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The Digital Revolution and Adolescent Brain Evolution

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Abstract

Remarkable advances in technologies that enable the distribution and utilization of information encoded as digital sequences of 1s or 0s have dramatically changed our way of life. Adolescents, old enough to master the technologies and young enough to welcome their novelty, are at the forefront of this “digital revolution”. Underlying the adolescent’s eager embracement of these sweeping changes is neurobiology forged by fires of evolution to be extremely adept at adaptation. The consequences of the brain’s adaptation to the demands and opportunities of the digital age have enormous implications for adolescent health professionals.

Introduction

The way adolescents of today learn, play, and interact has changed more in the past 15 years than in the previous 570 since Gutenberg’s popularization of the printing press. The Internet, iPads, cell phones, Google, Twitter, Facebook, and other modern marvels unleash a virtual gusher of information to the plugged in teen brain.

In 2010 U.S. adolescents spent an average of 8.5 hours per day interacting with digital devices, up from 6.5 hours in just 2006 [1]. Thirty percent of the time they are simultaneously using more than one device, bringing daily total media exposure time to 11.5 hours. These numbers are a moving target and vary by survey, socioeconomic status, ethnicity, and geography, but all indications are that the amount of screen time has been dramatically increasing and is likely to continue to do so as the technology improves and becomes even more widely available. The pace of “penetration” (i.e., the amount of time it takes for a new technology to be used by 50 million people) is unprecedented. For radio, technological penetration took 38 years; for telephone, 20; for television, 13; for the World Wide Web, 4; for Facebook, 3.6 years; for Twitter, 3 years; for iPads 2 years; and for Google+, 88 days. The pace and pervasiveness of these changes, i.e., the digital revolution, raise several questions relevant to adolescent health – relevance that extends to children, teens, parents, teachers, and society at large. What are the implications, for good or ill, of the dramatic changes in the way adolescents spend their time? How can the technology be harnessed to optimize the positive and minimize the negative? Might the unprecedented rate of change itself overwhelm adaptive mechanisms? The digital revolution gives us unique insight how experience shapes the brain, and, in turn, how these brain changes may change our experience. Consideration of the neurobiology and evolutionary history of the adolescent brain may provide some context to explore these questions.

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The Adolescent Brain: Evolution and Neurobiology

The adolescent brain is not a broken or defective adult brain. It has been exquisitely forged by the forces of evolution to have different features compared to children or adults, but these differences have served our species well. The three most robust adolescent behavioral changes are (1) increased risk taking; (2) increased sensation seeking; and (3) a move away from parent toward greater peer affiliation. That these changes occur not only in humans, but in all social mammals, suggests a deeply rooted biology, which fosters independent functioning and separation from the natal family.

Another highly adaptive feature of the adolescent brain is its ability to change in response to the demands of the environment. This changeability is often referred to as “plasticity” and it is a defining feature of the human brain. The fossil record shows a tripling of braincase volume between *Homo habilis* and *Homo sapiens*, followed by a slight decrease over the course of 30,000 years of human civilization. It is no coincidence that our brains are also adaptable over the lifecourse. We descend from a long line of ancestors who were able to choose the former of the “adapt or die” proposition.

Brain plasticity is a lifelong process but tends to be most robust earliest in development. Compared to other species humans have a very protracted period when we are dependent upon our parents or other adults for survival. A benefit of this protracted period of protection is that it allows our brains to stay flexible to changing demands, even more so than our close genetic kin, the Neanderthals, whose tool use changed remarkably little in over 1 million years [2]. They were well suited to deal with a stable, albeit harsh, environment at the time but less facile at adapting to changing demands.

Humans, on the other hand, are remarkably adaptable. We can survive everywhere from the frigid North and South poles to the balmy islands on the equator. With technologies developed by our brains we can even live in vessels orbiting our planet. Survival skills in cold climates may entail learning how to find shelter and obtaining nutrients from hunting. In tropical climates it may be more a matter of avoiding certain predators or identifying which fruits are edible and which are toxic. The changes in demands across time are as striking as the changes across geography. Ten thousand years ago, a blink of an eye in evolutionary terms, we spent much of our time securing food and shelter. Modern humans now spend relatively little time and energy obtaining calories (a factor that may, through epigenetic or other factors, be related to earlier puberty and greater height/weight). Instead many of us spend the majority of our waking hours dealing with words or symbols – a particularly noteworthy departure given that reading, which is approximately 5,000 years old, did not even exist for most of human history. Having a highly plastic brain is particularly useful during the second decade when the evolutionary demands of adolescence – being able to survive independently and reproduce - rely critically on the ability to adapt.

Insight into the neurobiology of the developing brain has been greatly enhanced by the advent of magnetic resonance imaging (MRI), which allows exquisitely accurate pictures of brain anatomy and physiology without the use of ionizing radiation (see [3] for review).

After puberty the brain does not mature by growing larger; it matures by growing more specialized. Gray matter volumes during the first three decades of life follow an inverted “U” shaped developmental trajectory with peak size occurring at different ages in different regions. Total cortical gray matter volume peaks at around age 11 in females and 13 in males. The complementary mechanisms of overproduction / selective elimination allow the brain to specialize in response to environmental demands. Areas such as the prefrontal cortex - a key component of neural circuitry involved in judgment, impulse control, and long range planning - are particularly late to reach adult morphometry, continuing to undergo

dynamic changes well into the 20's. Subcortical gray matter structures involved in decision-making and reward circuitry undergo dramatic changes around the time of puberty.

White matter volumes increase throughout childhood and adolescence reflecting ongoing myelination allowing greater "connectivity" and integration of neural circuitry from disparate parts of the brain. This increased coordination of brain activity is a hallmark of maturation, and is accompanied by an age-related increase in the correlation of activities in different parts of the brain on a wide variety of cognitive tasks. A tradeoff for the increased connectivity is that myelin releases molecules that impede arborization of new connections and thus decrease plasticity [4–10].

These features of prolonged plasticity (but late maturation) of prefrontal (and other high association regions which integrate information from many parts of the brain), revamping of reward circuitry that guides decision making, and increasing connectivity of neural networks all support the adolescent brain's fundamental mission of optimizing adaptation to its environment.

The link between adolescent brain evolution and the digital revolution does not lie in a selection pressure wherein those with greater capacity to handle the demands of the technological changes have greater reproductive success. Even if that proved true, it would take many generations to have an evolutionary effect in that sense. The link lies in the evolutionary history that has made the human adolescent brain so adaptable.

With these principles in mind let us examine the neurobiology-environment interaction of the digital revolution with respect to the domains of education, entertainment, and social interactions.

Education in the Digital Age

The greatest benefits of the digital revolution will stem from ease of information access - never before has so much information been available to so many. Increasingly ubiquitous and immediate access to information has profound implications for how to optimize our educational system. "Google it" is sound advice to begin learning about any topic imaginable. Amazing free content, such as through the Khan Academy's math curriculum videos (www.khanacademy.org) or TED talks compilation of lectures from leading thinkers (www.ted.com), provide unprecedented access to the finest ideas and knowledge the world has to offer. Of course, in the vast expanse of the Internet the quality of the content varies greatly. One of the most useful skills for children and adolescents to acquire will be the ability to effectively utilize this universe of information - to critically evaluate the data, to discern signal from noise, to synthesize the content, and to apply it to real-world problem solving.

Unfortunately, the teaching of these skills has not yet been widely embraced by educators. There remains a wide generational gap between students and teachers on the use and valuation of information technologies. Interactive online video displays have gone from luxuries available only in a small number of specialized classrooms to widespread use in most U.S. public schools. The in-class use of a variety of technologies is a passionately debated and unresolved issue amongst educators from pre-K through graduate school.

A prominent concern is that ease and immediacy of information, and the increasing propensity amongst teens toward multitasking, may promote "mile wide, inch deep" thinking and a resistance to the patience and persistence required for in-depth scholarship. The 2010 data from the Kaiser Foundation survey [1] indicates that when teens are doing their homework at the computer, two-thirds of the time they are also doing something else

(e.g., instant-messaging, listening to music, texting, surfing the Internet, updating/viewing Facebook pages, etc.).

“Multitasking” is an imprecise term ranging from a concept such as doing more than one of anything (e.g., walking and chewing gum) to simultaneously processing conflicting information streams (e.g., listening to a physics lecture and composing an e-mail regarding spring break). For the latter more stringent definition, there is a consensus from decades of investigations that division of the brain’s attention systems has costs both in time and performance [11–14]. At the neural level, what the brain is really doing is rapidly shifting between the tasks – and for each switch we pay a metabolic and time toll.

A high-stakes example of the perils of multitasking is the use of cell phones while driving, which impairs performance to the same degree as driving while intoxicated (i.e., over the .08% legal limit.) [15, 16]. For example, in a fMRI study, participants performed a driving simulation task either without a competing demand or while judging whether statements they were hearing were true or false. Listening to the sentences resulted in dramatically decreased driving performance and was associated with a 37% reduction in activation in the spatial processing areas of the parietal lobe [17].

Other fMRI studies (almost all involving subjects 20 years of age or older) have also confirmed the inefficiencies of multitasking, pointing to the prefrontal cortex as a “bottleneck” for the brain’s ability to process and prioritize competing streams of information [18]. The prefrontal cortex involvement in multitasking raises the question of whether its ongoing plasticity might mean that young people, with proper training, might be able to increase the capacity to rapidly and effectively switch between tasks. This is consistent with behavioral studies indicating the ability on such tasks improves until age sixteen [19].

Entertainment

The most common forms of digital entertainment are TV (4.5 hours/day), music (3 hours/day), and non-gaming use of computers (1.5 hours/day) [1]. Next most common are video games (1.25 hours/day) - from computers, the Internet, game consoles, or handheld/mobile devices.

Video games are a \$25 billion per year industry and are popular and available across socioeconomic status and gender - 99% of teen boys and 94% of teen girls play video games on one or more of the above platforms [20]. The amount of time spent on video games is increasing across all age groups as the quality and variety of games continues to improve and the availability of mobile devices becomes more ubiquitous.

Highly popular games encompass a wide range of genres, degree of intellectual demand, and solitary versus interpersonal formats. Game consoles such as Wii Fit and Kinect interact with body movement providing infinitely scalable physical challenges that blur the distinction between video gaming and conventional athletic endeavors.

From a neurobiological perspective the popularity of the games reflects their capacity to stimulate the brain’s reward circuitry. Dopamine is the predominant molecular currency of the reward system and a key component of the circuitry is the nucleus accumbens. The commonality of reward circuitry across domains is striking. All of our basic drives (e.g., hunger, sex, sleep), all substances of abuse, and everything that may lead to addiction (i.e., compulsive behavior characterized by loss of control and continuation despite adverse consequences) increases dopamine in the nucleus accumbens [21].

At puberty there are profound hormone-related changes in the dopaminergic system, the nucleus accumbens, and related circuitry. Sexual thoughts become potent factors in attention allocation and decision-making. Aggressive tendencies increase, especially amongst males. Aggression can lead to criminal violence but it is also adaptive for the acquisition of resources and protection of self and family. Sex and violence not only sell, they are of great relevance to our brain's reward system and vital to our survival.

Sex

From July 2009 to July 10 about 10–15% of web searches and 4% of the top one million most visited sites were sex related [22]. It is hard to estimate the amount of this accounted for by adolescents, although given the ease of accessibility and the intensity of the drive it seems reasonable to assert that teen exposure to sexually explicit material is abundant. Even inadvertent exposure is widespread – about 20% of YouTube profiles contain sexual references or pictures [23].

How does the unprecedented access to sexually explicit material during the formative years of sexuality affect sexual behaviors and relationships? Data is surprisingly sparse — there are no longitudinal studies of sexual behavior subsequent to viewing online pornography. It is interesting to note that the rise in adolescent access to online sexually explicit material corresponds to a decrease in teen pregnancies and teen birth rates. The birth rate for American teenagers is the lowest it has ever been in the 69 years for which national data are available (39.1 per 1000 females aged 15–19 years) and 37% lower than the most recent peak in 1991[24]. Similar declines are evident in the proportion of high school students who have ever had sexual intercourse and in abortion rates. The declines were seen for younger and older teens and for all racial and ethnic groups.

I am not suggesting a direct causal relationship between exposure to online pornography and decreased teen pregnancy, but the epidemiological data does suggest the impact is nuanced and merits objective study.

Violence

Contrary to the scarcity of studies examining behavioral effects of exposure to online pornography, there is a sizeable literature examining the relationship between violent games and real-world violence. However, the hundreds of papers on the topic have not led to a clear consensus. Meta analyses by different groups, using different statistical approaches, different measures of violence, and different inclusion criteria for studies included in the analysis, come to diametrically opposed conclusions with some reporting strong effects (for a recent review see [25]) and others reporting no or negligible effects [26–29].

Proponents of the view that violent video games do lead to real world violence note behavioral, galvanic skin response, and neuroimaging studies demonstrating desensitization to violence with repeated exposure [30] [31]. Opponents of the view acknowledge the laboratory and neuroimaging desensitization or habituation findings but point out these changes have not led to increases in real-world violence. In fact, historically there has been an *inverse* relationship between video game use and violence. From 1995–2008 as sales of video games quadrupled, hours spent playing them doubled and violent content increased, rates for juvenile murders decreased 72%, and rates for violent juvenile crime decreased 49% to a 30-year low [32]. As is the case for the inverse relationship between online pornography exposure and teen pregnancy rates, this does not establish causality, but is intriguing. Explanations offered include that the games allow adolescents a forum to work through fears and aggression without suffering real-world consequences and that they do not have difficulty discerning fantasy from reality.

Attention Economy

In the fiercely competitive video game industry, top selling games are masterful at engaging our brain's reward system. Homework is up against some challenging foes. Might the availability of technologies that can persistently keep dopamine levels so high raise the threshold for what our brains deem rewarding in terms of relationships, studying, or working toward other long-term goals that may not have immediate reinforcements?

Digital Revolution - Social

The human brain is a social brain. Our ability to gauge the moods and intentions of others, to detect the truth or falsehood of their communications, to discern friend from foe, and to form alliances are amongst its most complex and important tasks. These skills are of premier importance to fulfill our biological imperatives of staying alive (through the protection of the group) and reproducing. From this perspective, it is no wonder that so much of our brains are dedicated to social cognition. In fact, across primate species, the single best predictor of the size of the neocortex is the size of that species' social group [33]. Combining data from 38 primate species, Dunbar estimated that based on neocortex size the number of meaningful social relationships (i.e., where everyone knows everyone) for humans should be between 100 and 230. The value of 150 has been popularized as "Dunbar's number" as converging evidence from diverse fields seem to coincide with the prediction. For instance, 150 is the approximate size of military units from Roman antiquity to the present, religious communities (e.g., Amish, Hutterite), Aboriginal groups, villages in England before the Industrial Revolution, and the number of people on holiday card lists [34].

The central hub of circuitry related to social skills is the late maturing highly plastic prefrontal cortex. Like any complex skills, mastery requires lots of practice. Much of the discernment relies on exquisitely subtle detection of non verbal cues such as slight changes in eye gaze, millisecond differences in speech timing, synchrony of response to shared environmental stimuli, breathing patterns, body posture, touch, odors, etc. Might the increasing reliance on digital social interactions hinder exposure to the "real-world" experiences necessary to master these most important skills?

Social interactions in the Facebook era

Cell phones, e-mail, texting, and multi-user video games are all technologies that have dramatically changed how adolescents interact with each other socially. However, the most striking transformation has been from online social networks such as Facebook. Facebook was launched in February 2004 and membership has grown exponentially since that time. As of March 2012 over 900 million people have a Facebook page (1 of 8 humans) accounting for 20–25% of all the time spent on the Internet.

The average number of "friends" per adolescent Facebook user is 834 - far outpacing Dunbar's number. The discrepancy may arise from different definitions of "friendship" or "relationship" – perhaps adolescents are not maintaining meaningful interactions with all 800+ of their contacts. This appears to be the case, as graph theory analysis of social network interactions indicates that the number of relationships maintained by regular exchange of information falls back to the 100–200 range [35]. Although digital interactions are not the same as face to face relationships, they are social, they are meaningful to the adolescents, and they are associated with other measures of well-being [36, 37].

It is not clear whether social networking sites make teens inherently more or less social. The technologies may modify interpersonal interactions but they also create the capacity to mirror and magnify existing traits and tendencies. Outgoing gregarious teens are now able to

keep up with the moment-to-moment activities of dozens of their friends. Shy teens may find a virtual community or alternate video game universe in which to fulfill their social needs and spend very little time with direct human contact.

The playing out of social life in a transparent global digital domain has raised the specter of cyberbullying. The National Crime Prevention Council (NCPC) defines cyber bullying as “when the Internet, cell phones or other devices are used to send or post texts or images intended to hurt or embarrass another person”. Statistics regarding its prevalence vary enormously depending on what threshold is used for abuse [38]. One aspect that is different from traditional bullying is that the acts are distributed to a much wider audience and once on the Internet they are potentially permanent. This has implications both for the bullied and the bullies. Several high profile and tragic cases have ignited efforts by schools, communities, and organizations to increase awareness and curtail the practice of cyber bullying.

A positive social aspect is that the technologies enable adolescents to connect with a much wider portion of the world and broaden their exposure to ideas, customs, and ways of life. Appreciating the commonalities among other young people throughout the world may help to overcome many of the fears and prejudices that underlie global conflict.

Discussion

The digital revolution is altering the arena in which teens pursue the perpetual tasks of adolescent development – to learn about the world, to establish their independence and identities, and to socialize with their peers. The Pew Internet and American Life Project Foundation synthesized results from their survey of over 1000 technology stakeholders and critics in a report with the less-than-decisive, but I think ultimately accurate, title of “Millennials will benefit and suffer due to their hyperconnected lives” [39].

There is little to be gained from trying to make a blanket characterization of the phenomena as good or bad. The digital genie is out of the bottle and not going back in. The danger paradigm that dominates much of the current literature on social media is reminiscent of alarmist rhetoric that had been historically voiced for the telephone, dime novels, comic books, and TV. All were feared by some to erode the moral fabric of our nation and lead to the impending doom of our civilization. More likely risks include negative effects related to non-productive use of time, less in-depth analytic thinking related to multitasking, or possibly effects related to greater exposure to violence or sexually explicit material. The potential upsides of the technologies are enormous and include phenomenal educational opportunities, great entertainment, and expanding social interactions.

Adolescent neurobiology provides optimism that our species has the capacity to adapt to the changing demands. Adolescent health workers will need to work diligently to understand and keep up with the changes - and sound research will need to be conceived, funded and implemented - so that we can be a force to optimize the good and minimize the bad impacts of the digital age.

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