Original article

Adolescent brain and the natural allure of digital media

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The growing amount of screen time among adolescents has raised concerns about the effects it may have on their physical and psychological health. Although the literature is divided on whether the effects are mostly positive, neutral, or mostly negative, it is likely that the impacts will be highly individualized with a mixture of good and bad consequences for each person. Understanding behavioral and neurobiological phenomena of adolescence may help to guide research and interventions to optimize the benefits and minimize the risks. Particular aspects of adolescent development relevant to the issue include: (i) hunger for human connectedness; (ii) appetite for adventure; and (iii) desire for data.

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Introduction

Digital technologies such as computers, tablets, smartphones, and gaming consoles are having a dramatic impact on the way adolescents learn, play, and interact with each other.[1] Time spent with such devices continues to rise around the world. In the United States, teen screen time averages over 7 hours a day, and this is excluding time used for homework.[2] This has naturally led to growing concerns about the impact of increasing screen time on the health and well-being of youth.[3]

Although there is little disagreement on the growing amount of screen time, there is much disagreement regarding the implications.[4] Some studies report correlations of screen time with depression, anxiety, sleep disturbance, and poor school performance.[5-7] Additional studies report changes in brain anatomy and physiology related to digital media.[8,9]

However, other studies point out that the variance of negative outcomes attributed to screen time is less than 1% (less than whether or not the student wears glasses) and that it is spurious to scapegoat screen time for increases in social ills that have complex and nuanced origins and influences.[10,11] They also note that rigorous data and sophisticated methods of analysis are essential to address the arrow of causality of technology use and negative outcomes (eg, people feeling depressed may seek out more social media use).[12] One of the clear implications is that not only the quantity of screen time but also the type and quality of screen time needs to be considered with attention to interactions with age, whether male/female, culture, socioeconomic status, and other variables.

As data continues to be gathered about the specific positive and negative effects of interactions with specific digital technologies for specific individuals in specific contexts, there remains a common refrain that despite some possible benefits there is something about the whole phenomenon that is just plainly and simply not "natural." The argument is that we did not evolve to be staring at a screen for most of our waking hours. We evolved to be interacting with

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each other face to face, using our senses of smell and touch and taste, not just sight and sound. The argument leads to the assertion that it cannot be healthy to stray so far from the activities for which nature has shaped our brains and our bodies. Articles in general readership magazines with titles such as "Have smartphones destroyed a generation?," catchy acronyms such as FOMO (fear of missing out), and colorful descriptions such as smartphones being "weapons of mass *distraction*" capture the public's attention. Negative implications are eagerly embraced by a generation not as facile with the technologies as their children.

The desire for digital media is in fact exquisitely aligned with the biology of the teen brain and our evolutionary heritage

In assessing the data, we should be careful to avoid the historically common pitfall of viewing change as inherently dangerous. For example, the following quote—:

> …This discovery will create forgetfulness in the learners' souls, because they will not use their memories; they will trust to the external and not remember of themselves. It is an aid not to memory, but to reminiscence, and will give youth not truth, but only the semblance of truth; they will be hearers of many things and will have learned nothing; they will appear to be omniscient and will generally know nothing; they will be tiresome company, having the show of wisdom without the reality.

is attributed to Socrates (~370 BC),[13] and the dangerous "discovery" he was referring to was reading. Similar generational pronouncements of impending doom, sounding strikingly similar to today's headlines about smartphones and social media, were heralded with the introductions of radio, television, pulp novels, comic books, music, and fashion preferences of youth throughout the ages. Use of digital technologies joins a long list of human activities that have been initially deemed as unnatural, immoral, and dangerous. From the perspective of an evolutionary time scale, reading—which is only approximately 5000 years old—has been around only slightly longer than smartphones, and neither existed for the vast majority of humanity.

With no intention to dismiss or undermine the many legitimate concerns of negative effects of digital media and other technologies, I challenge the notion that the appeal is not "natural" (ie, in accordance with our nature/biology). The desire for digital media is in fact exquisitely aligned with the biology of the teen brain and our evolutionary heritage. Three features of adolescence that are particularly relevant to the issue are: (i) hunger for human connectedness; (ii) appetite for adventure; and (iii) desire for data.

Hunger for human connectedness

Behavior is driven by desire. The neuroanatomical substrate of desire involves complex interacting circuitry incorporating dozens of brain components including areas of the cortex, basal ganglia, thalamus, cerebellum, ventral striatum, amygdala, and hippocampus. The brain reward system undergoes dramatic changes during adolescence with an ignition of passions driven by hormonally mediated changes in anatomy, neurotransmitter type and distribution, and connections among brain regions.

A remarkable feature of brain reward circuitry is its commonality across a vast range of stimuli. For example, all addictions (eg, behaviors repeated compulsively despite adverse consequences) increase dopamine in a small part of the brain called the nucleus accumbens. The staggering array of conditions that engage our brain reward system are united by the common theme of fulfilling our evolutionary imperatives of survival and reproduction. Obvious triggers include the desire for food, sex, sleep, homeostasis for heat and cold, and safety. However, we are a species that also relies heavily upon social connections for survival. Early in life we rely on members of our group to regulate our basic physiology (ie, allostasis).[14] During the teen years, social connections become vitally salient for our very existence.[15]

The high reward valuation of successfully connecting with others is reflected in numerous functional magnetic resonance imaging (fMRI) studies of the adolescent brain showing large changes from baseline, both for the sorrow of social exclusion and the joy of social acceptance. Brain effects of social exclusion are commonly assessed using a variation of the Cyberball paradigm.[16] In a virtual environ-

ment, a game of catch among three avatars is manipulated to exclude the in-scanner participant, which leads to strong negative feelings and robust brain imaging effects. Facebook's social media ostracism paradigm similarly examines online social exclusion.[17] Powerful effects of social acceptance on the brain are also demonstrated in many fMRI studies,[18] an example of which is the number of "likes" in a chat room correlating with activity in the ventral striatum part of the reward system.[19,20] Relevant to the use of social media is that disclosure of personal information is in itself rewarding.[21] The brain effects of social acceptance have effects similar in location and magnitude to enjoying pleasant tastes, inferring that "hunger" for human connectedness is an apt metaphor.[22]

Appetite for adventure

It may seem that we should have evolved to seek nothing more than peace and quiet, comfort, and safety. However, because it is not the mundane and predictable that pose the greatest risks to our survival, our brain reward systems reinforce our efforts to seek out and engage in adventure. Even other primates engage in play that seeks to master the threats that may harm them. It is part of the phenomenon of why the teen years are the peak market for scary carnival rides and frightening movies. That adolescent increases in sensation seeking and risk taking occur not only in humans but in all social mammals is a testament to how deeply rooted in our biology this drive is.[23] In teens, the desire to overcome boredom rivals that of the desire for social acceptance.

The internet, social media, and game technologies provide fantastic outlets for adventures. They offer an arena to explore, express, experiment upon, and refine the puberty-related surges in drives of sex and aggression. It is interesting to note that despite extreme amounts of sex and violence in some games, limited only by human imagination, real-world behaviors in these domains do not seem to be taking a turn for the worse. In fact, teen pregnancies, sexually transmitted diseases, and the number of serious violent crimes committed by youth aged between 12 and 17 years are at historical lows in the United States.[24,25] Perhaps it is that youth are in their basement playing games and not on the street mugging strangers. However, it may also be the case that adolescents are working through some of the powerful dynamics of emerging sex, aggression, sensation seeking, and risk taking in ways that may be extreme in the virtual world but are not harmful to others in the real world and overall safer than in times of past.[26]

As the winners of an intensely competitive multibillion-dollar industry engaging some of the brightest and creative minds, today's games are masterful at engaging the brain reward system. The obvious notion is that by continuous improvement of variable reinforcement practices, bolstered by decades of data from Las Vegas, the game developers have optimized the games to be easy enough to win sufficiently often to not give up playing, but difficult enough to maximize the sense of achievement. This is undoubtedly part of the story, but an extensive body of literature involving thousands of subjects has convincingly established that conventional reward reinforcement theory is insufficient to account for the persistence of gaming behavior. One of many aspects of this is a concept termed "gamer identity strength," the degree to which people define gaming as part of their social identity. It is an essential variable to augment traditional reinforcement theory in predicting and understanding gaming behavior. As alluded to in the preceding section, the desire to belong to a group, to have an identity in common with others,[27] is a fervently compelling drive in adolescence.[28] Being a "gamer" is an increasingly common group by which people share and shape their identity.

Pursuing adventure, developing a sense of mastery, and exploring different identities and values in a virtual environment can be as rewarding to the brain as those achievements in the real world. At the level of brain synapses, the distinction between "virtual" and "real" is not as large as some would expect. In both, the brain receives input in the form of patterns of electrical activity that help it create a model of the world. Virtual wins can be every bit as rewarding to the brain, but the downsides of failure in a virtual world are much more forgiving. Failure is much easier to bear if no one is watching, and being able to start over again and again with the stroke of a key is a luxury rarely afforded in the real world. In a virtual world, we are emboldened to take risks. Teens do not have to inhibit their emotions and rein in their passions. They can have the freedom to alter contingencies and rules (ie, have controllable agency) to suit their preferences, as opposed to their limited control in the real world. Video games are most appealing and have the greatest impact on emotions when they close the gap between how they are and how they wish to be.[29]

Another relevant behavioral aspect of adolescence is the yearning for immediacy. Neuroanatomically, this is related to the ongoing maturation of the frontal lobes, which are involved in "executive function," including such things as delaying gratification, controlling attention, inhibiting impulses, and considering longer-term consequences of our choices. Frontal-lobe function is far from absent in adolescents, but it is not as good as it is going to get.[30] Sleep deprivation, sometimes related to screen time, further impairs frontal-lobe inhibitory functions. A strength of digital technologies is the ability to provide immediate results, immediate access to information, and immediate novel stimuli. From an evolutionary standpoint, there is a premium valuation placed on immediate, actionable information. It is often not a matter of eventually finding the best or "right" solution but rather the immediate "right now" solution. The ability to delay gratification generally improves with age, but most teens are more likely to choose sooner, smaller rewards over larger, later rewards.

A concern is that the social interactions occurring during modern gaming is quite different than in the past. Popular board games such as Monopoly were often mere mechanisms to foster face-to-face peer interactions useful for honing social skills. Like the stone in the stone soup fable, the game itself was not the important ingredient, it was the ensuing social interactions that mattered. There is a possibility that with so much immediate gratification available, our motivation for delaying gratification will lessen and youth will fail to learn the discipline necessary to achieve worthwhile goals. However, there is also a possibility that social interactions fostered via the new digital media will be healthy and that with greater access to information and knowledge, and a broader peer group with potentially positive attributes to emulate, today's youth will far surpass the accomplishments of their parents' generation.

Desire for data

The brain's fundamental mission is to assess the environment and initiate behaviors to survive. We are hard-wired to attend to the most relevant data that informs the accuracy of the brain's internal model of the world. One of our most effective strategies has been to learn survival strategies from imitating the behavior of others. For young children, the modeling of behavior is often learned from parents and older siblings. During adolescence, the modeling often switches from parents to peers. Like increased sensation seeking and risk taking, this phenomenon also occurs in all social mammals. For adolescents, the influence of peers is a dominant factor in shaping values, opinions, and decision making.[31] Throughout most of human history, adolescent peer interaction was with those geographically nearby. Now, the potential pool of adolescent peers to emulate is global, which may have positive or negative social effects, but is a profound departure from the past.

These tendencies to seek new and relevant information would not be enough to fully justify the classification of the allure of digital technologies as natural if it were not for the brain's yearning to embrace change. Prolonged plasticity and environmentally driven specialization are the key additional neurobiological attributes to make the digital appeal so compelling. It may seem out of place to discuss Neanderthals in a manuscript addressing the impact of digital media on youth of today, but a key difference in the rate of brain development between the species may shed light on the strong attraction human youth have to current technologies. Neanderthal brains were approximately 13% larger than human brains, and Neanderthals were able to survive in quite harsh conditions. However, their tool use changed little over 200 000 years. They were well adapted to a certain climate and environment, but when the climate and environment changed, they were not as flexible as humans in adapting. The less-adaptable Neanderthal brain may be related to their faster maturation.[1] Maturation can be thought of as achieved when developmental changes stop or greatly reduce. Rate of maturation can be inferred from studies of fossilized teeth. Like trees, teeth have growth rings. Less space between growth rings indicates stabilization and has been shown to correlate highly with other measures of maturation.[32] Comparisons of human and Neanderthal tooth fossils suggest that Neanderthals matured more rapidly than humans.[33] If you find the tooth of an 11-year-old Neanderthal in a cave, when you find other teeth in the cave, you are likely to find her children, not her parents. Rapid maturation is not inherently maladaptive. However, it could be detrimental in a situation of rapid environmental change where a premium would be placed on ongoing plasticity—the ability of the brain to change in response to environmental demands.

Brain maturation and ongoing plasticity are fundamentally at odds with each other at a cellular and molecular

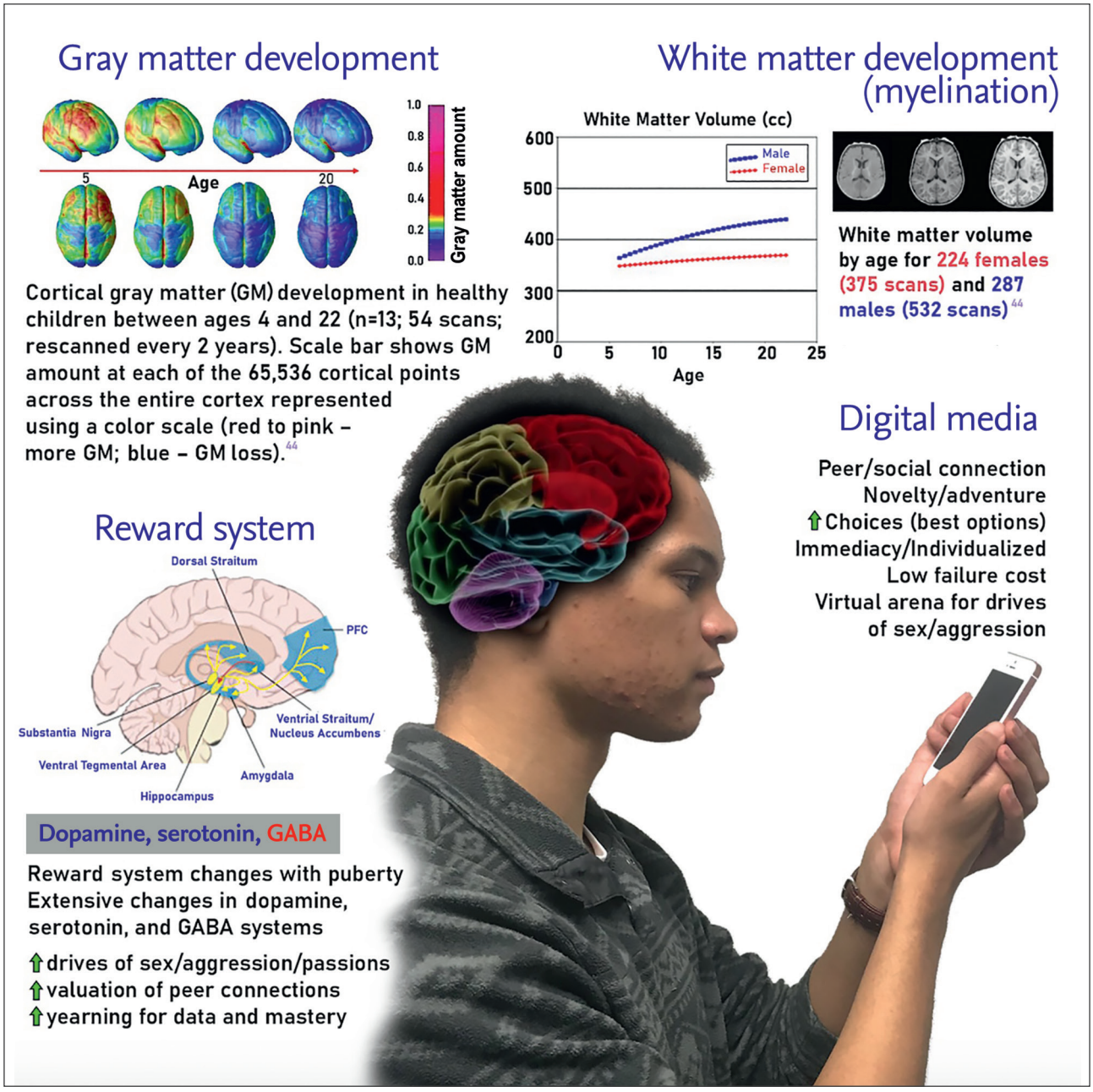

Figure 1. Illustration of naturally alluring features of digital media with adolescent neurobiological changes of steadily increasing white matter (greater connectivity), decreasing gray matter (environmentally driven specialization active through at least the mid 20's), and puberty-related changes in reward circuitry with intensification of drives.[42-44] GABA, γ-aminobutyric acid. Compiled by Jacob B. Giedd. Two images reproduced from ref 44: Lenroot RK, Giedd JN. Brain development in children and adolescents: Insights from anatomical magnetic resonance imaging. *Neurosci Biobehav Rev.* 2006;30(6):718-29. Copyright © 2006 Elsevier. Every effort has been made to trace copyright holders and to obtain their permission for the use of copyright material. The publisher apologizes for any errors or omissions in the above and would be grateful if notified of any corrections that should be incorporated in future online editions of this article

level. A key component of childhood and adolescent brain maturation is an increase in connectivity among disparate regions of the brain. This greater connectivity is subserved by myelin, a wrapping around neuronal axons that can increase neural transmission speeds by 100x and reduce recovery time between firings by 30x.[34] The color of myelin is what makes brain white matter white, and white matter increases in the brain throughout childhood and adolescence. Myelination enables remarkable enhancements of physical and cognitive skills, but at a cost—myelin releases molecules that impede arborization of new connections and thus decreases plasticity.[35-41] Our evolutionary heritage has forged a balance between these forces that has resulted in unusually protracted maturation but equally unusually prolonged plasticity.

Across many species of birds and mammals, there is a positive correlation between the time of dependence upon a parent or caregiver and the size and functionality of the brain. For instance, species of crows that have longer periods of parental care have larger brains and more complicated vocalizations and food-gathering strategies than similarly sized crows with shorter dependency. Humans are the most extreme example of protracted maturation in all of nature. It is one of the most distinctive features of our species. With the adaptability afforded by our protracted maturation, humans can survive in nearly every habitat on earth. Survival skills are quite different in cold versus warm climates, and survival skills have changed dramatically across time as well. Ten thousand years ago, a brief time in evolutionary terms, humans spent much of their time securing food and shelter. Now, in relatively short amounts of time and energy expenditure, we can obtain all of the calories we need for survival. We have more time to feed our brain's yearning for information and novelty during the highly plastic periods of our adolescent development. It is no wonder that access to the internet, where the world's knowledge is a click away, is steep competition for attending to the often-mundane matters of parents, family, or even friends. As we seek to optimize our decision-making for the best outcomes, we constantly compare choices leading to a neverending search for "bigger and better options." The internet allows awareness of a far greater number of options, which may contribute to a feeling that we are missing out or not living an adequate life in comparison with others. It also allows ever greater ability to give our brains what they are seeking and to harness the collective wisdom of our species to live healthier, happier lives.

Summary

Our computer-age attraction to the nearly limitless novelty and socially relevant peer data afforded by modern screen-media technologies is deeply rooted in our stone-age brain.

Like fire, or any powerful tool, technologies can be used, misused, or abused. For many, technologies contribute to health, happiness, productivity, and prosperity. Others are mired in the irony that devices that can connect us to each other more effectively than ever before may lead to increased loneliness; that technologies that put the world's collective knowledge at our fingertips may lead to increased distractibility and lessened critical thinking; and that the same technologies that can lead to earlier detection and innovative treatments of mental illness may also be related to increased rates of anxiety and depression.

There is little utility in broadly labeling the phenomenon of digital media use as "good" or "bad." The technological genie is out of the bottle, and it seems unlikely that efforts to put it back would succeed even if we deemed it the desired course of action. Rather, our goal should be to maximize the positive aspects of digital media and technologies and minimize the negative. Toward that end, greater understanding of the adolescent brain may guide interventions and inform hypotheses to be generated and tested in future research projects. ■

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