn to the "lessons learned" from these studies and discuss a variety of key conditions that are necessary for technology to improve education. These factors, which repeatedly appear in the literature as crucial elements for successfully using technology, include the following:

- Technology is best used as one component in a broad-based reform effort.

- Teachers must be adequately trained to use technology.

- Teachers may need to change their beliefs about teaching and learning.
- Technological resources must be sufficient and accessible.
- Effective technology use requires long-term planning and support.
- Technology should be integrated into the curricular and instructional framework.

LEARNING "FROM" COMPUTERS

Learning "from" computers takes a variety of forms — including computer-based instruction (CBI), computer-assisted instruction (CAI), Integrated Learning Systems (ILS), and intelligent learning systems (ITS). All of these forms involve using the computer as a "tutor."

An examination of research studies that investigate the impact of technological tutoring systems on student achievement shows mixed results (e.g., Wilson, 1993; Butzin, 2000). While some suggest that CBI, CAI, and ILS can improve students' basic skills in such disciplines as mathematics (e.g., Koedinger, Anderson, Hadley, & Mark, 1997), others report that, in some instances, the use of computers to teach basic skills had a negative impact on academic achievement (Wenglinsky, 1998). Still others argue that many of the studies comparing CBI, CAI, and ILS with traditional instruction are so methodologically flawed that no conclusions can be drawn.

Despite these cautionary findings, the literature provides considerable evidence for how to make the most of using computers as tutors. Particularly in recent years, a number of studies have provided convincing evidence that such technology can be effective in teaching basic skills. For example, a study on the impact of learning technologies on student achievement in Illinois reported that scores on state assessments improved in many areas, such as 11th grade science and 10th grade reading, although gains were not uniform across subject matter areas (Silverstein, Frechtling, & Miyaoka, 2000). Similarly, a high school in Pittsburgh (PA) implemented a computerized "Cognitive Tutor" in its mathematics classes. This tutor presented students with real-world, contextualized problems and built learning profiles of its users. Evaluations showed that Algebra students who used this tutor outperformed students in traditional classes, having achievement gains of up to 25 percent in skill and up to 100 percent in problem solving (Hubbard, 2000). Retention in mathematics classes and attendance also improved among the students using the tutor.

The West Virginia Basic Skills/Computer Education Program (BS/CE) was a large-scale, longitudinal study designed to focus on the State's basic skill goals in reading, language arts, and mathematics. It began with a cohort of kindergarten students in the school year 1990–91. Each year the state of West Virginia provided every elementary school with enough equipment so that each classroom serving this cohort of children would have three or four computers, a printer, and a schoolwide networked file server. As the children of this first cohort moved through the elementary grades, their new teachers received technology training and the school received additional software, computers, and other technology tools.

Statistical analyses conducted by Mann and his colleagues (1999) show that, after the "technology-enhanced" cohort in West Virginia enrolled in grade three, statewide third grade Comprehensive Tests of Basic Skills (CTBS) scores went up five points in one year, after having risen only a total of six points over the previous four years. In 1997, the BS/CE cohort's fourth-grade reading scores were the second highest among southern states. (In terms of per-capita income, West Virginia is 40th in the US; in achievement, it is 17th.) A study of the first fifth-graders to have had consistent availability of BS/CE showed gains in the Stanford-9 achievement test, with higher gains for the students with more BS/CE experience. After conducting a regression analysis, researchers concluded that BS/CE accounted for a significant portion of the total variance in the basic skills achievement gain scores of the fifth graders.

In another decade-long study, researchers investigating the impact of a computer-integrated instructional program called Project CHILD (Computers Helping Instruction and Learning Development) found that elementary students in project classrooms from kindergarten through fifth grade have consistently had "higher test scores and better discipline than their counterparts in traditional, self-contained classrooms" (Butzin, 2000, p. 3). In CHILD classrooms, students engage in reading, writing, or mathematics tasks at learning stations, including a computer station with three to six computers. Positive results were found with students at both high- and low-achieving schools. Moreover, longitudinal studies found that students who had been in Project CHILD classrooms during their elementary years had higher grade-point averages, higher standardized test scores, and more enrollments in advanced math courses at the middle school level than students who had not participated in the project.

In addition to these longitudinal studies, a variety of meta-analyses conducted between 1985 and 2000 on the impact of CBI, CAI, ILS, drill-and-practice software, and computer tutorials on student achievement report that students using computers had higher test scores, typically as measured on standardized achievement tests. In 1994, for example, Kulik aggregated findings from over 500 individual studies of computer-based instruction. These studies showed percentile gains on achievement tests of 9 to 22 percent over control groups. On average, students who used computer-based instruction scored at the 64th percentile compared to students without computers who scored at the 50th percentile. Kulik also found that computer-based instruction can decrease the amount of time required for students to learn basic skills.

As a result of these meta-analyses, many conclude that computer-assisted instruction and drill-and-practice software can significantly improve students' scores on standardized achievement tests (Kulik, 1994; Sivin-Kachala & Bialo, 2000), in all major subject areas, preschool through higher education (Coley, 1997).

Looking across these studies, it is clear that using computers in a tutorial capacity can be beneficial — particularly in today's political climate — for schools and districts that are often heavily focused on increasing students' scores on standardized achievement tests. Moreover, some researchers argue that using technology to accomplish these kinds of goals requires less teacher training than more sophisticated uses and can often be accomplished with low-end technology. However, it would be shortsighted to focus only on how best to have students learn "from" computers — that is, using technology to tutor students on basic skills. Technology has advanced beyond this tutorial function and can do so much more than what is readily measured by standardized tests, as we discuss in the next section.

LEARNING "WITH" TECHNOLOGY

While evidence indicates that computers can help students improve their performance on tests of basic skills, many researchers investigating the use of technology in education have found that technology is most powerful when used as a tool for problem solving, conceptual development, and critical thinking (Culp, Hawkins, & Honey, 1999; Sandholtz, Ringstaff, & Dwyer, 1997; Means, 1994). In Reeves' (1998) terms, this kind of use consists of learning "with" technology. It involves students using technology to gather, organize, and analyze information, and using this information to solve problems. In this manner, the technology is used as a tool, and teachers and students (not the technology) control the curriculum and instruction. Tool applications can be used in a variety of curricular areas (Means, Blando, Olson, & Middleton, 1993).

Using technology in this manner has become possible through increases in the sophistication and versatility of computer-based technology. As a result, early studies of CAI, ILS, and other forms of computer tutoring offer little insight into the impact of students learning "with" technology. Furthermore, early studies tended to focus on specific software or technology, severely limiting the generalizability of their results. In most instances, these early studies treat technology "as a discrete and isolated . . . input" (Honey, Culp, & Carrigg, 1999), and fail to take into account the larger classroom, school, and district context in which the technology was being used (Heinecke, Blasi, Milman, & Washington, 1999).

By contrast, much of the research literature on learning "with" technology takes into account these larger issues of the learning context and educational benefits that are harder to quantify than basic skills. Current instructional technologies can give visual representation to higher-order concepts, use graphics and simulations to link mathematical concepts to real-world applications, provide tools for data analysis which can reveal subtle patterns in data, and supply contextual information through interactive dictionaries, encyclopedias, and similar resources. With technology, students can spend less time doing calculations and more time creating strategies for solving complex problems and developing a deep understanding of the subject matter. Word processors have greatly simplified some aspects of writing, editing, and rewriting. Video has long been a way to present unfamiliar material that would be difficult to conceptualize when presented verbally, and today's interactive video combines the power of visual presentation with the interactive and information-processing capabilities of the computer (Knapp & Glenn, 1996).

Computers may not provide the best means to read large blocks of text, such as complete books, but they are useful for scanning smaller sections of written material. Moreover, using hypertext links to browse through related material is a very efficient method for collecting information. With the Internet, students can have access to libraries many times more extensive than libraries in their schools or communities, and can take advantage of information that is up-to-date, not found in their textbooks, and perhaps unfamiliar to their teacher. Interactions through email have been shown to be motivating factors for students to improve their reading and writing skills. Email also allows students to collaborate with people not physically present, over large distances.

One of the most powerful uses of technology in education is to tailor instruction to students' individual learning needs. Technology can provide the means for students with special needs to communicate via email and use the Internet for research, and can also help teachers accommodate students' varying learning styles (Silverstein et al., 2000). Gifted students can work at their own pace and explore subjects in more depth than the basic curriculum. Technology can also analyze and provide immediate feedback on performance, and can suggest modifications in instruction where necessary to improve student achievement (CEO Forum on Education & Technology, 2001). Online sites are available 24 hours a day for students who need additional instructional guidance (Riley, Holleman, & Roberts, 2000). As Culp and her colleagues (1999) state, "The combination of computation, connectivity, visual and multimedia capacities, miniaturization, and speed has radically changed the potential for technologies in schooling" (p. 2).

Impact on students

Technology used in these ways leads to outcomes that tend to be difficult to measure. The difficulty results not only from rapid changes in technology, but also because many existing assessments do not adequately capture the skills that this technology enhances, such as critical thinking, other higher order thinking skills, writing, and problem solving ("Critical Issue," 1999). As a result, studies examining the impact of students learning "with" technology are far from conclusive (Heinecke et al., 1999; Coley, 1997).

Nonetheless, some studies exist that illuminate the conditions under which technology can improve student learning. The Apple Classrooms of Tomorrow (ACOT) project, for example, was a 10-year study that set out to investigate how routine use of technology by teachers and students would affect teaching and learning. ACOT equipped project classrooms in five different schools throughout the country with computers, printers, scanners, laser-disc and videotape players, modems, CD-ROM drives, and a variety of software packages. ACOT teachers were provided with training on telecommunications, basic troubleshooting, and tool software such as spreadsheets, databases, and graphics programs. The project also helped fund a coordinator at each school site to provide technical and instructional assistance.

Researchers evaluating the impact of ACOT conducted a longitudinal study of project students, and reported that, when compared to their non-ACOT peers, they "routinely employed inquiry, collaborative, technological, and problem-solving skills uncommon to graduates of traditional high school programs" (Sandholtz et al., 1997). In these ACOT classrooms, students routinely used tool software such as word processing, databases, spreadsheets, hypermedia, and multimedia. Interdisciplinary, project-based learning was commonplace at this site, where teachers worked in teams to integrate technology into the curricular framework. The skills ACOT students developed as a consequence were similar to those argued for by the U.S. Department of Labor (Secretary's Commission on Achieving Necessary

Skills [SCANS], 1991). According to the Commission, in addition to basic language and computational literacy, high school graduates must master the abilities to work with others; locate, evaluate, and use information; organize resources; understand complex work systems; and work with a variety of technologies.

In another longitudinal study, researchers investigated the impact of project-based learning using multimedia (Penuel, Golan, Means, & Korbak, 2000). The project, funded through a federal Technology Innovation Challenge Grant, was aimed at helping teachers implement an exemplary model of interdisciplinary, project-based learning with multimedia, and thereby provide students with the opportunity to acquire content knowledge, as well as improve composition and presentation skills. In completing the projects, which were built around real-world problems, students used a variety of technological tools, including video cameras, digital editing, and Web authoring programs. Data from teachers' self-reports, as well as classroom observation data, suggest that project teachers were less likely to lecture than non-project colleagues, and instead took on the role of facilitator or coach. In project classrooms, students spent a greater amount of time than non-project peers in active, small-group collaborative activities or small group discussions. In short, project classrooms were much more student-centered than non-project classrooms, and were "organized around the collaborative construction of complex products" (Penuel et al., 2000, p. 109).

Given the difficulty of measuring the effects of this kind of technology use, researchers designed a complex performance assessment to determine what students were learning. The assessment required students to work in small groups for an hour to construct a brochure to inform elementary school principals and teachers about the problems that homeless elementary students encounter when they go to school. The assignment required students to document these problems, suggest solutions, and propose arguments about why these solutions would work. Brochures were rated on a variety of dimensions related to communication and presentation skills, including: students' understanding of the curriculum content; students' attention to an external audience; and design (e.g., integration of text, images, and graphics). Students from project classrooms as well as non-project classrooms completed the assessment. Their brochures were rated by judges who were blind to students' affiliation (project or non-project). Results indicate that project students outperformed non-project students on all dimensions. Moreover, gains were not achieved at the cost of growth in basic skills, since researchers found that project students scored comparably on standardized tests to their non-project peers.

In addition to having a positive impact on the higher-order skills described above, numerous studies have reported that technology can lead to increased student motivation and improved self concept. In 2000, for example, researchers commissioned by the Software and Information Industry Association (SIIA) examined 311 research reviews and reports from published and unpublished sources. They concluded that technology has been found to have a positive effect on student attitudes toward learning, self-confidence, and self-esteem (Sivin-Kachala & Bialo, 2000). Other reviews (e.g., Coley, 1997), have reported that technology has been found to improve school attendance, decrease dropout rates, and have a positive impact on students' independence and feelings of responsibility for their own learning. In ACOT classrooms, teachers reported that students displayed increased initiative by going beyond requirements of assignments, and that students spent more time on assignments and projects when working on computers. Students often chose to use technology during free time, and before and after school (Sandholtz et al., 1997). However, researchers noted that technology had an enduring, positive impact on student engagement in ACOT classrooms only under certain conditions, as we discuss further in the section below on lessons learned from the research.

Impact on and from education systems

In addition to examining the effect of technology on student outcomes, researchers have investigated the impact of technology on classrooms, schools, and districts. Results of a variety of studies (e.g., Hawkins, Spielvogel, & Panush, 1996; Means, 1994; Chang et al., 1998) suggest that, over time, technology can serve as a strong catalyst for change at the classroom, school, and district level. Glennan and Melmed (1996) point out, "Introducing information technology into the schools may provide the catalyst that enables and forces the restructuring necessary to meet our national education goals." Conversely, evidence also exists that technology will have a stronger impact when technology integration is part of a broader-based reform effort (Sandholtz et al., 1997). In other words, the relationship between technology and reform appears to be reciprocal. Each can benefit from the other.

Whereas using technology as a tutor tends to be associated with a focus on improving performance on standardized achievement tests, the type of instructional philosophy most consistent with learning "with" technology is constructivism. After the publication of *A Nation at Risk* (National Commission on Excellence in Education, 1983), educational reform efforts focused heavily on raising course requirements and scores on standardized tests of academic achievement, for which computer-based instruction, Integrated Learning Systems, and similar forms of learning "from" computers were most useful. However, according to Means and her colleagues (1993), "Achievement of more advanced skills in subject areas showed no discernable gains" (p. 2) as a result of these efforts. In the early 1990s, educators and psychologists, as well as groups such as the National Council for Teachers of Mathematics and the National Science Teachers Association, suggested a move toward more constructivist learning strategies, which calls for "teaching basic skills within authentic contexts … for modeling expert thought processes, and for providing for collaboration and external supports to permit students to achieve intellectual accomplishments they could not do on their own …" (Means et al., 1993, p. 2). (See Table 1 for a comparison between traditional teaching — instruction — and teaching strategies consistent with constructivism.)

Table 1: Contrasting views of instruction and construction, from Sandholtz, Ringstaff, and Dwyer (1997).

	Instruction	Construction
Classroom activity	teacher-centered didactic	learner-centered interactive
Teacher role	fact teller always expert	collaborative sometimes learner
Student role	listener always learner	collaborator sometimes expert
Instructional emphasis	facts memorization	relationships inquiry and investigation
Concept of knowledge	accumulation of facts	transformation of facts
Demonstration of success	quantity	quality of understanding
Assessment	norm-referenced	criterion-referenced portfolios and performances
Technology use	drill and practice	communication, collaboration, information access, expression

The more advanced uses of technology support the constructivist view of learning in which the teacher is a facilitator of learning rather than the classroom's only source of knowledge (Trilling & Hood, 1999; Penuel & Means, 1999; Silverstein et al., 2000; Statham & Torell, 1999). In numerous studies of student learning "with" technology, teachers have reported that technology encourages them to be more student-centered, more open to multiple perspectives on problems, and more willing to experiment in their teaching (Knapp & Glenn, 1996). In technology-rich classrooms, students become more engaged and more active learners, and there is typically a greater emphasis on inquiry and less on drill and practice (Sandholtz et al., 1997; Bozeman & Baumbach, 1995). Technology also encourages student collaboration, project-based learning, and higher-order thinking (Penuel et al., 2000). According to Means and her colleagues, "Technology supports exactly the kinds of changes in content, roles, organizational climate, and affect that are at the heart" of constructivist educational reform movements (1993, p. 1). Similarly, Bozeman and Baumbach (1995) report that schools that have embraced technological change in instructional delivery have seen dramatic improvements consistent with school restructuring.

LESSONS LEARNED: CONDITIONS THAT FAVOR DESIRABLE OUTCOMES

Whether the technology involved is the simpler computer-based tutoring systems or the more advanced technology suited to student exploration, and whether the goal is to raise student achievement on standardized tests or to serve as a catalyst for whole school reform, research studies consistently point to certain conditions that favor productive outcomes. The following sections identify and explain the conditions that educators and policymakers should strive to put in place in order to make the most of their technology investments.

Technology as one piece of the puzzle

Although technology can support educational change, it will have little impact without accompanying reform at the classroom, school, and district level. For example, in Union City, New Jersey, a study was conducted of the impact of a school-business partnership (Project Explore) designed to provide students and teachers with in-depth access to communications and information resources. Project students had access at home and at school to a variety of technological tools, including email, whereas non-project students had access only at school and were not provided with email. Researchers examining the impact of the technology on student achievement found a substantial improvement in students' standardized test results, particularly at the middle school level, where scores rose between 30 to 50 percentile points on a state-mandated test. While some of this improvement can be attributed to technology, researchers noted the importance of other restructuring efforts that were occurring simultaneously, such as a change in the reading curriculum from skill-based to whole language; the use of authentic literature instead of basal readers; block scheduling; extensive staff development; and increased parent involvement. Researchers concluded, "The magic lay not exclusively in the technology, but in the interweaving of a systematic program of education reform with the judicious use of technology-based resources" (Chang et al., 1998, p. 43).

Researchers in the ACOT study noted that technology had an enduring, positive impact on student engagement only under certain conditions, particularly when the technology was integrated into other aspects of the students' experience. For example, students were less likely to become bored with computers when teachers used technology as one tool among many in their instructional repertoire. In such classrooms, teachers used computers only when they were the most appropriate tool for completing the assignment, not simply because they were available. Student engagement was more likely to endure in classrooms that emphasized the use of tool software rather than drill-and-practice applications. In order to maintain student engagement, teachers also needed to take into account individual differences in interest and ability. Finally, student engagement remained high in classrooms emphasizing interdisciplinary, project-based instruction (Sandholtz et al., 1997). Other researchers have reported similar results related to student motivation (Silverstein et al., 2000; Penuel et al., 2000).

Studies of IBM's Reinventing Education program showed that students' reading skills improved in schools that had leadership committed to a school reform plan as well as clear, meaningful educational goals. Walt Disney Elementary School in Burbank, California, used technology for the purpose of improving standardized test scores, but first organized the curriculum and teachers of the school for the effective integration of technology (Reksten, 2000). In ACOT classrooms, researchers found a strong complementary relationship between the adoption of technology and the creation of collaborative learning environments for teachers (Sandholtz et al., 1997). And in a study of five technology-rich schools (Glennan & Melmed, 1996), goals for student learning were clearly articulated prior to the introduction of technology. These technology-rich schools were restructured (e.g., longer class periods and project-based learning), were learner-centered, and had enhanced collegial relationships among adults (more consultation among teachers about curriculum and individual student learning). In contrast, technology has been shown to be less effective when learning objectives are unclear and the focus of technology use is diffuse (Schacter, 1999). Similarly, technology will not live up to its promise when teachers fail to focus on improving student learning (Glennan & Melmed, 1996).

Adequate and appropriate teacher training

A variety of studies indicate that technology will have little effect unless teachers are adequately and appropriately trained (Office of Technology Assessment, 1995; Coley, Cradler, & Engel, 1997; Silverstein et al., 2000;

Sandholtz, 2001). Studies suggest that teachers who receive formal training use technology more frequently for instruction, and this use can lead to significant improvements in student achievement. According to a report by the National Center for Education Statistics (1999b), teachers who report feeling prepared to teach using technology use it more frequently and in a greater variety of ways, and are more likely to have their students use technology as a tool in tasks that require higher-order thinking.

In a report that examined the results of over 300 studies of technology use, authors concluded that teacher training was the most significant factor influencing the effective use of educational technology to improve student achievement. Specifically, the report states that students of teachers with more than ten hours of training significantly outperformed students of teachers with five or fewer training hours (Sivin-Kachala & Bialo, 2000).

Researchers investigating the BS/CE program in West Virginia also found that timely and comprehensive teacher training was a key factor in the program's success (Mann, Shakeshaft, Becker, & Kottkamp, 1999). Evaluations showed that the use of technology was linked to higher scores made by eighth graders in problem solving and critical thinking, but only if the technology was used by trained teachers who use it in the most productive ways. Follow-up evaluations of this program also showed that the greatest gains in student achievement occurred when teachers were trained in the use of technology (Schacter, 1999).

A study of the 1996 NAEP results in mathematics found that teachers who are more knowledgeable about the use of computers were more likely than their less knowledgeable colleagues to use technology for higher-order purposes, and that students whose teachers received professional development on computers showed gains in math scores of up to 13 weeks above grade level (Wenglinsky, 1998). Teacher training was also shown to be crucial in research studies of programs such as Simcalc, the Adventures of Jaspar Woodbury, and the National Geographic Society's Kids Network (Heinecke et al., 1999).

In a wide-scale effort to improve the use of technology in classroom instruction throughout Rhode Island, 2,400 teachers — 25 percent of all teachers in the state — participated in the Teachers and Technology Initiative. As part of this program, teachers spent 60 hours in training on hardware, software, and technology integration. In addition, teachers were provided with sample units and laptop computers to use both in the classroom and at home (Henriquez & Riconscente, 1999). Researchers found an increase in the percentage of teachers using email and the Internet (from 39 to 98 percent) as a result of this training. Researchers conclude that the training gave teachers "a solid foundation in the use of technology as a core component of their instructional practices" (p. 76).

In Project CHILD, developers of the program clearly recognized the importance of teacher professional development. The CHILD model provides teachers with a full year of training and classroom coaching on using technology and on collaborative teaching strategies, as well as research-based materials to help teachers effectively integrate the instructional software (Butzin, 2000).

In a paper discussing the cost, utility, and value of technology, Wahl (2000) suggests that organizations should spend 30 percent of their budget on equipment and 70 percent on the "human infrastructure" to support ongoing training and technical assistance. Since many schools and districts prefer to spend their limited funds on tangible goods such as hardware and software, it is not surprising that researchers investigating the impact of technology on education report that insufficient teacher training is a significant barrier to successful integration (e.g., Mann & Shaefer, 1997). Statham and Torell (1999), for example, state that 80 percent of districts spend less than 10 percent of their technology budget on training, and that, on the average, teachers were offered only 21 hours of training in technology.

Research also suggests a lack of sufficient teacher training in technology use at the preservice level (Willis & Mehlinger, 1996). As is the case with inservice professional development, the content of preservice education related to technology is "fundamental computer operation rather than preparation on how to use technology as a teaching tool and how to integrate it across the curriculum" (Sandholtz, 2001). Moursund and Bielefeldt (1999) report that student teachers often do not have the opportunity to routinely use technology during their field experiences, and typically are not provided guidance by a master teacher on how to integrate technology into their instruction.

Given the lack of preservice and inservice training, teachers who want to hone their technology skills often do so on their own time (Mann & Shafer, 1997). Statham and Torell (1999), for example, indicate that 90 percent of teachers report that they are self-taught. A 1994 survey for the Office of Technology Assessment reports that less than 10 percent of new teachers felt prepared to use multimedia and communication technologies in their teaching, and only about half felt that they were competent enough with tools such as word processing or spreadsheets to use them in the classroom (Statham & Torell, 1999). In 1999, the National Center for Education Statistics indicated that only 20 percent of teachers report feeling well-prepared to integrate technology into their teaching (Sandholtz, 2001).

Even those schools and districts that do provide teachers training typically offer after-school workshops that concentrate on the basic mechanics of hardware and software. Brief sessions on word processing, scanning, or using spreadsheets are commonplace. While many teachers have participated in this type of training, most report that it was too short in duration and too limited to be helpful (National Center for Education Statistics, 1999b). Although teachers do need to understand fundamental computer operation to have the confidence and expertise to use technology, they need to be taught much more.

Specifically, teachers need to be taught how to use technology to deliver instruction. Helping teachers to learn to integrate technology into curriculum is a critical factor in the successful implementation of technology in schools (Sivin-Kachala & Bialo, 2000), but most teachers have not had training in using technology effectively in teaching (Coley et al., 1997; Silverstein et al., 2000). Even when professional development does focus on technology integration, teachers typically receive little follow-up training or support (Statham & Torell, 1999).

In an effort to create a model of staff development that overcomes the shortcomings of traditional inservice training, the Apple Classrooms of Tomorrow project, along with the National Science Foundation and three school districts, joined in 1992 to create teacher development centers at three of ACOT's original sites. At the centers, visiting teachers observed and worked in ACOT classrooms for one-week practicums during the school year, or for four-week institutes during the summer. Unlike typical after-school programs, this model of staff development allowed participants to see expert teachers modeling instructional use of technology as they worked with students. Participants learned about integrating specific hardware and software into their instruction, and explored issues such as interdisciplinary instruction, alternative assessment, project-based teaching, and team teaching. ACOT coordinators also provided follow-up support for participants for one year after visiting the centers.

Researchers investigating the impact of the program found that when teachers are learning to integrate technology into their classrooms, the most important staff-development features include opportunities to explore, reflect, collaborate with peers, work on authentic learning tasks, and engage in hands-on, active learning. In essence, the principles for creating successful learning environments for children apply to teachers as well (Sandholtz et al., 1997; Sandholtz, 2001).

In addition to receiving training on how to use technology instructionally, research also suggests that teachers need additional help in learning how to assess products created using technology (e.g., Penuel et al., 2000). Just as students sometimes focus too heavily on the technology-related aspects of assignments (Henriquez & Riconscente, 1999), teachers also can be distracted by the "glitz" of technologically sophisticated student work and lose sight of the "guts" or content. It is not uncommon, for example, for teachers beginning to use technology to create grading rubrics where students are assessed on the number of different fonts used, or the number of different slides in a multimedia presentation, rather than on the actual content. Other reports (e.g., "Research on Internet Use," 2000) indicate that in classrooms using multimedia, technology tends to be over-emphasized, while the underlying content is under-emphasized.

Changing teacher beliefs about learning and teaching

If technology is to be used in powerful ways — to support student collaboration, inquiry, and interactive learning — then teachers' beliefs about learning and teaching often must change. For those teachers who firmly believe that the lecture-recitation-seat work model of instruction is the best teaching method under all circumstances, even the best professional development on technology will have limited success. Integrating technology into instruction is a difficult, time-consuming process; only those teachers who believe that technology use will lead to significant benefits for their students will undertake the associated challenges.

One study that carefully examined the changes in teachers' beliefs as they integrated technology into instruction was on the ACOT project. Researchers found that the introduction of technology into project classrooms did not radically change teaching; instead, technology seemed to serve as a symbol for change, granting teachers a license for experimentation. To describe the changes that occurred over the course of three to five years in teachers' instructional practices, researchers developed a five-stage model, which includes entry, adoption, adaptation, appropriation, and invention. In the ACOT model, text-based curriculum delivered in a lecture-recitation-seat work mode was first strengthened through the use of technology, and then was gradually replaced by more dynamic learning experiences for students, such as collaborative, project-based, interdisciplinary learning. The instructional changes that occurred during these stages were closely tied to changes in teachers' beliefs about classroom management, learning, teacher-student roles, and instructional practices. ACOT researchers believe that the shifts in teachers' beliefs occurred when teachers began to see firsthand the benefits of technology use (Sandholtz et al., 1997).

The development of ACOT Teacher Development Centers was based in part on the idea that if visiting teachers could see for themselves the potential benefits of using technology, then they, too, would confront and possibly change their beliefs about learning and teaching, and as a consequence more successfully integrate technology into their classrooms. Other researchers have drawn similar conclusions about the value of providing teachers with a vision of what is possible, and have noted that teachers who volunteer to be a part of a reform initiative can serve as models and mentors for those who are reluctant to adopt an innovation. In Project Explore, for example, researchers felt that the project "benefited by capitalizing on teachers who were willing and motivated to bring about change and incorporate new technologies into the teaching and learning process" (p. 42). Teachers who were involved during the early stages of the project opened their classrooms so colleagues could observe for themselves the impact of technology use on learning and teaching. Chang and his colleagues noted, "For more skeptical teachers, having an opportunity to look before they leapt was key to building momentum . . ." (Chang et al., 1998, p. 42). These types of observational experiences can often serve as a strong impetus for changing teachers' beliefs about learning and teaching and bolster their motivation for undertaking the difficulties associated with technology integration.

Sufficient and accessible equipment

Adequate computer-to-student ratio

Without sufficient access to technology, of course, even well-trained, highly motivated teachers will not be able to integrate technology effectively into instruction. Although studies are inconclusive about the optimal number of computers per classroom (Mann, 1999), research is clear that students and teachers are best served if they have convenient, consistent, and frequent access to technology. For example, a RAND study (Glennan & Melmed, 1996) of technology-rich schools suggested that the most successful of these schools had a high density of computers and high access to them. In these schools, the expenditure per pupil on technology was three to five times the U.S. average. Similarly, the West Virginia BS/CE study indicated beneficial effects from instructional technology are unlikely unless there is sufficient equipment and access to it.

A study of 55 schools in New York (including data from 4,041 students, 1,722 teachers, 159 principals, and 41 superintendents) investigated the impact of increased access to technology (Mann & Shafer, 1997). Results indicate that in schools that had more instructional technology — as well as teacher training — the average increase in the percentage of high school students who took and passed the state Regents exam in mathematics was 7.5. Using principal and teacher reports related to technology access, researchers concluded that "42% of the variation in math scores and 12% of the variation in English scores could be explained by the addition of technology in the schools" (p. 1). Researchers also found a "strong relationship" between higher scores on the state's Comprehensive Assessment Report on sixth grade mathematics tests and increased access to technology. Moreover, researchers reported a positive relationship between the amount of technology available and teachers' self-reports of their skill using the technology (Mann & Shafer, 1997).

While recent surveys about the status of technology in schools suggest that the amount of technology is increasing (Statham & Torell, 1999; National Center for Education Statistics, 1999a), teachers continue to report that lack of access is a significant barrier to technology integration. Many schools have computers that are obsolete. It is not uncommon for schools to still be using machines that are over a decade old (Barnett, 2000; Statham & Torell, 1999). The results of a national survey of technology use conducted by Henry Becker revealed that fewer than 20 percent of schools have "at least one computer of any kind for every four students enrolled, one Pentium or Power Macintosh for every six students, one CD-ROM-equipped computer for every six students, and . . . at least half of all instructional rooms connected to the Internet by a high-speed, direct connection" (Becker, quoted in Soloway et al., 2001). Moreover, there are wide discrepancies in accessibility from state to state and from school to school, with high poverty schools typically having fewer technological tools (National Center for Education Statistics, 1999b).

Statham and Torell (1999) suggest that a 1:5 computer-to-student ratio would assure students "near universal access." In the ACOT project, researchers investigated the impact of "universal access" by providing all project students with a computer both at school and at home. Over the course of the project, researchers learned that, although computer access was important, access did not necessarily require a computer on every desk. Eventually, the configuration of computers in ACOT classrooms changed to require the sharing of resources. In the later years of the project, most classrooms had a ratio of about five students per computer, consistent with the recommendation of Statham and Torell.

Unfortunately, a 1:5 ratio far exceeds what is found in most classrooms. When ACOT began training teachers in their Teacher Development Centers in 1992, visiting teachers who participated in the program often found it difficult to transfer what they had learned in technology-rich classrooms to their own setting. Some felt limited by insufficient hardware and software in their own classrooms, but others learned how to use their one or two computers creatively. For example, some teachers used a "station approach," where students rotated through a variety of different activities on a daily or weekly basis. In such cases, teachers realized that they could manage effectively with only one or two "computer stations." Despite the success of this approach, other researchers have argued that if students are to use computers to be better writers, researchers, and problem-solvers, they need to have access to computers when they are engaged in these processes, not only at some regularly scheduled time (Knapp & Glenn, 1996).

Soloway and his colleagues (2001) believe that handheld devices (personal information managers or personal digital assistants) “are the answer to the access challenge in K–12 education” (p. 17). Preliminary research with over 2,000 students in a variety of schools around the country suggests that, despite their limitations, these devices can be effective tools in content areas such as physics and mathematics. Applications in reading, writing, and mathematics are currently available, and more are under development.

Appropriate placement: Classrooms versus computer labs

In addition to the number of computers available, the location of the hardware affects accessibility (Statham & Torell, 1999; National Center for Education Statistics, 1999a). Computers can be either in a centralized location (such as a computer lab), distributed (in the classrooms), or a combination of the two. All three models were used in the West Virginia BS/CE program. The results from this program indicate that student outcomes are most improved by the distributed model. Students who had access to computers in their classrooms showed more improvement in basic skills than those who received instruction in computer labs. In addition, teachers who had computers in the classroom reported greater confidence and competence in using computers and more time using the computers (Mann, 1999; Mann et al., 1999).

In recent years, schools and districts have been working to connect students and teachers to the Internet. As is the case with computers, whether or not teachers use the Internet for instruction appears highly dependent on classroom connectivity. As researchers for the Software and Information Industry Association report (Sivin-Kachala & Bialo, 2000), “Classroom connectivity to the Internet was found to be the best predictor of teachers’ professional use of the Internet. Furthermore, classroom connectivity in general and, more specifically, connectivity with four or more computers were found to be important factors in predicting whether teachers directed student research involving the Internet.” Similarly, Henriquez and Riconscente (1999), in a study involving almost 600 teachers in Rhode Island, concluded that a lack of computers connected to the Internet at the classroom level was the most significant barrier to the use of this important tool.

Computer access at home

In addition to investigating the importance of school access, researchers have examined the impact of students’ and teachers’ use of home computers. For example, in Union City, New Jersey, researchers examined a cohort of project students who had sustained access to technology at home and at school, and compared their performance on standardized tests to non-project students who had a more limited, school-only access (Chang et al., 1998). Specifically, project students had access to tools such as word processing, spreadsheet, and database programs, as well as access to communication resources such as email and information resources such as the Internet. Non-project students had access to similar resources at the school, but did not have access to email. Researchers found that project students did significantly better than the non-project students on standardized writing tests at the seventh, eighth, and ninth grade levels.

In Indiana, students participating in the Buddy project were supplied with home computers and modem access to the school. An evaluation comparing seven project classrooms to three non-project classrooms showed significant differences in a number of student outcomes. Specifically, project students "showed improvement in all writing skills, a better understanding and broader view of math, more confidence with computer skills, an ability to teach others, greater problem-solving skills, and greater self-confidence and self-esteem" than non-project peers (Coley, 1997, p. 4). Similarly, in "Children and Computer Technology" (2000), the authors report that children's use of home computers is linked to slightly better academic performance.

Of course, having a computer at home does not necessarily ensure that students are using the computer in ways that will increase their academic achievement. In the ACOT project, for example, researchers found that teachers at the elementary level did not have time to develop appropriate homework assignments utilizing computers. Consequently, in later years of the project, ACOT continued providing home computers only at the high school site.

Like students, teachers can often improve their skills with access to a home computer. Teachers typically do not have enough time on the job to learn to use technology, to practice what they have learned, and to explore further uses of the computer. Teachers who have computers at home have more time not only to learn to use technology, but to become more comfortable with it.

Long-term planning

Too often, technology is purchased without a clear vision of how it is to be integrated into the mission of the school or district. Research suggests that technology projects should be implemented only after a planning stage, where administrators and other stakeholders develop clearly articulated standards and goals for technology use. The most successful schools in IBM's

Reinventing Education program, for example, were willing to allocate time and other scant resources for planning how best to use the technology to improve instruction (Trotter, 2001). Moreover, since hardware and software are constantly changing, schools and districts must revisit their technology plan on an ongoing basis and make revisions, as necessary, to take advantage of new opportunities and innovations (Sivin-Kachala & Bialo, 2000).

Many schools and districts also make the mistake of spending most or all of their technology funds on initial purchases of software and hardware, and overlook the fact that replacing, maintaining, and supporting computer equipment will also require money. Unlike many items purchased for schools, such as library books or physical education equipment, computer hardware and software, as well as peripheral devices, quickly become obsolete. In some schools, printers sit idle because money was not budgeted to replace ink cartridges, toner, or paper. For this reason, costs of educational technology should be built into school budgets on an ongoing basis (Glennan & Melmed, 1996).

Technical and instructional support

Although adequate access to technology is a key factor in successful implementation, researchers investigating the impact of technology on student learning have found that a major barrier to technology use is the lack of technical support. Even teachers who enjoy using computers will stop using technology if the equipment is unreliable. Many teachers lack adequate troubleshooting skills — not to mention time — to fix equipment, especially if it breaks in the middle of a lesson. Consequently, the effective use of technology requires an adequate school and district infrastructure and must include timely, on-site technical support.

Longitudinal research examining teachers' use of technology suggests that the support teachers need changes as they become more and more proficient in integrating technology into instruction (Sandholtz et al., 1997). In the early stages of the ACOT project, for example, teachers needed basic technical support as they learned to use new hardware and software. Later, when teachers began experimenting with team teaching and interdisciplinary, project-based instruction, teachers needed professional development related to alternative student assessment strategies, such as performance-based assessments. Clearly, as teachers begin using technology for more sophisticated purposes, instructional support is as essential as technical support. At ACOT sites, a full-time coordinator gave teachers this crucial assistance.

The ACOT project also provided clear and striking evidence about the importance of principal and administrative support. In order for teachers to be eligible to participate in the ACOT Teacher Development Center project, their principals had to make a commitment to support them in three important ways when they returned to their schools. Specifically, principals were required to: 1) provide time for teachers who had attended the center to plan together and to reflect on their practice; 2) give recognition for the teachers' efforts; and 3) ensure that teachers had the authority and flexibility to adjust daily instructional schedules and to develop curriculum objectives that promote team teaching and interdisciplinary instruction. ACOT staff also strongly encouraged principals to attend selected portions of the program with their teachers. Despite these commitments, administrators varied dramatically in their attitudes toward technology and in what actions they took to help teachers when they returned to their classrooms. Researchers found that the most crucial determining factor in whether teachers who participated in the program successfully integrated technology into their classroom was the level of support they received from school and district administrators (Sandholtz et al., 1997). These findings are consistent with research conducted by the Office of Technology Assessment (1995).

Technology integrated within the curricular framework

To use technology effectively, teachers must understand how its use fits into the larger curricular and instructional framework. Researchers at Educational Testing Service (Coley et al., 1997), for example, state that courseware (computer software designed to be used in an educational program) should reflect curricular standards, and should take into account research on how students learn. According to Statham and Torell (1999), however, a survey in 1995 of elementary teachers reveals that schools used technology primarily to improve basic skills, rather than integrating it into the curriculum. They also report that only "nineteen percent of English classes, six to seven percent of mathematics classes, and three percent of social studies classes in high school integrated technologies into learning" (p. 7).

According to researchers at the North Central Regional Educational Laboratory (Valdez et al., 1999), CBI, CAI, ILS, and other forms of computerized tutoring are most likely to be effective when there is a match between the software, the objectives of the instruction, the students' prerequisite knowledge and skills, and teachers' understanding of the needs of the learners. And in the ACOT study, student engagement remained highest when technology use was integrated into the larger curricular framework, rather than being an "add-on" to an already full curriculum (Sandholtz et al., 1997).

Advocates of technology use in the classroom sometimes cite the importance of developing students' job skills, and teachers often respond by "teaching technology," such as keyboarding or word processing, rather than using it as a tool to teach the curriculum. However, research suggests that when technology is integrated into the larger instructional framework, students will not only learn how to use the equipment and software, but will also gain content knowledge (Silverstein et al., 2000). Moreover, using technology within the curriculum framework can enhance important skills that will be valued in the workplace, such as locating and accessing information, organizing and displaying data, and creating persuasive arguments (Sandholtz et al., 1997; "Critical Issue," 1999).

Other research has shown the importance of integrating technology into the curricular framework. For example, West Virginia's BS/CE program integrated technology into instruction rather than isolating computer skills from content learning. Researchers identified this characteristic of the program as one reason for its effectiveness (Mann et al., 1999).

Research on the Middle School Mathematics through Applications Project (MMAP) provides a striking example of how powerful technology can be if its use is embedded in content-rich activities (Penuel et al., 2000). MMAP was created to help students learn mathematics as they designed solutions to real-world problems with the use of technology. At first, both students and teachers were so deeply engaged with the technology itself that little attention was paid to content learning. With proper support from project staff, however, mathematical content became more of a focus and the use of technology became more transparent. Specifically, project staff structured MMAP problems, activities, and assessments to enhance the subject matter content. Eventually, a balance was achieved: Students continued learning about and using the technology and many also reached middle-school mathematics standards.

CONCLUSIONS

As numerous researchers have pointed out (e.g., Reeves, 1998; Means et al., 1993; H. J. Becker, personal communication, 2001), measuring the impact of technology use on student achievement is fraught with difficulties. Classrooms are not experimental laboratories where scientists can compare the effectiveness of technology to traditional instructional methods while holding all other variables constant. Moreover, few reliable, valid, and cost-effective assessments exist that measure students' higher-order thinking skills, problem-solving ability, or capacity to locate, evaluate, and use information — skills that many researchers and teachers believe can be enhanced through technology use. Technology has also been shown to increase student motivation and engagement, prepare students for jobs, and enhance students' ability to work collaboratively, but we have few, if any, tools and methods to measure impact in these domains. Thus, it is not surprising that the impact of technology on education continues to be debated by educators and researchers alike.

Debates aside, there is a substantial body of research that suggests that technology can have a positive effect on student achievement under certain circumstances and when used for certain purposes. However, there is no magic formula that educators and policymakers can use to determine if this "return" is actually worth the "investment." Perhaps, rather than asking, "Is technology worth the cost?" the more important question is, "Under what conditions does technology have the most benefits for students?" The research presented in this paper seeks to answer this question, and offers some suggestions — related to issues such as teacher training, access to technology, and long-term planning — that policymakers should seriously consider as they seek to enhance student learning through technology use.

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