The Teenage Brain: Under Construction

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ABSTRACT: Can sexual activity, alcohol and drug use, violent video games, pornography and other activities, including use of social media, damage adolescent minds? Early high-risk behaviors appear to have significant harmful effects on the brain's development. Evidence suggests that the hormones and neural patterns triggered may lead to addictive, and other high-risk behaviors, social withdrawal, and depression. Compounding these concerns are the immature decision-making processes during adolescence. Fortunately, parents can positively impact the brain development of adolescents as they assist in decision-making, provide structure to the adolescent's environment, and monitor the adolescent's activities.

Introduction

Shakespeare wrote, "I would there were no age between ten and three and twenty... For there is nothing in the between but getting wenches with child, wronging the ancientry, stealing, fighting." (*The Winter's Tale,* Act III, Sc. iii) It is amazing that over 400 years later, scientists are confirming Shakespeare's observation that the adolescent's brain is not fully mature until approximately 23 – 25 years of age. New and ongoing scientific research, utilizing functional magnetic resonance imaging (f MRI), demonstrates that during adolescence nearly every aspect of the brain is undergoing dramatic changes—changes that are not just genetically determined, but are greatly affected by experiences and environment. The "nature versus nurture" debate is no longer relevant, as research clearly documents that both have

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impressive impact. Environment affects the growth and development of brain cells, impacts the wiring of these cells, and affects which cells live or die. More importantly, it is possible through epigenetics for environmental influences such as alcohol and other drugs to turn on or off genes within the genome that is contrary to the usual expression of those genes.[1,2] Thus, activities and experiences have the potential to impact the development and functioning of the brain, not just during the adolescent years, but for a lifetime.

Structural Changes in the Brain

The brain undergoes extensive structural remodeling beginning at approximately 12 years of age, and continuing through young adulthood.[3] During adolescence each lobe of the brain changes in its composition of grey and white matter, in its connections with other lobes, and in its hormonal environment. These changes do not occur simultaneously, but rather each area of the brain undergoes structural remodeling on its own timeline, with the prefrontal cortex being one of the last areas to fully mature. As each lobe matures, it also develops increased connections with other areas of the brain, thus allowing for improved communication with better coordination and integration of perceptions, emotions, and actions.[4]

Some specific changes include increased myelination of the brain neurons as well as pruning of unused neurons. Myelin, an insulating sheath of lipids and proteins, encircles the neurons, allowing stimuli to be transmitted more rapidly and facilitating the coordination between various areas of the brain. This is visualized as increased white matter on brain imaging.

As the brain experiences crowding of the nerves, there is competition for space and nutrients. Consequently, growth is followed by a time of "pruning," when underutilized nerve cells are deprived of nutrition and atrophy, often referred to as the "use it or lose it" principle. MRIs show this as a decrease in the grey matter volume of the brain. The pruning process allows the adolescent brain to function more rapidly for tasks that are already known, but decreases the brain's capacity to learn new tasks or acquire new skills.[5]

The frontal lobe serves as the judgment center of the brain, allowing the individual to contemplate and plan actions, to evaluate consequences of

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[1] Masten AS, Faden VB, Zucker RA, et al. Underage drinking: A developmental framework. *Pediatrics*.2008;121(Suppl 4): S235–S251

[2] Berger SL, Kouzarides T, Shiekhattar R, Shilatifard Al. An operational definition of epigenetics. Genes and Development. 2009; 23:781–783.

[3] Blakemore S-J. Imaging brain development: The adolescent brain. NeuroImage. 2011; doi:10.1016/ j.neuroimage.2011.11.080

[4] Crone EA and Konijn EA. Media use and brain development during adolescence. Nature Communications. 2018;9:588

[5] Giedd JN. Structural magnetic resonance imaging of the adolescent brain. *Annals N.Y. Acad Sci* 2004;1021:77–85.

behaviors, to assess risk, and to think strategically. It is also the "inhibition center" of the brain, discouraging the individual from acting impulsively. The frontal lobe ultimately develops connections to many other areas of the brain, enabling experiences and emotions to be processed through the judgment center. The frontal lobe does not fully mature both anatomically and functionally until approximately 23 – 25 years of age when all areas are myelinated and connected to the frontal lobe.[6] This lack of maturation helps explain the adolescent's relative limitations to properly interpret experiences in the environment and arrive at appropriate considered decisions.[7]

Many other areas of the brain likewise are not completely myelinated until the early 20s. The amygdala, which is the emotion center of the brain, is immature in adolescents and not fully connected to the frontal lobe. Adolescents, then, may have a more difficult time interpreting their emotions, as well as the emotions of others.[8] More importantly, since the amygdala is poorly connected to the judgment center of the brain, the adolescent is more likely to make decisions based upon emotional impact rather than upon logic. As Pustilnik and Henry state, "Executive function and emotional responses are not just less developed or different in teens: These two capacities are also less closely linked than in the typical adult brain. As a result, a teen may intellectually understand an issue and emotionally have a response to that issue, but those two processes may occur nearly in parallel rather than in dialogue. Emotional and executive functions must work together to bring about almost any kind of decision."[9]

The hippocampus, the memory center of the brain, is also immature and is very susceptible to the effects of alcohol and marijuana. Alcohol and marijuana can hinder the ability to develop memories and thereby impact learning. Adolescents who binge drink are particularly susceptible to the negative effects of alcohol on the developing hippocampus.[10]

Another area of the developing brain deserving of attention are the cells that compose the mirror neuron system. Mirror neurons are those cells that

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[6] National Institute of Mental Health (2001). Teenage Brain: A work in progress. National Institute of Mental Health publication accessed March 22, 2011 at: http://www.nimh.nih.gov/health/publications/teenage-brain-a-work-in-progress-fact-sheet/index.shtml.

[7] Diekema DS Adolescent brain development and medical decision-making. Pediatrics. 2020; 146(s1): e20200818F

[8] National Institute of Mental Health (2001). Teenage Brain: A work in progress. National Institute of Mental Health publication accessed March 22, 2011 at: http://www.nimh.nih.gov/health/publications/teenage-brain-a-work-in-progress-fact-sheet/index.shtml.

[9] Pustilnik AC, and Henry LM. Adolescent Medical Decision Making and the Law of the Horse *Journal of Health Care Law and Policy* 2012; 15:1–14. (U of Maryland Legal Studies Research Paper 2013–14).

[10] Brown A, Tapert S, Granholm E. et. al. Neurocognitive functioning of adolescents: Effects of protracted alcohol use. *Alcoholism: Clinical and Experimental Research*. 2000; 24: 164–171.

assist in the development of empathy and compassion as the cells are active when an individual either experiences an emotion or observes that emotion being experienced by another person. This is 'cognitive empathy'—the ability to take another person's perspective—and this system is also undergoing dramatic changes during adolescence. Researchers from UCLA studied the impact of cell phone use and screen time on the ability of adolescents to interpret the emotions of others. Sixth graders who attended a science and nature camp and who went without smartphone or digital screen time for just five days improved in their ability to interpret facial expressions seen in photos and videos. The authors state, "The displacement of in-person social interaction by screen interaction seems to be reducing social skills."[11]

It is also important to note there are many sexual differences in the developing brain as documented by brain imaging techniques.[12] The amygdala, the center of emotions noted above, grows faster in adolescent boys than in girls and there are more testosterone receptors in the amygdala of males.

The hippocampus, however, appears to grow faster in adolescent girls and this area has more estrogen receptors.[13,14] Even the cerebellum, an area of the brain utilized in complicated problem solving, differs in size between males and females, being 10 – 13% larger in adolescent males.[15] These sexual variations are important to understand as their onset may begin with in utero development and will contribute to the different way males and females tend to respond to learning environments, risk seeking, and even discipline; yet each human male and female is an individual with considerable variation between different areas of the brain and considerable overlap in brain features among men and women.[16]

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[11] Uhls YT, Michikyan M, et al. "Five days at outdoor education camp without screens improves preteen skills with nonverbal emotion cues" *Computers in Human Behavior*. Oct 2014 39:387-392. http://www.sciencedirect.com/science/article/pii/S0747563214003227.

[12] Ruigrok AN, Salimi-Khorshidi G, Lai MC, et al. A meta-analysis of sex differences in human brain structure. *Neuroscience and Biobehavioral Reviews*. 2014; 39:34–50.

[13] Blakemore SJ, Burnett S, and Dahl RE. The Role of Puberty in the Developing Adolescent Brain. *Human Brain Mapping*. 2010; 31:926-933.

[14] Gillies GE and McArthur S. Estrogen actions in the brain and the basis for differential action in men and women: a case for sex specific medicines. *Pharmacol Rev*. 2010 62(2): 155–198.

[15] Tiemeier H, Lenroot RK, Greenstein DK, et al. Cerebellum development during childhood and adolescence: a longitudinal morphometric MRI study. *Neuroimage*. 2010; 49(1): 63–70.

[16] Joel D, Berman Z, Tavor I, et al. Sex beyond the genitalia: The human brain mosaic. *Proceedings of the National Academy of Sciences*. 2015; 112 (50): 15468–15473.

Hormonal Changes in the Brain

Along with changes in the number of neurons, the brain also experiences changes in its hormonal environment. It has been known for decades that adolescence is characterized by surges in sex hormones—estrogen and testosterone. Recently it has been demonstrated that receptors for these hormones exist in many organs of the body, including the brain. In addition, other hormones and neurotransmitters such as oxytocin, vasopressin, dopamine, and serotonin also influence brain development.

Dopamine, the neurotransmitter most responsible for feelings of pleasure, has a powerful impact. The early adolescent brain, with its increased number of nerve cells, has higher levels of dopamine circulating in the prefrontal cortex, but dopamine levels in the reward center of the brain (nucleus accumbens) are changing throughout adolescence. These changes in the dopamine levels in the reward center suggest that the adolescent requires more excitement and stimulation to achieve the same level of pleasure as an adult.[17,18] So the teenager will attempt riskier behaviors to achieve elation. Dopamine is also the neurotransmitter secreted when individuals participate in various addictive behaviors. Drug use, gambling, video gaming, pornography, and sexual experiences can all become addicting as the individual strives to achieve a dopamine-mediated pleasure. As their brains are under construction and nerve pathways are forming, adolescents become addicted more easily.[19] This vulnerability of the developing brain may well explain why these addictive behaviors identified in adults often have their onset during adolescence or early adulthood. For example, 40% of adult alcoholics identify onset between 15 and 19 years of age.[20] In addition, adolescents are more likely to become addicted with even minimal exposure to a high-risk behavior. Although an adolescent may smoke fewer cigarettes than an adult, the adolescent demonstrates higher rates of addiction.[21]

Recent research has investigated the influence genes exert on an individual's willingness to take risks. Dopamine receptor DRD4 appears to play a ma-

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[17] Galvan A, Adolescent development of the reward system. *Frontiers in Human Neuroscience* 2010; 4:1–9.

[18] Spear LP, Adolescent Neurodevelopment. *J Adolescent Health.* 2013; 52(2 0 2): S7–13. doi:10.1016/j.jadohealth.2012.05.006.

[19] Spear LP, Neurobehavioral changes in adolescence. *Current Directions in Psychological Science*.2000;9:111–114.

[20] Helzer JE, Burnam MA,McEvoy LT. Alcohol abuse and dependence. In Robins LN, Regier DA, eds. *Psychiatric Disorders in America: The Epidemiologic Catchment Area Study*. New York: Free Press;1991: 81–115.

[21] Chambers RA, Taylor JR, Potenza MN. Developmental neurocircuitry of motivation in adolescence: A critical period of addiction vulnerability. *Am J Psychiatry*.2003;160: 1041–1052.

jor role in determining the risk-taking behavior of the individual. Adolescents may be viewed as either "high risk takers" or "low risk takers" depending upon their genetic propensity to seek excitement through risky behaviors. Alcohol can affect the expression of the risk-taking gene, causing adolescents who are not generally considered "high risk takers" to take risks when under the influence of alcohol.[22]

Research also demonstrates that adolescents who drink alcohol are more likely to participate in other high-risk behaviors, including sexual activity. Marijuana is another drug that can affect an adolescent's decision making, decrease inhibitions, and thereby increase risk-taking behaviors.[23]

These behaviors in turn further modify the structure and function of the brain.

Oxytocin and vasopressin function as "bonding" hormones. Oxytocin, a peptide secreted during labor, delivery, and breastfeeding, is also powerfully active in the female brain during physical touch or even intense gazing. Oxytocin release increases the likelihood that the female will trust her sexual partner but decreases the functioning of her frontal cortex, the judgment center. The hormone serves to bond the woman to her mate with repetitive touches and sexual relations increasing the likelihood of monogamy.[24] Vasopressin serves much the same role in men.

Adolescents who initiate sexual activity early are more likely to have more sexual partners by early adulthood. The Centers for Disease Control and Prevention documented that 49.2% of girls and women report more than five lifetime sexual partners if their sexual debut occurred younger than 16 years of age. However, if sexual debut occurred at age 20 years or older, only 9.0% had more than five sexual partners during their lifetime.[25] Since sexual touching brings pleasure and raises dopamine levels, the developing adolescent brain, in its craving for repetitive elevations of dopamine, overrides the healthy bonding effects of oxytocin and vasopressin. This, in turn, makes it more difficult for the adolescent to maintain a monogamous relationship later in life, as demonstrated by studies reporting that married adults who have experienced premarital sex are more likely to suffer divorce than those who abstained.[26]

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[22] Helzer JE, Burnam MA,McEvoy LT. Alcohol abuse and dependence. In Robins LN, Regier DA, eds. *Psychiatric Disorders in America: The Epidemiologic Catchment Area Study*. New York: Free Press;1991: 81–115.

[23] Lane SD, Cherek DR. Risk taking by adolescents with maladaptive behavior histories. *Experimental and Clinical Psychopharmacology*.2001; 9: 74–82.

[24] Brizendine L. *The Female Brain*. New York: Morgan Road Books; 2006:. 68.10.

[25] Chandra A, Martinez FM, Mosher WD, et al. Fertility, family planning, and reproductive health of U.S. women: Data from the 2002 National Survey of Family Growth. National Center for Health Statistics. *Vital and Health Statistics*.2005; 23(25):1–160.

[26] Heaton T. Factors contributing to increasing marital stability in the United States. Journal of Family Issues. 23; April 2002; 392–409.

Unfortunately research also documents that adolescents who initiate early sexual activity are more likely to experience depression and anxiety, with subsequent increased risk of substance abuse, thus demonstrating the interconnection of many of the high risk behaviors.[27,28] Given all these changes, we see that adolescence is a time of great vulnerability.

Adolescent Brain Development and Decision-making

Researchers investigating decision-making in adolescents often use hypothetical dilemmas in a laboratory setting. In one early study investigators demonstrated that 14 year olds did not differ significantly from 18 and 21 year olds in their ability to make informed decisions and went so far as to conclude that "children as young as 9 appear able to participate meaningfully in personal health-care decision making."[29]

This article, along with many other similar laboratory-based studies, were used to develop health care policies allowing adolescents to obtain confidential care for sexual health related concerns, including abortion. Based on evaluations of decision-making that focused on the adolescent's ability to understand and make rational decisions, bioethicists Weir and Peters argued that health care professionals should presume "all adolescent patients between fourteen and seventeen have the capacity to make health care decisions, including end-of-life decisions" except in unusual circumstances.[30]

However, newer research is evaluating two areas of decision-making: the various components of decision making as well as the ability to make decisions in real-life situations that may be emotionally charged, stressful, or peer influenced. Studies confirm that adolescents, when faced with real life decisions, are much more likely to demonstrate an immaturity that is more dependent upon emotions and peer pressure with less use of the cognitive reasoning of the frontal lobe and less concern for future consequences. Thus the new schema for decision-making demonstrates that there are two systems in the brain that are utilized—"a socioemotional system composed largely of limbic and paralimbic structures and a cognitive-control system composed of prefrontal and parietal cortical structures."[31]

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[27] Baiden P, Panish LS, et al. Association between first sexual intercourse and sexual violence victimization, symptoms of depression, and suicidal behaviors amont adolescents in the United States: Findings from 2017 and 2019 National Youth Risk Behavior Survey. Int J Environ Res Public Health. 2021. 18.7922.

[28] Cioffredi L-A, Kamon J, Turner, W. Effects of depression, anxiety and screen use on adolescent substance use. Preventive Med Reports. 2021; 22:101362.

[29] Weithorn LA, Campbell SB. The competency of children and adolescents to make informed treatment decisions. Child Dev. 1982; 53(6):1589–1598

[30] quoted in Diekema DS Adolescent brain development and medical decision-making. Pediatrics. 2020; 146(s1):e20200818F

[31] Diekema DS Adolescent brain development and medical decision-making. Pediatrics. 2020; 146(s1): e20200818F

As one might expect, the socioemotional system often involves intuitive responses that are made rapidly and unconsciously as the individual responds to personal feelings, while the cognitive-control system is much more reasoned and deliberate. Coordination between both systems is important in order to make good decisions, and neither system is mature during adolescence.

Although it appears that the socioemotional system matures earlier in adolescence than the cognitive-control system, the relative imbalance means the adolescent is less able to regulate and understand personal emotions, is more susceptible to peer influence, is less likely to delay gratification and more likely to engage in risky behaviors when benefits appear to outweigh the risks. Diekema describes adolescents as experiencing "prefrontal cortex deficit disorder" as they lack the control provided by a mature prefrontal lobe. So he cautions, "the desire to respect adolescent decisions must be coupled with the recognition that decision-making, even of mature adolescents, may occasionally be flawed," and suggests, "the current age of majority (18-21 years of age depending upon the state) is not clearly supported by empirical data...it may well be that the age of majority should be reconsidered."[32]

Other researchers have termed a similar phenomenon the "maturity gap" when psychosocial maturity (the ability to restrain one's actions during times of emotional stress) lags behind cognitive capacity (the important determination of logical thinking). In a study of 5227 individuals between 10 and 30 years of age from 11 countries, researchers demonstrated "Juveniles may be capable of deliberative decision making by 16, but even young adults may demonstrate 'immature' decision making in arousing situations."[33]

A study of over one hundred 13 – 25 year olds showed "diminished cognitive performance" when the individuals were exposed to emotionally charged situations, even in those 18 – 21 years of age compared to adults over 21. The researchers were able to correlate this reduction in performance with changes on fMRI scans that showed decreased activity in the fronto-parietal circuitry that is important in cognitive control. Conversely there was increased activity in the emotional processing areas of the brain (ventromedial prefrontal cortex).[34]

Adolescents (and young adults) are also more susceptible to peer influence than adults age 24 and older. In a study of 306 individuals between 13 and 24 years of age, researchers found risk taking and risky decision making increased

[32] Diekema DS Adolescent brain development and medical decision-making. Pediatrics. 2020; 146(s1): e20200818F

[33] Icenogle G, Steinberg L, Duell N, et al. Adolescents' cognitive capacity reaches adult levels prior to their psychosocial maturity: Evidence for a "maturity gap" in a multinational, cross-sectional sample. Law Hum Behav. 2019; 43(1):69–85.

[34] Cohen AO, Breiner K, Steinberg L, et al. When is an adolescent an adult? Assessing cognitive control in emotional and nonemotional contexts. Psychological Science. 2016; 2794):549–562.

when in peer groups. Significantly even the young adults aged 18 – 22 years of age were more strongly affected by their peers than were older adults.[35]

Interestingly, another component of decision making may also be immature in adolescents. The ability to integrate personal ethics and values into the cognitive process is obviously important, especially as an individual encounters more significant, high stakes decisions. Researchers utilizing fMRI imaging in 13 to 20 year olds found that younger adolescents (13 – 18) did not increase their cognitive control performance when faced with high stakes decisions, and this was most likely due to decreased connectivity in their corticostriatal pathways. In other words, adolescents are less likely than adults to improve their decision making when faced with a more significant and important decision.[36]

This research all demonstrates the adolescent brain is immature, not just in structure, but in function, and clearly reveals the adolescent's need for adult assistance when facing difficult and emotionally charged decisions.

Impact of Exercise on Brain Development

There is mounting evidence that regular exercise is beneficial for physical and emotional well-being. The World Health Organization recommends that children and adolescents should experience 60 minutes of moderate-to-vigorous physical activity daily. Unfortunately, in the United States, only 24% of children between 6 and 17 years of age daily participate in physical activity.[37]

Now studies are demonstrating that physical activity is linked to school performance and cognition because of its effects on brain structure and function. In one study from Minnesota, involving 4746 middle and high school students, those who participated in team sports with regular physical activity had higher grade point averages.[38] Similar results have been found in studies from other countries.[39]

In addition, research is showing a link between aerobic exercise and distinct cognitive abilities that are important for academic achievement, including attention, planning, problem solving, working memory, spatial learning,

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[35] Gardner M and Steinberg L. Peer influence on risk taking, risk preference, and risky decision making in adolescence and adulthood: an experimental study. Dev Psychol. 2005; 41(4): 625–35.

[36] Insel C, Kastman EK, Glenn CR and Somerville LH. Development of corticostriatal connectivity constrains goal-directed behavior during adolescence. Nature Communications. 10.1038/s41467-017-01369-8

[37] (CDC, 2017 https://www.cdc.gov/healthyschools/physicalactivity/facts.htm)

[38] Fox CK, Barr-Anderson D, Neumark-Sztainer D, Wall M. Physical activity and sports team participation: associations with academic outcomes in middle school and high school students. J Sch Health. 2010; 80(1):31–37.

[39] Haverkamp BF, Oosterlaan J, et al. Physical fitness, cognitive functioning and academic achievement in healthy adolescents. Psychology Sport Exercise. 2021; 57:102060

and inhibitory control. Utilizing MRI scans and diffusion MRI, Herting and Chu evaluated the brain structure and white matter microstructure in adolescents who exercised regularly compared with lean controls who did not exercise. Improved aerobic fitness was related to larger hippocampal volumes as well as other structural brain changes.[40]

There is evidence from other studies that exercise may influence how the brain encodes new memories in the hippocampus and may improve the teens' ability to efficiently process task requirements.[41] In one prospective 4 month study 67 adolescents were randomized to three different groups who were assigned varying levels of physical activity. Those students in the high intensity group improved their school grades as well as their cognitive performance on specialized testing that included verbal and non-verbal ability, abstract reasoning, spatial ability, numerical ability.[42]

Impact of Sleep on Brain Development

During early adolescence there is a delay in the circadian timing system so that melatonin, the sleep inducing protein, is excreted later in the evening, leading to delays in bedtimes. In combination with the normal increase in activity during adolescence and use of social media at night, adolescents fall asleep later and experience less total sleep than is healthy for brain development. Despite the recommendations that adolescents should sleep 8 – 10 hours daily, 72.7% of high school students in grades 9 – 12 report not getting enough sleep on school nights.[43]

Sleep may actually play a role in sculpting the adolescent brain, and one study demonstrated that children and adolescents who experienced more sleep had corresponding increases in hippocampal grey matter.[44] Interestingly, sleep studies demonstrate progressive changes in the sleeping EEG during adolescence, so that as grey matter decreases and white matter increases, sleep slow-wave activity decreases.[45]

Numerous studies link sleep deprivation with health risks including obesity, diabetes, injuries, poor mental health, and problems with learning, memory,

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[40] Herting MM and Chu X. Exercise, cognition, and the adolescent brain. Birth Defects Res. 2017; 109(20):1672–79.

[41] Herting MM and Nagel BJ. Differences in brain activity during a verbal associative memory encoding task in high and low-fit adolescents. J Cogn Neurosci. 2013; 25(4):595–612,

[42] Ardoy DN, Fernandez-Rodriquez JM, et al. A physical education trial improves adolescents' cognitive performance and academic achievement: the EDUFIT study. Scandinavian J Med Sci Sports. 2014; 24:e52–61.

[43] https://www.cdc.gov/healthyschools/features/students-sleep.htm

[44] Tarokh L, Saletin JM, and Carskadon MA. Sleep in adolescence: physiology, cognition and mental health. Neurosci Biobehav Rev. 2015; 70:182–188.

[45] Buchmann A, Ringli M, et al. EEG sleep slow-wave activity as a mirror of cortical maturation. Cerebral Cortex 2011;21:607–615

attention and behavior, so it is crucial for adolescents' lives to be structured in ways that promote optimal sleep.

Impact of Alcohol on Brain Development

Alcohol remains the most commonly abused substance among adolescents and young adults. According to the National Center for Drug Abuse Statistics for 2020, over 1 million 12 to 17 year olds reported binge drinking within the last month and over 400,000 teens of the same age actually met criteria for Alcohol Use Disorder.[46] Because of the immaturity of the adolescent brain, and its unique susceptibilities and vulnerabilities to addiction, it is not surprising that alcohol can have a greater adverse impact on adolescents than on adults.

Researchers following adolescents prospectively have noted that binge drinking or excessive drinking is associated with decreased performance on visuospatial and memory abilities as well as attention difficulties in adolescents and adults.[47] This has been correlated with brain imaging studies showing reduced grey matter volume.[48] A longitudinal study from the Netherlands in which three separate cohorts of children were followed evaluated participants between 8 and 29 years of age via neuroimaging.[49] The authors stated, "Alcohol use was associated with adolescent's brain morphology showing accelerated decrease in grey matter volumes."

Especially impacted is the hippocampus, the area of the brain that is important for learning and memory. One study of adolescents aged 15 - 18 years of age showed that those who abused alcohol demonstrated hippocampal asymmetry and a reduced left hippocampal volume compared to non-using controls. This correlated with difficulties with verbal learning.[50]

This decrease in hippocampal volume may also impact the ability of the adolescent to pay attention. Smaller hippocampal volumes were associated with auditory omission errors and longer auditory response times in a study of 115 children and adolescents.[51]

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[46] https://drugabusestatistics.org/teen-drug-use/

[47] Hanson KL, Medina KL, Padula C, et al. Impact of adolescent alcohol and drug use on neuropsychological functioning in young adulthood: 10-year outcomes. J Child Adolesc Subst Abuse. 2011; 20(2):135–154.

[48] Heikkinen N, Niskanen E, et al. Alcohol consumption during adolescence is associated with reduced grey matter volumes. Addiction. 2017; 112(4):604–613,

[49] Marroun HE, Klapwijk ET, et al. Alcohol use and brain morphology in adolescence: A longitudinal study in three different cohorts. Eur J Neurosci. 2021; 54:6012–6026.

[50] Medina KL, Schweinsburg AD, Cohen-Zion M, et al. Effects of alcohol and combined marijuana and alcohol use during adolescence on hippocampal volume and asymmetry. Neurotoxicol Teratol. 2007; 29(1): 141–152.

[51] Kim T-H, Choi E, Kim H, et al. The association between hippocampal volume and level of attention in children and adolescents. Frontiers in Systems Neuroscience. 2021; 15:671735,

Impact of Marijuana on Brain Development

Tetrahydrocannabinol (THC) is the main psychoactive component of the marijuana plant and specifically acts upon the cannabinoid receptors in the brain that are predominantly found in the areas of the brain that are involved with concentration and thinking, pleasure and memory formation, and coordination. THC over activates the endocannabinoid system, causing the high and other effects that users experience. These effects include distorted perceptions, psychotic symptoms, difficulty with thinking and problem solving, disrupted learning and memory, and impaired reaction time, attention span, judgment, balance and coordination.[52] Since these areas of the brain are all rapidly changing during early adolescence, they are vulnerable to any adverse influences.

Reports of adverse effects of marijuana on the brain include structural abnormalities in the density and volume of the gray matter, reduced connectivity in the prefrontal networks that control the executive functions and reduced volume and connectivity in the hippocampus, the learning center of the brain.

More significant are the associations between marijuana use and mental health concerns, especially with the higher concentrations of THC now available. One of the first studies linking marijuana use with schizophrenia was reported in 1987. A prospective study of 45, 570 Swedish conscripts interviewed the adolescents at age 18 years and followed them for 15 years. By 1983, 246 (0.54%) had been diagnosed with schizophrenia. In the group of individuals who had never used marijuana, only 0.47% were diagnosed with schizophrenia. However, in the group of 752 who had smoked more than 50 times by age 18, 21 cases were diagnosed or 2.8% of the group—a six fold increased risk.[53]

More recently, a review of ten studies found a 10 – 25% increased risk of psychosis among cannabis users versus non users.[54] A systematic review and meta-analysis of 15 studies found just one dose of THC could induce psychosis in adults who had no history of previous mental illness.[55] Risk has also been shown to increase with younger age at initiation of drug use, higher potency cannabis and use of synthetic cannabinoids.[56] In fact, the authors state that their research indicates "if high-potency cannabis were no longer available, 12.2% of cases of first-episode psychosis could be prevented across the 11 sites" they studied.

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[52] Nistler C, Hodgson H, Nobrega FT, Hodgson CJ, Wheatley R, Solberg G. Marijuana and adolescents. Minn Med.2006 Sept:49–51

[53] Andreasson S, Allebeck P, Engstrom A, and Rydberg U. Cannnabis and schizophrenia. A longitudinal study of Swedish conscripts. Lancet. 1987; 26(2):1483–6.

[54] Gage SH, Hickman M and Zammit S. Association between cannabis and psychosis: Epidemiologic evidence. Biol Psychiatry. 2016; 79(7):549–556.

[55] Hindley G, Beck K, Borgan F, et al. Psychiatric symptoms caused by cannabis constituents: a systematic review and meta-analysis. Lancet Psychiatry. 2020;7:344–353

[56] Di Forti M, Quattrone D Freeman TP, et al. Lancet Psychiatry 2019; 6:427–36

A systematic review of 124 studies that evaluated all behavioral sequelae of cannabis use identified negative effects on "cognition, motivation, impulsivity, mood, anxiety, psychosis, intelligence and psychosocial functioning."[57] In addition, these authors also found "frequency of cannabis use, THC (but not CBD) content, age of onset and cumulative cannabis exposure can all contribute to these adverse outcomes in individuals without a pre-existing medical condition or psychiatric disorder."

Other studies have linked marijuana use with depression and suicidal ideation.[58] In addition, there may be genes that increase risk for developing psychosis with THC use.[59]

Not only are the effects on mental health of adolescents serious enough to encourage total abstinence during the years of rapid brain development, but there are also other adverse effects noted with the use of THC during early and mid-adolescence, including difficulties learning and remembering,[60] permanently lowered IQ,[61] and difficulties processing information.[62]

In chronic adolescent users, marijuana's adverse impact on learning and memory persists long after the acute effects of the drug wear off. A major study published in 2012 in Proceedings of the National Academy of Sciences provides objective evidence that marijuana is harmful to the adolescent brain.[63] As part of this large-scale study of health and development, researchers in New Zealand administered IQ tests to over 1,000 individuals at age 13 (born in 1972 and 1973) and assessed their patterns of cannabis use at several points as they aged. Participants were again IQ tested at age 38, and their two scores were compared as a function of their marijuana use. The results were striking: Participants who used cannabis heavily in their teens and continued through adulthood showed a significant drop in IQ between the ages of 13 and 38—an average of eight points for those who met criteria for cannabis dependence. Those who started

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[57] Sorkhou M, Bedder RH, George TP. The behavioral sequelae of cannabis use in healthy people: A systematic review. Frontiers in Psychiatry. 2021; 12:1–19.

[58] Hallfors DD, Waller MW, Ford CA, et al. Adolescent depression and suicide risk: association with sex and drug behavior. Am J Prev Med. 2004;27(3):224–230

[59] Di Forti M, Iyegbe C, et al. Confirmation that the *AKT1*(rs2494732) genotype influences the risk of psychosis in cannabis users. Biol Psychiatry. 2012; 72(10):811–816.

[60] Nistler C, Hodgson H, Nobrega FT, Hodgson CJ, Wheatley R, Solberg G. Marijuana and adolescents. Minn Med.2006 Sept:49–51

[61] Meier MH, Caspi A, Harrington H, et al. Persistent cannabis users show neuropsychological decline from childhood to midlife. ProcNatlAcadScie2012 Oct 2;109(40):E2657–64

[62] Kelleher LM, Stough C, Sergejew AA, Rolfe T. The effects of cannabis on information-processing speed. Addict Behav. 2004 Aug;29(6):1213-9. doi: 10.1016/j.addbeh.2004.03.039. PMID: 15236825.

[63] Meier MH, Caspi A, Harrington H, et al. Persistent cannabis users show neuropsychological decline from childhood to midlife. ProcNatlAcadScie2012 Oct 2;109(40):E2657-64.Available at http://www.ncbi.nlm.nih.gov/pubmed?term=persistent%20cannabis%20users%20and%20meier.

using marijuana regularly or heavily after age 18 showed minor declines. By comparison, those who never used marijuana showed no declines in IQ.

In addition, it is important to remember that adolescent females who experiment with drugs are also at high risk for pregnancy. Although the risk of using marijuana during pregnancy is unrecognized by the general public, research demonstrates infants and children exposed prenatally to marijuana have a higher incidence of neurobehavioral problems. THC and other compounds in marijuana mimic the human brain's cannabinoid-like chemicals, thus prenatal marijuana exposure may alter the developing endocannabinoid system in the fetal brain, which may result in attention deficit, difficulty with problem solving, and poorer memory.[64] Evidence especially suggests an association between prenatal marijuana exposure and impaired executive functioning skills beyond the age of three. Specifically, children with a history of exposure are found to have an increased rate of impulsivity, attention deficits, and difficulty solving problems requiring the integration and manipulation of basic visual perceptual skills.[65] These changes occur even when mothers discontinue marijuana after learning they are pregnant.[66]

Impact of Media on Brain Development

Since adolescence is a period of time during which parental influence decreases while peer acceptance is increasingly desired, the impact of social media on teens is intensified, Giedd mentions three characteristics of adolescence that contribute to the attraction of digital / social media: teens seek human connectedness, have a desire for adventure, and want to learn.[67]

Today the social interactions of adolescents increasingly consist of media-related activities where they make connections, seek peer acceptance, and monitor peer activities.[68] Adolescents in the United States currently average over 7 hours of screen time each day, and this does not include time spent doing homework.[69] There are numerous social media sites available to adolescents,

[64] Drug Facts. National Institute on Drug Abuse. www.drugabuse.gov/drugs-abuse/marijuana. Published December 2012.

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with YouTube, Instagram and Snapchat now more popular than Facebook, according to the Pew Research Center's report in 2018, and teens generally access more than one platform. For example, 85% of adolescents report using YouTube, 72% Instagram, 69% Snapchat and 51% Facebook.[70]

Adolescents themselves acknowledge both the positive and negative aspects of social media. The positive effects include the ability to connect with family and friends, the ability to meet others who have similar interests, and as a means of self-expression. Negative effects reported by teens include bullying, harmful effects on relationships with lack of personal contact, giving an unrealistic view of others' lives and causing distraction or peer pressure.[71]

Since adolescence is a time of rapid brain development, it is important to evaluate the impact of media, especially social media, during this vulnerable time. As noted in Nature Communications, "...changes in grey matter volume are observed most extensively in brain regions that are important for social understanding and communication such as the medial prefrontal cortex, superior temporal cortex and temporal parietal junction."[72]

Social connection involves several different neuroanatomical circuitries in the brain but the reward system is especially active. Many stimuli such as the desire for hunger, sleep, and sex stimulate this reward system, but social connections, particularly during the adolescent years, also contribute to activity in this region of the brain.

One of the ways brain development of children and adolescents may be impacted by social media is via social rejection. Researchers have utilized functional MRI neuroimaging to evaluate the impact of rejection on social media on brain activity of 7 – 10 year olds and have found changes in several regions of the brain associated with judgment and emotions.[73] In addition, when adolescents perceive rejection in research situations, they often respond more aggressively towards those who have rejected them.[74]

Conversely, acceptance on social media (receiving "likes") generates brain responses that are similar to receiving rewards such as money with increased

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[70] Anderson M and Jiang J. Teens, Social Media & Technology. Pew Research Center. May 31, 2018. Retrieved from https://www.pewinternet.org/2018/05/31/teens-social-media-technology-2018.

[71] Anderson M and Jiang J. Teens, Social Media & Technology. Pew Research Center. May 31, 2018. Retrieved from https://www.pewinternet.org/2018/05/31/teens-social-media-technology-2018.

[72] Crone EA and Konijn EA. Media use and brain development during adolescence. *Nature Communications*. 2018. 9:588.

[73] Achterberg M, van Duijvenvoorde ACK, van der Meulen, et al. The neural and behavioral correlates of social evaluation in childhood. *Developmental Cognitive Neuroscience*. 2017;24:107-117.

[74] Achterberg M, van Duijvenvoorde ACK, Bakermans-Kranenburg MJ and Crone EA. Control your anger! The neural basis of aggression regulation in response to negative social feedback. *Social Cognitive and Affective Neuroscience*. 2016; 11(5):712–720.

activity in the brain regions associated with pleasure and reward (the ventral striatum).[75,76]

Both rejection and acceptance on social media appear to be moderated by the dorsolateral prefrontal cortex, the area of the brain associated with executive functions, such as judgment. Since this area is not fully mature until around 24 years of age, the adolescent may be more susceptible to the emotional content of social media.[77] More specifically, the adolescent may be more sensitive to rejection, peer influence and emotional interactions on social media.

Relationship Between High Risk Behaviors

All this research demonstrates the adolescent's brain is immature—in virtually every area that has been studied. The adolescent's brain is prone to seek excitement at a time when the frontal lobe is not mature enough to moderate such behavior. This is also the time when the developing brain is at greatest risk to form neuronal connections that may lead to addictions and impact future emotional well-being and decision making. Making matters worse, modern media portrays high-risk behaviors as admirable, exciting, and even safe, while discouraging parental involvement that would positively modify the behaviors.

There is a clear link between high-risk behaviors and subsequent depression and even suicide. In the National Longitudinal Study on Adolescent Health, 13,491 adolescents in grades 7 to 11 were interviewed in 1995 and again one year later. The authors differentiated the cause and effects of depression and found that early high-risk behaviors, including sexual activity and drug use, were linked with later depression, but early depression did not cause high-risk behaviors.[78]

Further analysis of the same study revealed that adolescents who had involvement in any drinking, smoking, and/or sexual activity were significantly more likely to suffer from depression, suicidal ideation, and suicide attempts."[79]

Impact of Parents on Adolescent Brain Development

The good news is that parents play a pivotal and crucial role during the adolescent years, and the influence of parents can positively impact the

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[75] Crone EA and Konijn EA. Media use and brain development during adolescence. *Nature Communications.* 2018. 9:588.

[76] Davey CG, Allen NB, Harrison BJ, et al. Being liked activates primary reward and midline self-related brain regions. *Human Brain Mapping*, 2010. 31(4):660–668.

[77] Crone EA and Konijn EA. Media use and brain development during adolescence. *Nature Communications.* 2018. 9:588.

[78] Hallfors DD, Waller MW, Bauer D, et al. Which comes first in adolescence –sex and drugs or depression? *Am J Prev Med.* 2005; 29:163–70.

[79] Hallfors DD, Waller MW, Ford CA, et al. Adolescent depression and suicide risk: association with sex and drug behavior. *Am J Prev Med.* 2004; 27:224–31.

developing brain. Since their prefrontal cortex is immature, adolescents will benefit from the wisdom and guidance of their parents in making decisions and strategizing. Limit setting, structure, and communication that help minimize exposure to high-risk behaviors will protect the adolescent, not just during the adolescent years, but also long term. Parents can even take advantage of the need for excitement by seeking positive experiences for their adolescents. Parents can challenge their teens to find excitement in learning new things. For academic teens it might be learning a new language or skill. For athletic teens it might be learning how to dive or some other physical skill. These challenges produce the same sort of dopamine high that teens receive from things that are risky, dangerous and sometimes illegal.[80]

Participating in exciting activities together will also help parent and teen to bond and connect with each other. Research from the National Longitudinal Study on Adolescent Health demonstrated that adolescents are less likely to participate in high risk behaviors when they are highly connected to their parents.[81] Alan Booth, a researcher at Pennsylvania State University, evaluated the role of parenting on adolescent high-risk behaviors and found that even adolescents who are more prone to them will be less likely to participate if they have a close relationship with their parents.[82]

Parents not only protect their adolescent when they have a close relationship, they can also prevent high risk behaviors by decreasing the teen's opportunities to participate in those dangerous activities. Researchers at the National Center on Addiction and Substance Abuse (CASA) at Columbia University (now called drugfree.org) demonstrated that adolescents with "hands-on" parents (those who monitored the activities of their adolescents and participated in family dinner hour together) are at one-fourth the risk of substance abuse as those with "'hands-off" parents.[83] An international study of over 5000 adolescents and young adults between 10 and 30 years of age from 11 countries showed that adolescents in all countries experienced heightened risk taking. However, risk taking is manifest in various ways depending upon the cultural context, so the authors of the study state, "the broader context in which adolescents develop exerts a powerful impact on the extent to which young people

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[80] Galvan A. Adolescent development of the reward system. Frontiers Human Neuroscience. 2010; 4(6)10.3389/neuro.09.006.2010

[81] Resnick MD, Bearman PS, et al. Protecting Adolescents From Harm—Findings From the National Longitudinal Study on Adolescent Health. JAMA 1997; 278:823–832.

[82] Booth, A, Johnson DR, et al. Testosterone and child and adolescent adjustment: The moderating role of parent-child relationships. Developmental Psychology. 2003; 39(1):85–98.

[83] WebMD Health News. Hands-on parents help teens so no to drugs. 2001. Accessed February 1, 2022 at https://www.webmd.com/parenting/news/20010221/hands-on-parents-help-teens-say-no-to-drugs#:~:text=Results%20released%20Wednesday%20by%20the,'hands%2Doff'%20parents.

engage in risky and health-compromising behavior."[84] In an interview with the *New York Times,* the lead author, Dr. Laurence Steinberg stated the lowest rates of adolescent risk-taking occur in cultures that "encourage self-control from a very early age and structure adolescence in a way that doesn't give kids a lot of free, unstructured time to get into a lot of trouble."[85]

Improved connection between parents and adolescents even helps to buffer the effects of social exclusion and peer victimization. In a study of 166 Mexican-origin adolescents who were recruited from a ten year longitudinal study, researchers demonstrated specific changes in MRI brain scans when students faced a hostile school environment and found those students were more likely to later demonstrate social deviance.[86] However, connectedness with their family protected the adolescents from the neurobiological changes on MRI that correlated with the risk for social deviance.

Parents can help shape their adolescent's environment, affect the adolescent's tendency to participate in high-risk behaviors, and can help them in their decision-making and critical thinking skills. An adolescent's close relationship with his/her parent is protective despite other negative environmental factors. Research clearly shows that parents play a critical role in the healthy development of their adolescents. Health care professionals should acknowledge this, encourage parents to develop healthy relationships with their children, and support them in the parenting role. On a broader level, public health policies that currently treat adolescents as young adults in their abilities to problem solve and make decisions should be re-evaluated and revised based on this new research and will need continued revision as new information emerges.

Conclusion

In summary, evidence-based research on brain development should serve as an impetus for adults who interact with and care for adolescents to reconsider the health information provided to youth. The adolescent brain is under construction and can be adversely affected by high-risk behaviors and the teen's environmental milieu and experiences. The judgment center is immature, contributing to poor decision making. The dopamine pleasure system is in a state of rapid change, leading to higher potential for participation in high-risk behaviors and addictions. Oxytocin and vasopressin are present and ready to emotionally bond the teenager to any individual with whom he or she has

[84] Steinberg L, Icenogle G, Shulman EP, et al. Around the world, adolescence is a time of heightened sensation seeking and immature self-regulation. *Developmental Science.* 2017; Feb 01

[85] Damour L. Teenagers Do Dumb Things, but There Are Ways to Limit Recklessness. *The New York Times.* March 8, 2017.

[86] Schriber RA, Rogers CR, Ferrer E, et al. Do hostile school environments promote social deviance by shaping neural responses to social exclusion? J Res Adolesc. 2018; 28(1): 103–120.

sexual experiences, and heighten the consequences of the likely ending of the relationship.

Clearly, the adolescent years are a time of rapid brain development, a time of susceptibility. Those who care about the future of the adolescent must acknowledge that high-risk behaviors encountered during these vulnerable years can have lasting adverse consequences and should be avoided. The importance of parental supervision, coaching, and assistance in decision making cannot be overstated.