

Children, Wired: For Better and for Worse

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Children encounter technology constantly at home and in school. Television, DVDs, video games, the Internet, and smart phones all play a formative role in children's development. The term "technology" subsumes a large variety of somewhat independent items, and it is no surprise that current research indicates causes for both optimism and concern depending upon the content of the technology, the context in which the technology immerses the user, and the user's developmental stage. Furthermore, because the field is still in its infancy, results can be surprising: video games designed to be reasonably mindless result in widespread enhancements of various abilities, acting, we will argue, as exemplary learning tools. Counterintuitive outcomes like these, besides being practically relevant, challenge and eventually lead to refinement of theories concerning fundamental principles of brain plasticity and learning.

Introduction

It is Monday morning at 7:58 a.m. when John enters the building. Immediately a dossier is uploaded to his iPad, complete with a schedule, maps to relevant locations, and background information for the various tasks he will need to complete. As he reads that his first assignment begins in 2 minutes in the physics lab two floors above, his walk becomes a light jog...

In this story John is not a spy, but is instead an average eighth grader sometime in the near future. In the physics lab, he will have to complete computer-administered problem sets on Newton's laws and work with a team to build a video game that incorporates the principles he has learned. While this scenario may seem far-fetched, pilot programs such as the *School of One* (2010) or the *Quest to Learn* (2010) program have already embarked on this journey, exploring how technology may be best harnessed for teaching.

Beyond these limited and controlled settings though, a far larger experiment of nature is unfolding before our eyes. While there are certainly innate or genetic limitations to our various capabilities, an enormous part of "who we are" is shaped by our experiences—experiences that today are defined by the pervasive influence of technology. This fact is particularly relevant in the case of children, both because children are at the forefront of the technological revolution (Rideout and Hamel, 2006) and because the developing brain is more malleable in response to experience than is the adult brain (Neville et al., 2009; Hensch, 2004). The central question for researchers is therefore not whether technology is affecting cognitive development—that is a given. The question is instead, *how* is technology affecting cognitive development? Are the changes for the better or for the worse? How can we harness technology to effect more changes for the better? How do we limit technology's ability to effect changes for the worse?

However, before we can begin, we must first admit that the overarching question "How is technology affecting cognitive

development?" is poorly posed. "Technology" is not a single unique entity, and thus it is unlikely to have a single unique effect. One can no more ask, "How is *technology* affecting cognitive development?" than one can ask, "How is *food* affecting physical development?" As with food, the effects of technology will depend critically on what type of technology is consumed, how much of it is consumed, and for how long it is consumed.

Persistent, but Not Transient, Effects

Technology use is associated both with transient changes in arousal/mood and with long-term changes in behavior/brain function. Therefore, in the same way one cannot simply lump together the short-term effects of consuming a single caffeinated soda with the lasting effects of consuming multiple such sodas daily for years, we need to be sure to distinguish between the temporary and the long-term effects of technology consumption. Transient changes are likely to be shared across all experiences that similarly affect mood and arousal, rather than be specific for any one type of experience. One such example of this is what has been dubbed "the Mozart Effect," or the finding that listening to an up-tempo piece of music composed by Mozart temporarily enhances performance on some IQ tests (Rauscher et al., 1993). Subsequent research demonstrated that the Mozart Effect is not specific to pieces by Mozart, or even to classical music, but instead is observed after any experience that leads to a comparable temporary increase in arousal and mood (Thompson et al., 2001). Anyone who has played, or has even watched another individual playing, many of today's video games understands technology's ability to manipulate mood and arousal. Yet, as the Mozart Effect illustrates, any temporary effect of technology use, albeit important, is unlikely to be specific to technology per se. Furthermore, because changes in mood and arousal quickly diminish and eventually disappear following the cessation of the experience, so too do the changes in behavior. Because our interest is in sustained behavioral outcomes, the remainder of the review will therefore focus on the long-term effects of technology use, where changes induced

by technology are visible for days, months, or even years afterwards.

Content Matters

In the same way that there is no single effect of “eating food,” there is also no single effect of “watching television” or “playing video games.” Different foods contain different chemical components and thus lead to different physiological effects; different kinds of media have different content, task requirements, and attentional demands and thus lead to different behavioral effects. Even products that seem on the surface to be extremely similar—for instance, the children’s television shows “Dora the Explorer” and “Teletubbies”—can lead to markedly different effects (e.g., exposure to “Dora the Explorer” is associated with an increase in vocabulary and expressive language skills in two-year-olds, while exposure to “Teletubbies” is associated with a decrease in both measures; [Linebarger and Walker, 2005](#)). Furthermore, again as with food, the actual consequence of exposure to a given form of technology can confound “common sense” predictions. Technology specifically developed for the purpose of enhancing cognitive abilities, such as infant-directed media including the “Baby Einstein” collection or various “brain games” designed for adults, may lead to no effects or, worse, may lead to unanticipated negative effects ([Owen et al., 2010](#); [Zimmerman et al., 2007](#)). Meanwhile, technological applications that on the surface seem rather mindless (such as action video games) can result in improvements in a number of basic attentional, motor, and visual skills ([Green and Bavelier, 2008](#); [Greenfield, 2009](#)). Thus, although content clearly matters, the disconnect that can occur between the predicted and actual outcomes is a clarion call for more theoretically driven work in this new, emerging field.

Causes for Optimism and Concern

While a strictly dichotomous classification into “good” and “bad” makes for nice headlines (e.g., “Coffee: Science Says It’s Good for You!”), such a scheme ignores the fact that human experience is intrinsically multidimensional; almost all experiences are “good” in some ways and “bad” in others. Not surprisingly, then, technology has been linked with both positive and negative effects ([Johnson, 2005](#); [Small and Vorgan, 2008](#)). Here we consider the behavioral and cognitive effects of technology use separated by the intent of the technology. We will first examine the effects of “educational” technology, followed by the effects of “entertainment” technology. As we will see, some products designed to benefit cognitive development actually hinder it, while some products designed purely for entertainment purposes lead to long-lasting benefits.

Educational Media

Lessons from 60 Years of Television. Television first entered our households more than 60 years ago, and for nearly as long, individuals have sought to harness the form for the betterment of children. Because the introduction of television in the 1950s did not occur simultaneously throughout America, but was instead geographically localized, this allowed researchers to follow preschoolers who had access to television and compare them to preschoolers from matching demographics who happened to live in an area where television was introduced

later. Preschoolers whose family owned a television set showed an overall positive, albeit small, effect years later on their adolescent test scores as compared with those that did not view television as preschoolers ([Gentzkow and Shapiro, 2008](#)). Although suggestive, this positive outcome could be due to the stimulating effect of introducing a new experience in the life of preschoolers rather than the specific technology per se. Of greater interest is the research that has compared and refined television programs intended specifically for young children. And indeed, although the literature is certainly mixed, exposure during the preschool years (2.5 years to 5 years) to certain educational media has been linked to many positive effects ([Anderson et al., 2001](#)). For instance, a number of shows over the years have been developed in an attempt to promote language literacy and early mathematical skills in children. “Sesame Street,” which premiered in 1969, has been repeatedly associated with various positive outcomes including school readiness, vocabulary size, and numeracy skills ([Zill et al., 1994](#); [Fisch and Truglio, 2001](#); [Schmidt and Anderson, 2007](#)). Relatively newer programs including “Blue’s Clues,” “Dora the Explorer,” and “Clifford the Big Red Dog” have also been correlated with positive outcomes such as greater vocabulary and higher expressive language skills ([Linebarger and Walker, 2005](#)). Whereas these studies are typically correlational in nature (i.e., cross-sectional or longitudinal designs), a recent randomized controlled trial in preschoolers, the Ready to Learn Initiative, compared a literacy curriculum that included television shows such as “Sesame Street” with a science curriculum with more science-based television shows ([Penuel et al., 2009](#)). After 10 weeks, the students in the literacy group showed increased literacy skills as compared with those in the science group, indicating a direct causal link between the media activities in the literacy curriculum and improvements in literacy.

However, it is not the case that all television/media intended for children have positive effects. For example, time spent watching the children’s television show “Teletubbies” has been linked with a reduction in language skills ([Linebarger and Walker, 2005](#)). Such contrasts in outcome—between “Sesame Street,” “Blue’s Clues,” “Clifford the Big Red Dog,” and “Dora the Explorer” on one hand, and “Teletubbies” on the other—are theoretically important because they allow us to ask what characteristics lead to beneficial outcomes and what characteristics lead to negative outcomes. In the case of promoting early literacy, the use of child-directed speech, elicitation of responses, object labeling, and/or a coherent storybook-like framework throughout the show appears positively related to vocabulary acquisition and better language expression ([Linebarger and Walker, 2005](#)). Thus, to be effective, early intervention programs need not only engage the young viewer, but they must also elicit direct participation from the child, provide a strong language model, avoid overloading the child with distracting stimulation, and include a well-articulated narrative structure. In addition, effective educational shows also exemplify how to resolve social conflicts and productively manage disagreements and frustration. This social teaching may be as important to child development as academic content, because antisocial behavior has been linked to poor academic outcomes ([Caprara et al., 2000](#)). The advances in our understanding of the content and

structures that best foster learning in young children have only been possible by strong partnerships between content producers and scientific researchers that were first formed in the early days of public broadcasting. Unfortunately, the economics of television, and media at large, has shifted since those early days, creating an ever-widening gap between the entertainment industry and educational media, severely diminishing the ability of those seeking to create educational media to leverage the knowledge and infrastructure possessed by the entertainment industry (Mayo, 2009).

Formal and Informal Access to Media. A recurrent concern about television viewing is the passive mode it enforces upon the user. The best television shows (given the goal of enhancing cognitive development) foster active participation of the viewers, such as asking the child to repeat, point, or answer questions at the same time as the lead character. Given the importance of active participation, it is no surprise that personal computers and the interactive opportunities they afford have recently captured the attention of policy makers and educators as a tool for learning (Wellings and Levine, 2009). The data are still relatively scarce, but again a positive trend is emerging (Vogel et al., 2006; Greenfield, 2009). Computer access in informal settings outside of school improves school readiness and enhances academic achievement in young children as well as older ones (Li and Atkins, 2004; Fiorini, 2010; Beltran et al., 2008). In one such study conducted in the U.S., home computer ownership was associated with a 7% greater probability of graduating from high school, even after controlling for a number of confounding factors such as parental and home characteristics (Beltran et al., 2008). The impact of home computer use on social and emotional skills is more mixed. Whereas some studies report no effect, others document both positive and negative effects (Fiorini, 2010; Subrahmanyam et al., 2001; Kutner and Olson, 2008).

Current theories suggest that technology in informal settings may have positive effects because the activities it displaces are presumed to be of low educational value, such as hanging around with friends, playing sports, or watching entertainment television shows. This time displacement hypothesis contends that technology use has no intrinsic value per se, but instead has value only with respect to the activities it displaces (Vandewater et al., 2006; Mutz et al., 1993). Such a hypothesis leads to the prediction that technology in school settings, which displaces an already rich academic content, may not produce more learning than what human teachers are currently facilitating (and could even produce less; Angrist and Lavy, 2002). Consistent with this view, technology use in the K–12 school setting has led to mixed outcomes. An instructional computer program known as FastForWord designed to train language skills did not lead to widespread gain in either language acquisition or reading skills when introduced in U.S. grades 3–6 (Rouse and Krueger, 2004), and in one of the most comprehensive studies of its kind, conducted by the U.S. Department of Education, various types of reading software were not associated with enhanced literacy in first and fourth graders (Dynarski et al., 2007). The case for mathematics software seems more hopeful. Although some studies report no effect (Dynarski et al., 2007), many others indicate an increase in mathematics test

scores (Banerjee et al., 2007; Barrow et al., 2009; Kebritchi et al., 2010).

All parties agree that more research on this topic is needed, but two caveats come to mind. First, it seems urgent to run randomized, controlled studies in which the control group does not just follow the standard math or literacy curriculum. Introduction of new media in a school curriculum may stimulate students just because of the novelty of the experience and the resulting “I am special” feeling it may engender in students. However, once the media becomes the norm, such an effect would vanish. Studies need to establish that it is the *content* of the media that triggers the increase in knowledge. Second, while a key goal of the educational system is certainly to teach the basics of literacy and mathematics, it also aims to prepare students for the workforce in a 21st century economy. Given this, introducing technology in schools becomes not just a passing fad, but an educational necessity. This seems all the more urgent because a child in a family with a low socioeconomic status is more likely to suffer from lack of technology access and thus is more likely to be “left behind” (Attewell, 2001; Wenglinsky, 1998; Siegler and Ramani, 2008; Mackey et al., 2010).

Finally, it is striking that most, if not all, of the studies that address the impact of technology on academic achievement do so using standardized tests developed in the 20th century. Whether these tests are valid tools to evaluate how well our educational system prepares children for the demands of the 21st century economy remains largely unaddressed. Indeed, this may prove to be a significant challenge, because digital literacy is likely to become a key determinant of productivity and creativity.

Entertainment Media

While exposure to educational media is increasingly prevalent in the early 21st century, the preponderance of exposure to technology comes from entertainment media. This content, rather than being driven by the goal of improving human development, is driven exclusively by what sells—and what sells may not be the things that are good for us! Current research indicates that children may be wired, but also as a result, they may also be more violent, addicted, and distracted.

Violence. Perhaps the number one concern regarding the influence of technology among the general public is the potential for media to increase behavioral aggression and violent conduct. Children are often exposed to violent media, whether it is through television or video games (60% of TV programs contained violence in 1997 and this number is unlikely to be lower now, and 94% of games that are rated as appropriate for teenagers contain some violence; Wilson et al., 1997; Roberts et al., 2005; Haninger and Thompson, 2004). Because young children develop beliefs about social norms and acceptable behavior based on the content of their experiences, any activity that promotes violence is likely to be a risk factor for violent behavior in adulthood and is worthy of careful scientific examination. Meta-analyses, combining data from hundreds of individual studies, confirm an association between exposure to violence in media and antisocial tendencies such as aggression (note that aggression in this literature does not exclusively refer to aggressive or violent actions, but also includes aggressive

thoughts or violent feelings; Huesmann, 2009; Gentile et al., 2009; Paik and Comstock, 1994). Because long-term intervention studies are unethical, the best studies in this domain are arguably of the longitudinal variety, where a group of children is followed for several months or years, with researchers quantifying how their aggressive behavior evolves as a function of exposure to violent media. The effect size in these longitudinal studies, while again statistically significant, is small compared to other public health effects, accounting for less than 1% of the variance when confounding factors like gender are controlled for (whether these effects are large enough to be practically relevant is a matter of intense current debate; Gentile et al., 2009; Ferguson and Kilburn, 2009; 2010; Ferguson, 2007; Bushman et al., 2010). Thus, while exposure to violent media in childhood should be of concern, it should not overshadow addressing other known causes of aggressive behavior such as abusive home environments, substance abuse, and poor performance in school (Ferguson et al., 2008).

Addiction. A second growing concern is the potential for some forms of technology to be addictive. Anecdotal examples of technology addiction constantly hit the headlines—e.g., a 28-year-old collapsed on his game console in an Internet cafe after playing the game *Starcraft* for 50 hr in a row with only short pauses for basic needs (BBC News, 2005); a couple starved their 3-month-old baby girl to death as a result of becoming obsessed with caring for a virtual girl in the role-playing online game *Prius* (CNN News, 2010). While incidents of this severity are isolated, the general phenomena appear to be much more widespread. Recent surveys indicate that about 2% of youth can be described as having Internet addiction with 10%–20% engaging in at-risk Internet use (Johansson and Götestam, 2004; Cao and Su, 2007).

Actual scientific research on the topic has been somewhat hindered by the lack of firmly established standards (Byun et al., 2009). The American Medical Association does not currently recognize video game and Internet addiction as psychiatric disorders (see arguments for and against its recognition; Block, 2008; Pies, 2009). However, there does appear to be an emerging scientific consensus that Internet use and video game play has the potential to become pathological, with researchers adopting and/or adapting the criteria for pathological gambling (Tejeiro Salguero and Morán, 2002; Gentile, 2009; Griffiths and Hunt, 1998; Lam and Peng, 2010). It is important to note that “pathological” means more than simply spending a substantial amount of time playing video games or using the Internet—rather, it implies an actual reduction in the ability of the individual to function normally in society. Thus, while some individuals may be able to invest large amounts of their time in technology use without becoming a pathological user, others may exhibit pathological signs with relatively lighter use (Gentile, 2009; Han et al., 2007). Professional gamers, for example, may spend several hours a day training to perfect their skills without their behavior becoming pathological; such deliberate choice to practice a skill over engaging in other activities is a key determinant of expertise (Ericsson et al., 1993), be it in chess, music, or in this case, video game play.

A key issue for future research concerns the neural pathways involved in pathological use of technology. The fronto-striatal

pathway, which has been strongly implicated in both drug addiction and behavioral disorders such as pathological gambling (Hyman et al., 2006; Miedl et al., 2010; Hewig et al., 2010), is also activated by interaction with certain types of media technology, video games in particular (Han et al., 2007; Hoefft et al., 2008; Koeppe et al., 1998; Matsuda and Hiraki, 2006). Unfortunately, little is known about how these pathways mature or how their development is affected by technology use. Such research seems urgently needed given how disruptive technology use may be to some children’s ability to function normally in society.

Distraction. We watch television while playing games on our laptops; we take part in meetings while checking email on our phones; we browse the web while instant messaging with friends—and frankly, some of us have probably done all of these things simultaneously. Technology allows an incredible amount of information and potential stimulation to be constantly, and concurrently, accessible. However, there may be a behavioral cost to such multitasking in the form of attentional difficulties. For instance, in a recent study, Ophir et al. (2009) asked more than 250 Stanford University students about their use of different media forms, from print media to video games to web surfing. Those who reported high concurrent usage of several types of media were less able to filter out distracting information in their environment, more likely to be distracted by irrelevant information in memory, and less efficient when they were required to quickly switch from one task to another. Other studies have also linked time spent using technology with negative effects such as teacher-reported problems, paying attention in class, and deficits in attention, visual memory, imagination, and sleep (Swing et al., 2010; Kumari and Ahuja, 2010; Dworak et al., 2007).

Is Technology to Blame? Although there are clearly a number of potentially negative effects associated with technology use, the interpretation of these studies is not as straightforward as it appears at first glance. For example, most of these studies tabulate only total hours spent using technology rather than classifying technology use as a function of content type. As content clearly matters, the results from such reports are inherently noisy and thus provide unreliable data. Second, the vast majority of the work is correlational in nature and as we know, correlation per se cannot be used to infer causation. Technology use, in particular, is highly correlated with other factors that are strong predictors of poor behavioral outcomes, making it difficult to disentangle the true causes of the observations. For instance, children who watch the most television also tend to live in lower income homes and tend to have mothers with lower levels of education, both of which are strong predictors of a variety of diminished capabilities. In one large study of 800 infants, average daily television exposure was strongly correlated with lower language skills at 3 years of age when such factors were not considered, but when these (and many additional factors, some as detailed as the length of breast feeding) were controlled for, no relationship between television exposure and language development was observed (Schmidt et al., 2009). Furthermore, children who have attentional problems may very well be attracted to technology because of the constant variety of activities it permits. Accordingly, the strength of the relationship between technology use and attention disorders is significantly reduced after

controlling for whether the child suffered from attentional problems at the start of the study (Swing et al., 2010). Although researchers nearly always attempt to statistically control for known confounding variables, the possibility of additional lurking variables always remains. Controlled intervention studies would avoid these potential pitfalls and demonstrate a clear causal relationship between technology use and behavioral outcomes.

Although there are clear ethical concerns in doing large-scale randomized interventions when the predicted result is a long-term negative behavioral effect, these are not beyond our reach and are, we would argue, critical to society. A possible route is to select parents who plan to introduce a new technology in their homes and ask half of them to delay the introduction of the new technology by a few months, allowing researchers to compare children with and without access to the technology. A recent study by Weis and Cerankosky (2010) followed a similar logic to test the hypothesis that video game console ownership negatively affects academic performance. A large group of parents who were planning on purchasing video game consoles for their children were promised a video game console in exchange for their children participating in the study. The children were then split into two groups; the researchers provided consoles for one group immediately, while the other group did not receive their consoles for 4 months. Over the course of those 4 months, those children that received consoles demonstrated significant reductions in reading and writing skills (more than one-half of a standard deviation in the case of writing) as compared with the control group of peers who did not receive consoles yet. Teachers also tended to rate those children who received their consoles immediately as having greater learning difficulties, although no attentional problems were observed. We would note for future studies that, given the distinctly negative hypothesized effect of the introduction of technology in this case, there are definite ethical concerns about researchers actually providing the technology of interest and failing to inform the parents as to the true hypothesis being tested, both of which were true of this study. A more ethical design may involve researchers encouraging a subset of parents who are planning to introduce technology that has a predicted negative effect to not do so, while not intervening in a corresponding group (in which case the intervention has a predicted positive effect).

Defying Common Sense: "Good" Things Can Be Bad and "Bad" Things Can Be Good

When Good Turns Out Bad. The past decade has seen an explosion in the popularity of "baby DVDs," or media designed to enhance the cognitive capabilities of infants and toddlers. Forty percent of parents believe that child-friendly programming may benefit their infant or toddler, and some estimates suggest that roughly one in three U.S. infants were exposed to baby DVDs. However, this boom now appears to be a case of marketing and parents' common sense beliefs outpacing actual science. At best, current research suggests that these DVDs produce no changes in cognitive development—for instance, babies exposed to DVDs designed to teach new words, such as *Baby-Wordsworth* (The Baby Einstein Company; Glendale, CA), show no evidence of specific word learning (Richert et al., 2010; Robb et al., 2009). More worrisome however is that some studies actually report negative effects (Zimmerman and Christakis, 2005).

For example, in a recent cross-sectional study, Zimmerman et al. (2007) surveyed over 1,000 parents of 2- to 24-month old children. The parents were asked questions about general demographics and their child's television and DVD viewing habits, and were asked to complete a measure of language development. A large negative association between viewing baby DVDs (e.g., "Baby Einstein" or "Brainy Baby") and language development score was found for the youngest children (8–16 months), or in other words, each hour of daily viewing/listening in this group was associated with a significant decrement in the pace of language development. Furthermore, the size of the decrement was not minor—whereas daily reading with a parent is associated with a 7-point increase in language score, each hour of daily baby DVD viewing was associated with a 17-point decrease. What is the reason for this? Babies learn an enormous amount from real-world experience as they watch their parents or caregivers interact with the world or with them, yet when the same material is delivered through audiovisual media, much less is learned (Kuhl et al., 2003; Krcmar, 2010). Although videos are capable of attracting babies' attention (Barr et al., 2008), this alone is not necessarily sufficient to induce learning. A key determinant of whether learning occurs may be the ability of the infant to appreciate the symbolic nature of the video (DeLoache and Chiong, 2009). Very young children may not always be able to link objects, persons, and events in a video to reality. Therefore, young learners may not reach a maturational state at which they can truly learn from media until their preschool years. Research on technology and brain development may benefit from more systematically addressing the cognitive state of the learner, especially when it comes to the boundaries between video content, reality, and fantasy.

When Bad Turns Out Good. Although entertainment media is typically designed for entertainment purposes only, some forms of this technology have exhibited effects far beyond simple amusement. For instance, action video games, where avatars run about elaborate landscapes while eliminating enemies with well-placed shots, are often thought of as rather mindless by parents. However, a burgeoning literature indicates that playing action video games is associated with a number of enhancements in vision, attention, cognition, and motor control (for a review see Green and Bavelier, 2008). For instance, action video game experience heightens the ability to view small details in cluttered scenes and to perceive dim signals, such as would be present when driving in fog (Green and Bavelier, 2007; Li et al., 2009). Avid players display enhanced top-down control of attention and choose among different options more rapidly (Hubert-Wallander et al., 2010; Dye et al., 2009a). They also exhibit better visual short-term memory (Boot et al., 2008; Green and Bavelier, 2006), and can more flexibly switch from one task to another (Boot et al., 2008; Colzato et al., 2010; Karle et al., 2010).

Furthermore, these enhancements have been found to have real-world applications. On the medical front, action games have been harnessed for the rehabilitation of patients with amblyopia, a developmental deficit of vision (Li et al., 2010), and are being considered to treat attentional problems in children (NASA, 2003). Playing games, especially in a virtual reality environment, also appears to increase pain tolerance in both

controls and patients (Mahrer and Gold, 2009). On the job-training front, laparoscopic surgeons who are habitual video game players have been observed to be better surgeons than their more experienced peers, both in terms of their speed of execution and their reliability during surgery (Rosser et al., 2007; Lynch et al., 2010). Video game play also appears to be useful training for pilots (Gopher et al., 1994). Following this trend, in 2009, the Royal Air Force stopped requiring that only trained pilots control unmanned drone flight missions and opened its door to less experienced young gamers, after studies indicated that the best drone pilots were often young video game players (Daily Mail, 2009). This is not to say that all aspects of behavior may change for the better as a result of action video game play, but this abridged list already indicates much more benefit than one would have immediately suspected from watching an average 14-year-old blast monsters.

One of the strong points of the action video game literature is that, in contrast to much of the literature discussed earlier, a direct causal relationship has been established between the action game experience and the behavioral outcomes. The impact of action game play has been causally related to improved performance by having non-game players play action games for an extended period of time (e.g., 50 total hours spaced over 6 weeks) in a controlled laboratory environment. Furthermore, in addition to this experimental intervention group, these studies always also include a control group of subjects, drawn from the same participant pool as the experimental group, but who are required to play *non-action* games. These non-action games are also commercially available entertainment games, selected in part to be as equally enticing and stimulating as action games. All participants undergo visual, attentional, or cognitive tests before and after their respective video game training. Importantly, the post-tests take place at least 24 hr after the final session of video game play to ensure that any effects cannot be attributed to temporary changes in mood or arousal. Clear enhancements are noted in those that underwent action game training as compared with control game training. Furthermore, these effects last much longer than a few days after the final training session—in fact, enhancements are still noted anywhere from 6 months to 2 or more years later (Feng et al., 2007; Li et al., 2009). While a strong causal link has been observed between action game experience and improvements in perceptual, attentional, and cognitive skills, it should be noted that these studies have been carried out exclusively in young adults (18–30 years old), as it is ethically questionable to train children on action games (which tend to contain significant amounts of violence). However, despite the lack of training studies in children, we know that children who report playing action games show significantly increased attentional skills as compared with those who do not (Dye et al., 2009b; Dye and Bavelier, 2010; Trick et al., 2005). On some measures of attention, such as the temporal dynamics of attention, 7- to 10-year-old action gamers function at adult levels, indicating significant deviations from age-related norms.

Action video game training is of substantial theoretical interest because the improvements in performance that occur as a result of such training also transfer to tasks beyond the training regimen itself. In other words, playing an action game results in

behavioral changes in nongaming environments. This is in strict contrast with most other training regimens, wherein the learning is highly specific to the exact task, stimuli, and environment used during training (Fahle and Poggio, 2002; Fine and Jacobs, 2002; Owen et al., 2010). A possible mechanism for such wide transfer after action video game play may be that this activity teaches the player how to swiftly adapt to current task demands. Action game players may dynamically retune connectivity across and within different brain areas to augment information processing, and may thus be in a position to make more informed decisions. This was recently confirmed experimentally in the case of perceptually driven decisions (Green et al., 2010). According to this view, action video game experience would promote an essential feature of human cognition, “learning to learn.” This proposal is appealing because it readily captures why the effects of action game play transfer so widely. It will be, however, for future work to assess whether this “learning to learn” benefit is also found when information has to be retrieved from internal representations rather than from the external environment, such as when one thinks or solves problems.

The contrast between the widespread benefits observed after playing action video games and the limited value of training on “mini brain games” suggests that we may need to drastically rethink how educational games should be structured. While action game developers intuitively value emotional content, arousing experiences, and richly structured scenarios, educational games have until now, for the most part, shied away from these attractive features that video games offer. Instead, educational games have mostly exploited the interactivity and the repetitive nature of practice-makes-perfect that computer-based games can afford—often reducing the experience to automated flashcards. It is only very recently that the richness that the video game medium has to offer has been considered as an integral part of the learning experience (Mayo, 2009; Gee, 2003). However, in such rich environments, only a fine line separates a stimulating and successful media from an overloading experience, making the development of such games challenging (Kalyuga and Plass, 2009). Dimension M (from *Tabula Digita*), an action-packed video game geared toward teaching linear algebra to seventh and eighth graders, represents one such first attempt, and early results appear promising. In a recent intervention study, its introduction into high school mathematics classes led to significant benefits on benchmark mathematics tests (Kebritchi et al., 2010). Yet a gap remains between the entertainment industry and such “Serious Game” initiatives (Mayo, 2009). Theoretical work suggests that when the concepts to be learned are experienced across multiple contexts and domains, learning is more likely to transfer to new tasks or situations beyond those experienced during training (Schmidt and Bjork, 1992; Kornell and Bjork, 2008). The highly complex architecture of action games, afforded by sophisticated game engines, ensures a variety of emotional, cognitive, and attentional states as the player progresses in the game, which should foster learning and its transfer to new situations. In an elegant evaluation of this claim, Gentile and Gentile (2008) have shown that this is indeed the case with the violent content action games typically contain. Action games, thanks to their rich structure, efficiently teach aggression.

Replacing violent content with educational content is not out of reach, but it will require a degree of sophistication in game design and financial means that may call for a coherent, multidisciplinary “Big Science” approach rather than the proliferation of small, fragmented, and often uncoordinated endeavors.

Understanding Wired Brains

Much of what we know about technology and child development has been driven by advances in the fields of education and behavioral sciences. Yet, understanding how the brain is altered by technology use is essential to a furthering of this emerging field. Granted, no one will be surprised to learn that the visual cortex is activated when one watches a video, or that the motor cortex is challenged when playing an action game. Of greater interest is our understanding of how technology impacts regular brain functioning and changes brain organization over time. This calls for an array of studies, given the need to separately address different types of technology and content, as well as users. A recent seminal study by [Brem et al. \(2010\)](#) compared the impact of playing a grapheme-to-phoneme game versus a mathematics game in 6- to 7-year-olds on the maturation of the visual word form area (VWFA), a brain area important in mediating literacy. As assessed by functional magnetic resonance imaging, the group trained with the phoneme-to-grapheme game showed greater maturation of the VWFA than the control group, suggesting direct involvement of the VWFA in the acquisition of reading skills. In a similar vein, [Rueda et al. \(2005\)](#) compared the impact of playing simple games aimed at training attention versus watching popular children’s videos in 4- and 6-year-olds. Event-related potentials revealed more adult-like markers of the executive attention network after attention-game training than after watching videos. A working hypothesis is that the attention-game training may have allowed the brain system mediating conflict resolution to become more efficient, as it would during typical development. It is worth noting that in both this study and the Brem study, experimental trainees demonstrated significant brain changes from pre- to post-test compared with the control group, but with no significant behavioral improvement differences. Thus, brain-imaging studies may provide a more sensitive assay of the effects of technology than do behavioral studies. Brain imaging can also be used to document whose brain may best benefit from technology. In a recent study, structural brain scans of young adults were acquired before they learned to play a first generation computer game, Space Fortress (University of Illinois; [Erickson et al., 2010](#)). Those individuals with an initially larger caudate nucleus and putamen, two basal ganglia nuclei involved in the control of movement, reinforcement learning, and reward, were most likely to learn efficiently. In contrast, the size of the hippocampus, a key structure in memory and learning for declarative knowledge, was not predictive of learning. Thus, a computer game like Space Fortress requires cognitive and motor control skills best predicted by structures that regulate habit formation and reward processing rather than content learning.

Another fruitful line of research will be the investigation of which events during technology use enhance learning and brain plasticity. It is only recently that we have acquired the means to follow brain activity in real time as participants interact with tech-

nology ([Spiers and Maguire, 2007](#)). Thanks to these developments, we are in a position to isolate from a continuous media stream key events hypothesized to foster learning and brain plasticity (such as rewarding or salient events). Then by injecting content along with these events, learning can be directly assessed. This approach builds on an ever-growing literature documenting the critical role of neuromodulators in the control of learning and brain plasticity. Events that are arousing, and thus likely to trigger a release of acetylcholine, are prime targets for such a manipulation ([Kilgard and Merzenich, 1998](#)). It is hypothesized that acetylcholine facilitates the retuning of existing connectivity in an experience-dependent manner, which allows for better behavioral inference from the learned experience ([Yu and Dayan, 2005](#); [Goard and Dan, 2009](#)). Dopamine, a neuromodulator implicated in executive functions and the control of attention, also promotes brain plasticity. Its concurrent release during an auditory tone discrimination task increased the cortical area and the receptive field selectivity to learned tones in rats ([Bao et al., 2001](#)). This facilitatory effect was obtained by stimulating the origin of dopaminergic cell bodies, the ventral tegmental area, which is not only a key player in motivation and reward, but also in drug addiction. Unfortunately, only mixed reports exist about neuromodulator release and technology use ([Koepp et al., 1998](#); [Egerton et al., 2009](#)). Future research should capitalize on all of the tools at our disposal, from traditional neuroscience techniques such as PET and fMRI ([Egerton et al., 2009](#); [Shapiro et al., 2010](#)) to the wealth of new tools becoming available, including cameras that monitor facial emotions, smart controllers that record galvanic skin response and heart rate, and helmets fitted with electrodes that assess brain state, so as to adapt media experience in real time according to the user’s current experience.

Finally, the possibility of developing an animal model of young, wired learners is not as far-fetched as it may seem. Using a new virtual reality system in which a mouse interacts with a virtual maze through a spherical treadmill, [Harvey et al. \(2009\)](#) have characterized the intracellular dynamics of hippocampal coding in awake, behaving animals. Adapting such virtual navigation systems to study decision making and learning in fast-paced, mice-enticing environments will certainly require new developments, but appears within reach.

Concluding Remarks

The past half-century has seen a dramatic increase in the amount of technology available to and used by children—a fact that has clearly shaped the way children learn, develop, and behave. Given the multifaceted nature of technology, it is perhaps unsurprising that the story of its impact on child development is extremely complex and multisided. Some forms of technology have no effect on the form of behavior they were designed to transform, while others have effects that reach far beyond their intended outcomes. All of this is indicative of a field that is still emerging. What we do know is that, in technology, we have a set of tools that has the capability to drastically modify human behavior. What remains, which is not trivial, is to determine how to purposefully direct this capability to produce desired outcomes. In this endeavor it will be key for the field, which to this point has been largely behavioral in nature, to

partner with neuroscience (Meltzoff et al., 2009). For instance, given the goal of predicting behavioral outcomes, it would likely be of substantial benefit to describe forms of technology quantitatively in terms of the neural processing they demand, rather than describe them qualitatively based upon surface characteristics. Such collaboration would also benefit neuroscientific theories of learning, as it offers an opportunity to “reverse engineer” the learning problem—starting with a tool that strongly promotes learning and determining how and why it works, rather than starting with low-level principles of neural learning and building tools that may or may not produce the desired outcomes.

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