Save the Children®

Effective educational technologies by child developmental stage

A report for Save the Children

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The benefits (and challenges) of educational technology

The ubiquity of technology in the modern era is undeniable. Where society once questioned whether or not technology should be incorporated into learning domains, research over the past several decades has definitively shown that introducing children to technology as a learning mechanism can have a positive effect on their cognitive, academic, and social development. The question in modern times has thus shifted from *if* technology should be introduced to children to *how* technology should be leveraged to provide the greatest educational benefits.[1]

The benefits of edtech

Motivation and engagement

Research has consistently shown that higher student engagement in the classroom is positively correlated with improved academic performance.[2] Technology-based learning solutions have been shown to instill in young children a positive attitude towards learning, boosting their self-confidence and feelings of success.[3] One study of children in elementary and middle school found that the students were more likely to participate in classroom activities when technology was included in some way, and overall student engagement increased by 9% after the technological intervention was introduced.[4]

Hands-on learning

Technology is most effective as a learning tool when it provides four key features: active cognitive engagement, collaborative learning, frequent and immediate feedback, and connections to real-world contexts.[5] Technology has the potential to place learning in the hands of the students directly, a pedagogy that the International Society for Technology in Education identifies as the foundation for "the schools of the future."[6] Hands-on, active learning has been scientifically proven to stimulate the brain in different ways than passively consuming information, leading to better academic performance and deeper conceptual understanding.[7]

Immediate feedback and scaffolding

Educational software can provide instructional supports and scaffolding to dramatically improve students' learning, often in ways more effective than even traditional learning methods can provide. Software can deliver appropriately-leveled activities customized to individual learners' needs and provide hints and suggestions when necessary, resulting in a customized and dynamic

experience for each learner.[8] Software is also able to provide learners with immediate corrective feedback, allowing them to identify their mistakes as soon as they are made and learn how to correct them quickly and efficiently.[9]

Flexible, robust contexts

Technology can expose learners to the same information across multiple modalities, which research has shown to be an effective method for promoting learning gains.[10,11] For example, a student learning to read from an e-book can be given the option to hear the words read aloud and view a short animation illustrating the activities being described in the text, assisting their comprehension. The interactivity of computer-based instruction can also provide a platform for learners to apply the concepts they are learning in a variety of different contexts, which allows them to build more flexible knowledge representations and adapt their understanding to other contexts.[12]

Equitable access to education

Technology is highly beneficial for helping to close the "achievement gap" for children who are struggling to keep pace with their peers. Studies show that introducing technology into the learning environment can significantly improve test scores for students who are low-income and otherwise academically at-risk.[13] Integrating technology and interactive media into early classrooms, when done effectively, provides equitable access for all children to participate in the same learning activities.[14,15]

However...

Digital literacy is not a given

Digital literacy, a person's ability to "use computer technology for learning, work, socializing, and fun,"[16] is an imperative skill in modern society. A person who is digitally literate is able to understand and use information acquired from many different digital sources,[17] and—perhaps more importantly—adjust their usage to adapt to different sociocultural contexts.[18]

Digital literacy skills and technological competence must be explicitly taught: giving students access to technology does not inherently result in their understanding of technology. The more people are exposed to digital tools and technologies, the more adept they become at using them. Conversely, a lack of exposure to technology at a young age puts children at a disadvantage compared to their tech-savvy peers, and this skill gap grows wider over time, making these students less able to benefit from technological interventions.[19] If students are not

taught how to use digital tools effectively, they will not be able to reap the educational benefits of even the most well-designed edtech solutions.

Empty promises abound

Although there are many different tools and technologies on the market today that claim to have educational benefits for young children, the vast majority of these solutions have not been evaluated in any empirical way. Today, there are over 180,000 apps in the "education" category of the Apple App Store alone;[20] however, a study examining the most popular and expert-endorsed children's literacy apps in each of three major app stores found that 77% of these apps did not provide any sort of research to support their claims at all, and only 2% provided results of actual empirical efficacy studies, with the rest reporting only on usability and appeal.[21] The market is oversaturated with educational software products that make attractive promises about their educational benefits, but there is little evidence to either support or refute these bold claims.

Overemphasis of behaviorist learning

Many technology-based solutions, such as computer-aided instruction systems and assessment software, embrace the same behaviorist principles that guide traditional classroom practice. In behaviorist practice, learning occurs as a response to stimuli provided in a controlled environment: user input is mostly passive, objectives are predetermined, and responses are expected to conform to a small set of acceptable inputs.[22] The feedback a student receives is rarely dynamic and adaptable to their demonstrated needs, and higher-order thinking skills are difficult to promote through drill-and-practice. Educational paradigms in modern times are shifting towards more constructivist approaches, wherein the learner is an active participant and research and exploration is emphasized over consumption of knowledge.[23] Although there is value in many behaviorist technological applications, such as word processors and drill-and-practice games, there is often an overemphasis on these tools for learning, resulting in a mismatch between the technology being employed as educational tools and the pedagogical goals at the core of learning.[24]

Software should supplement, but never replace, teachers and caregivers

Research has consistently shown that adult mediation provides students with essential scaffolding and support throughout their learning process, a fact that remains equally true when technology is introduced. The US Department of Education emphasizes that, when it comes to implementing effective edtech solutions in schools, providing internet access and digital devices to students is less important than "preparing teachers to teach effectively with technology and

to select engaging and relevant digital learning content."[1] One study examined the impacts of the same educational software introduced at two different schools, finding that achievement gains occurred only for students in the classes where the teacher incorporated the information from the software into their own classroom instruction.[25]

For children outside of school, parent and caregiver engagement has been shown to be hugely influential in a child's academic success. Children whose parents are familiar with their children's homework assignments, engage them in conversations about school, and are involved in their educational planning have been shown to achieve better grades, higher test scores, and better behavior at school and at home.[26] When young children engage with technology, they have been shown to be more focused when their activities are supplemented with adult mediation and guidance.[27]

Conversely, a lack of parent engagement has been shown to have negative effects on intervention efficacy. One study of a novel literacy learning software found inconclusive results in children's learning gains, where half of the trials resulted in the control group learning more than the software users; because the adult facilitators were not trained in how to use the system themselves and how to provide adequate support to the children, the quality of their feedback was notably inconsistent, which resulted in very different outcomes for different test groups.[28] Another study found that children using learning software at home were initially very motivated and eager, but quickly lost interest due to a lack of parent encouragement.[29] These same parents were revealed to have a large disconnect between their desires for their children to learn from the software and their understanding of what the software could actually do as a learning tool, leading to disengagement from both parents and children.

Solutions must be developmentally appropriate

Children's cognitive abilities and executive functions develop as they age, and the digital tools they are exposed to must be reflective of this. A newborn baby, for example, cannot operate a keyboard and mouse to play even the most academically beneficial computer game. Providing children with technologies that are inappropriate for their age is ineffective at best, and in some cases can even be detrimental to their cognitive development.

In order for technology to serve as an effective learning tool for a child, it must be *developmentally appropriate* for their age. Activities are considered developmentally appropriate when they are "challenging but attainable for most children of a given age range" and "consistent with children's ways of thinking and learning."[30] Moreover, digital activities should always aim to keep children in their zone of proximal development,[31] challenging them with activities slightly outside of their independent learning ability, but within their ability to learn with some external assistance. This ensures that a child is neither overwhelmed by

concepts beyond their comprehension, nor disengaged by activities that do not stimulate them intellectually.

Developmentally-appropriate technologies for children

The following sections describe technologies that research has deemed to be developmentally appropriate for children in three different age categories: infants and toddlers, preschoolers and kindergarteners, and primary schoolers.

Infants and toddlers

According to Piaget's theory of cognitive development, infants and toddlers under two years old are in the sensorimotor stage of development.[32] At this stage, babies apply their senses of touch and taste to learn about the world around them, and their fine motor skills are not yet developed. Traditional computer interfaces with mouse and keyboard input are inappropriate and ineffective tools for babies, as children at this age do not have the physical capabilities to operate such devices.[33]

Passive screen-based media is ineffective

Babies have been shown to have little or no understanding of what they see on screens.[34] Until about 18 months old, a baby's brain is not developed enough to translate symbols on a screen into their equivalent representations in the real world. Even children as old as two years old often fail to understand that the world inside a television screen is a self-contained passive representation, and that the objects shown on screen are not able to be interacted with.[35]

Research has consistently shown that children under two require human interaction and feedback in order to process and retain language concepts,[36–38] rendering passive screen-based media such as DVDs ineffective for knowledge transfer. Several studies have shown that children under two were unable to learn or retain new words from watching baby media specifically designed to teach vocabulary.[39,40]

Passive screen-based media can be *harmful*

Any amount of time a baby spends engaged with screen-based media is time that is not being spent engaged with other human beings, depriving them of valuable learning opportunities and cognitive stimulation. One study estimated that every hour of screen media exposure for a baby aged 8-16 months, even "educational" programs designed to teach babies new words and concepts, correlated with that child knowing approximately 6-8 *fewer* words than their age-matched peers.[41] Exposure to screens has also been linked to poorer regulation of

executive functions, attention, thought, emotion, and behavior in young children.[42] As such, the National Association for the Education of Young Children and the Fred Rogers Center for Early Learning and Children's Media strongly discourages *any* amount of passive screen time for children under two years old.[43]

Screens can strengthen adult-child relationships if used appropriately

Where the research is very clear about the negative impact of passive screen media on infants and toddlers, new research is finding that certain types of screen-based technology can actually be beneficial for babies' learning and development. Technology can be developmentally appropriate for babies when it is used to facilitate exploratory play and foster human connections, which is well known to be how young children learn best.[44] Several studies have found that babies are able to understand and form social bonds when interacting with a live human on a screen through video conferencing software. Where passive screen media is ineffective at teaching babies new words, live video conferencing enables babies to learn from another person remotely, just as they can during face-to-face interactions.[45,46]

If children are allowed to explore technology at this age, it is recommended to always be accompanied by adult mediation to encourage responsive interactions and strengthen the social bonds between the adult and child. However, even for these types of beneficial screen interactions, technology use still should be very limited for children at this age.

Preschool and kindergarten

Beginning at age three, children's cognitive development and language improvements allow them to engage with screen media in ways that they could not do as infants.[34]

Children in preschool are in Piaget's pre-operational stage of development,[32] wherein their understanding of the world is self-centered and limited to their own perspectives. At this age, children begin to understand that they are capable of manipulating and interacting with elements on a screen, opening up a wider world of digital tools for their learning.

Digital literacy can, and should, be explicitly taught

The International Society for Technology in Education recommends that children be introduced to basic technology skills and concepts by the age of five in order to create a solid foundation for digital literacy acquisition and effective technology use.[6] Children should be taught not only how to physically use and interact with digital tools, but should also begin to be familiarized with more complex concepts like digital citizenship and how to use the internet safely.

Exposure to screen media is no longer inherently harmful

Between the ages of two and three, children's cognitive development is sufficient that screen media is no longer inherently detrimental to their learning. In fact, several studies have shown that exposure to well-designed educational television shows, such as Sesame Street, can improve children's vocabulary, literacy, and social behavior, leading to greater academic performance as they grow older.[47,48] Studies have also found that the presence of familiar characters in educational apps and media actually results in children being more receptive to learning, in math[49] as well as language and literacy.[50]

Touchscreens serve as a tactile extension of the real world

Due to their portable nature and streamlined design without the need for external input devices such as a mouse and keyboard, touchscreen devices like smartphones and iPads are particularly beneficial tools for younger children with developing motor control.[51] Tablets have been shown to be easier for preschool-aged children to interact with than smartphones and other smaller touch devices due to their size and relative durability.[52]

Touchscreens are particularly effective tools for children at this developmental stage because the gestures required to handle them, such as tapping and swiping, are very similar to the types of gestures that children spontaneously use when learning how to interact with physical objects, making them easy and intuitive to interact with. One study found that half of children in the 0-2 age range could independently tap on a tablet screen to open apps, swipe to turn pages in e-books, and trace shapes on the screen.[53] (However, more complicated gestures such as double-tapping, long-pressing, and two-finger rotations are difficult for children of this age to master.)[54]

Additionally, the interactivity of touchscreens has been shown to be beneficial to young children's attention and focus: one study found that preschool-aged children were more likely to respond to information presented in a video when the task involved touch input,[55] and another found that children learning to write letters performed better in post-tests when they learned to write using their finger on a tablet compared to using a traditional paper and pencil or a tablet and stylus.[56] Tablets have also been shown to be more naturally engaging for young children, and that this engagement actually increases with a child's age and use over time, rather than diminishing over time due to the "novelty effect."[57,58]

Ghost demonstrations are ineffective for conveying instruction

A "ghost demonstration" refers to an illustrative display wherein an object undergoes some sort of transformation without obvious human interaction, as if being influenced by a ghostly entity. A ghost demonstration in software is often used to convey instructions for how the user is meant to interact with the system or how virtual objects are intended to move, with images moving on their own to simulate the expected user input.

Several studies have shown that young children have difficulty interpreting and learning from ghost demonstrations in software. One study compared how preschool-aged children responded to learning how to assemble a three-piece puzzle on a tablet when taught by a ghost demonstration (watching the pieces move by themselves) and when taught by a human guide moving the pieces on the screen.[59] Only the children who received scaffolding from the human guide were able to replicate the task, suggesting that the adult presence and social interaction was essential to their ability to comprehend and complete the learning task. Another study found similar results when comparing four year old children's ability to learn from a computerized ghost agent and another human, finding that even when children received training prior to engaging with the ghost demonstration, they performed significantly worse at replicating the task than did children who received no prior training but learned from another human.[60]

The first study points out that many educational apps use ghost demonstrations as a method of conveying instructions, and parents may misinterpret a child's inability to complete the tasks as a cognitive failure rather than a result of inappropriate demonstration, suggesting that children at this age should not be exposed to learning software that relies on ghost demonstrations to convey content.

Children cannot easily transfer knowledge from screens to the real world

Young children have been shown to lack the cognitive flexibility to apply the concepts learned from two-dimensional sources (such as tablets, computers, and television screens) to three-dimensional real-world objects, a problem commonly referred to as the *transfer deficit*.[61] This results in children learning significantly less from screen-based media, due to their inability to turn this learned information into meaningful knowledge outside of the context in which it was originally learned.[61,62] (Conversely, children have been shown to be able to transfer between same-dimensional contexts more successfully, such as from touchscreen to TV, or between two physical objects).[63] This problem has been shown to persist even as children reach three years old, although the deficit is substantially greater for younger children.[64] However, studies have shown that this transfer deficit can be overcome with adult intervention, even for

very young children: one study found that infants were 19 times more likely to be successful at transferring from a touchscreen to a real object when they were taught to do so by a maternal caregiver providing verbal input, emotional responses, and appropriate guidance.[65]

Primary school

According to Piaget's theory of cognitive development, children at the primary school age are in the concrete operational stage, wherein they learn through trial and error and attempt to solve problems through physical manipulation.[32] Children in early elementary school can begin to utilize the full range of benefits of technology as it relates to education. Children at this age are likely to be familiar with digital tools to some degree, although they are only beginning to develop proficiency with technology and must therefore be given ample guidance and support from adults to ensure that it is being used appropriately and effectively.[57] At this age, children may have difficulty making sense of metadata as it relates to electronic media, and respond to visual cues more readily than text-heavy interfaces.[66] With increased exposure, primary school-aged children will gradually develop greater independence as both learners and users of technology.[67]

Primary school children's fine motor skills are usually developed enough at this age to allow them to use a computer mouse and operate tools with some degree of independence and autonomy, although tablets have still been shown to be more intuitive for children at this developmental stage.[68] One study found that children at five years old were capable of using a mouse to track objects moving on a horizontal plane, but were less successful at tracking objects in an arc pattern until they reached eight years old, suggesting that touchscreen interfaces are still a more accessible and accurate tool for young children.[69]

Proven technologies for: Literacy

The following section describes tools and technologies that have been empirically proven to be effective for improving young children's literacy acquisition.

Digital books lead to greater access and greater motivation

Research shows that being introduced to books and being read to at home prior to beginning school are the most impactful factors influencing a child's early academic success.[70] E-readers and digital book libraries can give a child with limited access to physical books, who would otherwise be highly disadvantaged from a lack of early learning opportunities, access to entire libraries worth of stories on a single device.

Studies have shown that children find reading more enjoyable when they are able to look at stories both in print and on touch screens.[71] A 2010 survey by the Organization for Economic Corporation and Development found that half of children surveyed said that having greater access to e-books would encourage them to read more for pleasure, and 15-25% of children felt that they read more when they were given access to books in electronic form.[72] Another study surveyed fourth grade students to determine which factors were most influential in determining how much and how often they read, finding that the majority of children considered having a large selection of books to choose from to be most influential in increasing their reading frequency.[73] There has been shown to be a direct correlation between reading for pleasure and reading attainment,[74] making e-books a valuable tool for improving reading ability for less enthusiastic struggling readers.

Tablets and touchscreens make reading hands-on

Studies have shown that tablets can be successful tools for supporting preschoolers' literacy acquisition through independent use, in small groups, and as class-wide group activities.[75–77] Preschool-aged children, even in a pre-literate stage, have been shown to improve their alphabetic knowledge, phonological awareness, and vocabulary from tablets and other touchscreen activities.[76]

One study found that preschool children could use iPads to learn how to manipulate letters on the screen to write their names and simple messages.[75] Another study gave preschoolers tablets loaded with literacy apps and no supervision, and found that the children were all able to learn how to use the tablets and explore all the apps independently after only one day.[78]

Furthermore, after four months of independent use, the children had learned six times as many words as they knew before the intervention began just from freely playing with the apps.

E-books can boost vocabulary, comprehension, and phonics

E-books are particularly beneficial for struggling readers due to their ability to provide helpful scaffolding for text, such as illustrative drawings and on-demand word definitions. Preschool-aged children have been shown to be able to learn to read new words from digital text when appropriate scaffolding and highlighting is provided, especially after repeated readings.[79,80] E-readers also allow the user to increase the size of the text being read, which allows for slower and more deliberate reading,[81] resulting in fewer instances of misread words, skipped lines, and missed punctuation cues.[82]

Several studies have also shown the benefit of electronic books on phonological awareness and elementary word reading skills.[83,84] While multiple studies have shown that drawing children's attention to printed text during shared reading has little effect on their learning of print concepts,[85,86] animated e-books which draw attention to the text as it is being read increases children's letter reading ability.[87] E-books are also beneficial as tools for promoting effective partnered reading between children: collaborative discussions between children about digital texts were significantly correlated with children's improved phonological awareness.[88]

Multimedia supplements the reading process

Research has shown that children are more successful at retaining new word knowledge and story meaning when the information is presented both visually and verbally: verbal information can help children make sense of complex images, while visual imagery can illustrate unfamiliar words and concepts.[89] E-books with multimedia integration such as animated pictures, sounds, and music have been shown to be particularly beneficial for children's story comprehension when compared to traditional books both with and without static illustrations.[90] Electronic images that illustrate details of the story have been shown to support both vocabulary gain and comprehension in young readers.[84,91]

...But interactive features are distracting

Conversely, interactive elements in e-books were found to be negatively impactful for children's comprehension, serving as distractions and needlessly increasing the learner's cognitive load.[90] Several studies have shown that interactive elements like games and hotspots embedded in digital text result in children recalling fewer elements of a story.[92,93] Even when adults and children read e-books together, the presence of interactive features has been shown to lead to

significantly more verbal interactions between the adult and child that are related to elements other than the story itself, reducing the child's story element recall.[94]

Game-like activities incorporated into story reading sessions have also been shown to interrupt children's focus, interfering with their ability to process story lines and diminishing their reading performance.[95] One study found that children using multimedia books with interactive elements recalled fewer story elements than children who were read to by an adult, due to the distractions provided by the on-demand resources embedded within: children spent 43% of their e-book usage time playing the games rather than engaging with the actual text.[96]

Technology helps teachers help young readers

Extensive research has shown that young children learn to read most effectively when they are supported by adults, either through co-reading or having stories read to them. However, in large group classrooms, it is not always possible for a teacher to give adequate attention to individual readers. One study found that introducing literacy software into classrooms of high-risk first graders allowed students to develop greater independence during group writing activities, which gave teachers greater flexibility to provide assistance to individual students with fewer interruptions.[97] Another study found that young children engaging with e-books independently were able to improve their conceptual understanding of print to the same degree of effectiveness as children engaging with printed books while shared reading with an adult, suggesting that e-books can serve as an effective stopgap solution in circumstances where adults are not readily available.[98]

Text messaging can get parents engaged

Several programs have shown the value of text messaging as a method of guiding parents to engage in literacy-building activities with their children at home. Parents often report that such programs are an effective method of engaging them in their children's learning without feeling obtrusive.[99] One program found that parents who were sent regular text messages with tips and suggestions for how to encourage literacy practice at home were 13% more likely to engage in these activities with their children, and were more likely to communicate with their children's teachers.[100] Two evaluation studies have shown that engaging parents through text message reminder programs can have significant positive impacts on preschool and primary school children's early literacy and reading comprehension skills.[101,102]

Proven technologies for: Science, Technology, Engineering, and Math

Experts agree that science, technology, engineering and math (STEM) are imperative skills for people of all ages. A report from the Carnegie Corporation Institute for Advanced Study declared that a solid foundation of math and science knowledge is required for innovation and success in the modern workplace.[103] STEM concepts can and should be taught at a very young age, as research has shown that STEM education leads to greater problem-solving skills, creativity, collaboration, and persistence, all of which are essential for future academic success.[104]

The National Council of Teachers of Mathematics has declared that technology is an integral tool for fostering the acquisition of mathematical understanding for children beginning in kindergarten.[105] Digital technologies are particularly valuable for teaching and reinforcing mathematical concepts due to their ability to provide models and visualizations of abstract concepts and facilitate hands-on experimentation.[106] Computer-based math interventions have proven to have significant positive effects on children's math achievement, particularly in elementary school classes and with special needs students.[107] Research shows that giving students autonomy to control their own mathematical learning in an interactive, investigative environment improves their performance and increases their enjoyment of the materials being taught.[108]

The following section describes tools and technologies that have been empirically proven to be effective for improving young children's understanding of math and science concepts.

Interactive whiteboards make math engaging and fun

Research has shown that interactive multimedia applications can greatly improve children's understanding of early math concepts. Kindergarteners were able to learn fractions and symbol notation faster and improve their memory of the learned materials when engaging in activities in a collaborative SMART-board environment.[109] Another study found that children in a pre-kindergarten classroom that used an interactive touchscreen whiteboard made significant improvements in counting, arithmetic operations, and shape awareness, with an overall 28% increase in math achievement over a year.[110]

In 2007, the Primary Schools Whiteboard Expansion Project found that students were universally enthusiastic about the inclusion of interactive whiteboards in their classrooms.[111] Findings revealed that integration of the interactive whiteboards over two school years resulted

in significantly greater learning gains for students in math and science, and was found to markedly improve children's attention and behavior in class.

Tablets minimize cognitive load and create better flow for learning math

Studies have shown that both computers and tablets can be effective tools for delivering math interventions to children, but tablets have been consistently shown to produce greater learning gains due to their interactive nature, which maintains children's interest longer and provides a more tangible learning environment.[112,113] One tablet-based intervention with an application called Math Shelf found that after just 15 weeks of practice, preschool-aged children gained an entire year in math skills.[114] Another tablet intervention with children aged 4-5 resulted in significant gains in number recognition and digit formation.[115]

Tablets are also an effective medium for teaching mathematical concepts in primary school, resulting in significant gains in foundational concepts such as arithmetic and number recognition.[116] They have also been shown to increased participation, interaction, and feelings of enjoyment in young math learners.[117,118] Touchscreen interfaces allow children to maintain a better flow of interaction and reduce the cognitive load required for them to manipulate the software itself, freeing up their mental resources to apply learning strategies and solve tasks more quickly and effectively.[119]

Games make math less intimidating

Effective learning games allow the user to experience *flow*: a human cognitive state of being wherein a person feels heightened motivation, becomes more receptive to information, and loses their sense of time as a result of their intense engagement. This state arises when participating in tasks with "clear goals, a need for concentration, feedback, a merging of action and awareness, matched challenge and skill, personal control, and intrinsic reward."[120] Flow state is achieved when six elements are present: a task to accomplish, the ability to concentrate, clearly stated goals, immediate feedback, a sense of control, and effortless involvement.[121]

Game-like activities have been found to be particularly appealing and engaging for young children.[122] Studies have described various educational math games which have significantly improved addition, subtraction, and number sense skills in at-risk elementary schoolers, and multiplication skills in fourth graders.[123] One study found that fourth graders who played a fraction-based iPad game improved test scores by 15% after playing for 20 minutes a day for 5 weeks.[113]

...But shallow gamification inhibits deep learning

Unfortunately, while some thoughtfully-designed learning games can utilize the elements of flow state to provide learning that is authentic, collaborative, and allows for learning-by-doing,[124] most educational apps on the market today fall into the *edutainment* category: drill-and-kill activities "sugarcoated with game characteristics."[125] These types of shallow games actually disrupt flow state by requiring players to switch their focus to extrinsic activities that remove them from the immersive elements of the game as a learning mechanism.[126]

Many extrinsic game elements, such as earning badges and virtual currency, are very easy to add into otherwise basic digital exercises in a shallow attempt to gamify them for greater appeal. However, research shows that such extrinsic motivators are less beneficial for long-term learning, as they distract from the learning task itself and become less effective over time.[127] One study of a math game with a virtual currency system found that even when children claimed they enjoyed the game for its "challenge," every child resorted to repeatedly playing the easiest level to maximize their earning of coins so they could play the reward games.[128] Children in another study reported enjoying a learning game and being excited to play it, but their time spent actually engaged with the game was found to be very low, and the game's embedded reward system had no effect on their total playtime.[129] Other extrinsic motivators, such as public leaderboards designed to stimulate competition between students, can actually be very harmful for young children, demotivating the weaker performers by harming their confidence and shifting the higher performers' focus to *winning* rather than learning.[130]

Intrinsic motivation, wherein the learning itself is the reward, is significantly more difficult to authentically embed in a game-based learning environment, but its effect is significant. One study created two versions of a math learning game, where one version embedded the math content into the game elements themselves and the other presented segments of gameplay followed by math quizzes, and found that children learned significantly more from the intrinsic version of the game, with extrinsic players performing barely better than the control group.[126]

Virtual manipulatives improve understanding of numbers and geometry

Virtual manipulatives refer to digital representations of physical objects that can be used to help convey mathematical concepts, such as blocks, rulers, and geometric planes. Extensive research has shown that virtual manipulatives have a positive effect on children's learning at the preschool and primary school ages when compared to more traditional instructional methods.[131] Virtual manipulatives allow children to explore abstract mathematical concepts with self-guided creativity: studies have shown that children manipulate virtual objects in more creative ways than their physical counterparts,[132] resulting in significant learning gains.[133] Virtual

manipulatives allow the learner to explore mathematical concepts through multiple representations, both graphically and abstractly,[134,135] allowing them to understand the links between observed effects and their related algebraic and geometric concepts.[136] Virtual manipulatives have also been shown to engage children more than traditional activities, resulting in more time spent on-task[137,138] and greater feelings of fun and enjoyment.[139]

Robots can teach computational thinking at a very young age

For very young children, visual programming is an effective way to teach computational thinking and coding logic. It makes it much easier for a child to focus on logical problem solving without needing to worry about the mechanics of proper coding syntax, and testing and debugging is much more natural and intuitive when the results are clearly visible.[112,140]

Programmable robots are one tool that is highly effective at allowing children to visualize the mathematical concepts and logical building blocks of coding in the form of play.[141] Studies have found that preschoolers are able to gain an understanding of sequencing[142] and improve their spatial thinking[143] through interacting with a programmable robot toy. One study found that both preschoolers and older children who engaged with a programmable robot were able to intuitively learn the concepts of sequencing, loops, parameters, and conditional statements, with the older children being able to further apply these concepts by combining them into sequences to create entirely new control programs.[144]

Proven technologies for: 21st century skills

The skills required for people to be successful in modern society, dubbed "21st century skills," include competencies such as critical thinking, creativity, leadership, curiosity, and social awareness.[145] Research has shown that educational technology is capable of supporting children's acquisition of many of these types of "soft" skills, including creativity, time sense, storytelling, meta-cognition, and independent thinking.[146] Computer-based education has also been shown to improve young children's skills in abstract reasoning, planning, visual-motor coordination, and memory.[147,148]

Research has shown that social and emotional skills directly contribute to academic performance. Children who are able to regulate their emotions are more able to focus on tasks, avoid distractions, and process newly-learned information, all of which are critical skills for effective learning.[149] Technology has the potential to improve children's social-emotional learning skills by providing children with opportunities to collaborate, communicate, and engage in creative play.

The following section describes tools and technologies that have been empirically proven to be effective for improving young children's social and emotional 21st century skills.

Computer use improves collaboration and communication

Contrary to earlier beliefs that technology usage might impede children's social development and encourage physical isolation, studies have shown that shared computer activities make children more sociable and more likely to interact with one another.[150]

One study explored how kindergarten children interacted with one another when in a computer lab together during free activity periods in a classroom, finding that children naturally engaged in cognitively-effective social interactions with one another, playing in parallel and participating in both sociable interactions and verbal conflicts.[151] They also engaged in multiple forms of knowledge construction, gained through positive and negative social processes and non-verbal communication, which often resulted in one or more of the children applying a newly-discovered problem solving strategy. Another study found that children spent nine times as much time socializing with their peers when they were participating in a computer-based activity compared to a physical puzzle.[152]

Technology can foster creative storytelling and remote play

One study explored software designed to support children's exploration of facial expressions for conveying emotion by allowing them to manipulate and explicitly discuss emotional expressions through collaboration with their partners.[153] Others have explored using video conferencing, as well as video and audio recording toys, to enable children to play and collaborate across distances, which has been found to be successful for facilitating meaningful social interaction.[154]

Conclusion

This report has outlined the most current research on how educational technology can be applied effectively for children at different age groups, from babies and toddlers to primary schoolers. Although edtech has the potential to be extremely beneficial for improving children's learning and cognitive development, it is imperative that technologies be developmentally appropriate, based around empirical evidence and sound learning science, and always coupled with adult mediation and guidance.

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