Review Article

Impact of Recreational Substance Use On the Adolescent Brain

Saba Brockhagen

Gilbert Christian High School, 3632 E Jasper Dr, Gilbert, AZ 85296, United States

ABSTRACT

Adolescence is a critical stage of brain development marked by rapid maturation of the prefrontal cortex and hippocampus, regions of the brain responsible for memory, decision-making, and emotional regulation. During this period of heightened neuroplasticity, the brain is especially sensitive to environmental influences, including the use of substances like alcohol, marijuana, and nicotine. This literature review examines how each of these substances disrupts brain development and impairs cognitive function. Alcohol use interferes with synaptic pruning and myelination in the prefrontal cortex, leading to poor impulse control and decision-making. It also causes hippocampal damage, including inflammation and volume loss, which impairs memory encoding and learning. Marijuana's active compound, THC, disrupts cannabinoid receptor function in the hippocampus, reducing neuroplasticity and leading to structural shrinkage and long-term memory deficits. Marijuana also thins the prefrontal cortex, delaying cognitive control development. Nicotine overstimulates acetylcholine receptors, hindering normal pruning and reducing gray matter volume, especially in the prefrontal cortex and hippocampus. This contributes to attention problems, increased impulsivity, and impaired working memory. Neuroimaging studies consistently show functional and structural differences in adolescents who use these substances compared to non-users. These changes may persist even after substance use stops, increasing the risk of long-term cognitive challenges and future substance use disorders. Early prevention and intervention efforts, such as school-based education and promotion of healthy habits, are essential to reduce adolescent substance use and protect brain development. This review highlights the urgent need for continued research and public health strategies to address the risks associated with early exposure to alcohol, marijuana, and nicotine.

Keywords: Adolescent; substance use; alcohol; marijuana; nicotine; brain

INTRODUCTION

Adolescence, defined as ages 11-19, is a critical time period of brain development, as the brain undergoes significant maturation of cognitive functions and neural structures. This is particularly true in the prefrontal cortex and hippocampus, which are regions of the brain essential for attention, memory, and decision making. The adolescent period is characterized by rapid synaptic

Corresponding author: Saba Brockhagen, E-mail: saba.brockhagen@gmail.com.

Received April 28, 2025**; Accepted** May 20, 2025
https://doi.org/10.70251/HYJR2348.336065

pruning and increased myelination that refine neural networks for more efficient cognitive processing (1). There is a heightened vulnerability to external influences during the adolescent developmental window, such as peer influence, social pressure, and risk-taking behaviors, which can contribute to higher risk of substance use (2).

Alcohol, marijuana, and nicotine are some of the most commonly used substances during adolescence, and the use of these not only disrupts brain development, but also has the potential to lead to long term cognitive and functional problems (3).

Previous research has shown that problematic use of alcohol, marijuana, and nicotine during adolescence can all contribute to deficits in cognitive performance through neurotoxic effects that disrupt brain development (4). In particular, use of these substances is linked to structural changes in critical brain regions such as the prefrontal cortex and hippocampus. Comparing adolescents who do and do not use substances can offer valuable insight on the long term consequences substance use can have on the adolescent brain.

Neuroimaging techniques such as magnetic resonance imaging (MRI) and functional MRI (fMRI) reveal differences between adolescents who do and do not use substances (5). MRI allows for the assessment of physical changes in the brain and fMRI provides insight into differences in brain activation patterns when engaged in cognitive tasks testing memory, attention, and decision making (5). Understanding these abnormalities is essential to recognizing the implications of adolescent substance use on long term mental health and behavioral outcomes, as well as increased risk of substance use disorder in the future.

The aim of this review is to evaluate how different substances, including alcohol, marijuana, and nicotine, affect brain structure and specific cognitive functions including attention, memory, and decision-making. By analyzing the impact substance abuse has on the adolescent brain function and structure, the broader implications of adolescent drug use will be revealed, which emphasizes how early substance exposure can result in academic challenges, problems with mental health, and increased likelihood of substance use disorder later in life. Early intervention and prevention of substance abuse is essential to protect adolescents during this critical developmental stage.

ALCOHOL'S IMPACT ON BRAIN STRUCTURE AND FUNCTION

Adolescence is a critical period of development and maturation in the brain, specifically in the prefrontal cortex and hippocampus, two regions of the brain that are strongly interconnected through neural pathways (6). The prefrontal cortex is the primary brain region responsible for decision-making and attention, and is especially vulnerable to external factors during this time of growth due to the active development taking place (7). Throughout adolescence, the brain undergoes synaptic pruning, or the elimination of inefficient neural connections, and myelination, which is a process that increases the speed of neural signaling to improve neural networks for efficient cognitive processing (1). Inefficient synaptic pruning and slower myelination in the prefrontal cortex negatively impacts the brain's ability to sustain attention and effectively regulate decision making, behavior and impulsivity (8). Alcohol use disrupts these developmental processes, leading to inefficient pruning, slower myelination, and cortical volume loss over time. For example, one study revealed that teens who drink alcohol heavily, defined as 3-4 drinks about 9.7 times per month, showed accelerated cortical volume loss in the lateral frontal compared to nondrinkers over a span of 4 years (9). Alcohol use in adolescence has also been found to lead to the retention of extra synapses in the prefrontal cortex (9). These retained synaptic connections may impair cognitive efficiency, particularly in self-regulation, decision-making abilities and impulse control, types of higher level skills that are important for adolescent development (3, 6). Moreover, neuroimaging studies have shown decreased activation in the prefrontal cortex during tasks that require cognitive control in adolescent drinkers compared to nondrinkers, suggesting that alcohol use impacts the prefrontal cortex's ability to allocate neural resources effectively (5).

In addition to disruption to higher level skills mediated by the prefrontal cortex, alcohol can also negatively impact learning (i.e.,encoding) and memory due to disruption to the hippocampus. Encoding is the first critical stage of memory formation and is a process by which information is made into a format that can be stored in the brain for later retrieval. Alcohol use in adolescence has been found to result in neuroinflammation and oxidative stress in the hippocampus which can contribute to neuronal loss (cell death) and reduced volume (10). This extensive structural damage may weaken the region's ability to encode and consolidate memories (11). Alcohol use may also weaken the neural connectivity between the hippocampus and prefrontal cortex, impacting the ability to integrate memory into future decision making.

Previous work has suggested that adolescents who engage in heavy drinking (3-4 drinks about 9.7 times per

month) over the course of about 4 years have decreased left hippocampal volume by 5.6% in comparison to adolescents who do not drink over the time frame based on structural MRI findings (9). This reduced left hippocampal volume loss was also associated with worse performance on memory and learning tasks (9). Another study revealed reduced activation in the hippocampus during memory encoding tasks in adolescents exposed to alcohol (12).

In sum, alcohol's impact on the adolescent brain is complex and multi-faceted. Alcohol use has significant implications on the functional integrity of the prefrontal cortex and hippocampal regions. Research also suggests that the changes that have been found to occur due to alcohol use in adolescence may be irreversible, even after stopping use (9).

MARIJUANAS IMPACT ON BRAIN FUNCTION AND STRUCTURE

Introduction of marijuana during the vulnerable period of adolescence may disrupt neurodevelopment, leading to structural and functional changes that can affect cognitive functions and behavior (13). The main psychoactive compound in marijuana is Tetrahydrocannabinol (THC) which interacts with Cannabinoid Receptor 1 (CB1) in the hippocampus (14). This interaction affects neurotransmitter balance and disrupts the hippocampus's role in memory formation and learning. Prior studies sought to understand the neural changes to the adolescent brain when using marijuana (15, 16). This neuroimaging research has shown that adolescent marijuana users have up to a 12% reduction in hippocampal volume compared to non-users, which correlates with poorer memory performance (17, 18). Memory problems are mainly due to the hippocampus' inability to process and store new information as it should (19). These deficits are not simply tied to acute intoxication, but indicate persistent impairments linked to structural changes in the hippocampus that may accumulate over time (20). Since the brain is still maturing and developing, specifically in the hippocampus, during adolescence, this may be why teens who begin use of marijuana at an earlier age experience more profound and lasting impacts (15).

Marijuana has also been found to affect the structure of the prefrontal cortex (16). Evidence shows that marijuana use in adolescence may reduce cortical thickness by about .25mm to .45mm in the prefrontal cortex, over the course of several years of heavy use (defined as around 1–2 times daily, most days of the week, for at least a year or more), potentially delaying maturation of this important region (21). The use of marijuana may negatively impact this pruning, hindering the prefrontal cortex's ability to strengthen the necessary neural pathways for developmental progression (17). Along with the structural changes, evidence has shown a decreased activation in the prefrontal cortex during tasks that require cognitive control in adolescents who use marijuana compared to those who do not (17). Together, these impacts may hinder the development of self-regulation skills, which may result in adolescents becoming more prone to poor decision making and impulsivity.

In summary, adolescent marijuana use alters the development of key brain regions especially involved in memory and self-regulation. These structural and functional disruptions may contribute to long-term cognitive challenges, particularly in learning, attention, and decision-making. Such impairments can interfere with an adolescents academic performance, emotional regulation, and can cause increased vulnerability to future substance use.

NICOTINES IMPACT ON BRAIN FUNCTION AND STRUCTURE

Nicotine exposure during the adolescent stage has also been shown to disrupt the vital developmental process taking place in the brain, leading to structural and functional impairments specifically in the prefrontal cortex and hippocampus, like those seen in alcohol and marijuana use (22). Nicotine activates acetylcholine receptors (nAChRs), which are abundant in the prefrontal cortex and critical for brain development (23). Overactivation of the nAChRs during adolescence inhibits normal synaptic pruning processes, resulting in a dysregulated neural network (24). This altered pruning and signaling may contribute to long-term changes in executive functioning and emotional regulation.

Previous research has sought to understand the impacts of nicotine on the adolescent brain. Revealed through neuroimaging techniques, such as functional and structural MRI scans, studies have revealed a significant difference in brain structure and function between the adolescents who do and do not consume nicotine (25). For example, adolescents who smoked at least 10 cigarettes per day for over two years showed reduced gray matter volume in the prefrontal cortex and hippocampus by about 8.3% compared to adolescents who did not smoke (25). These brain changes have been linked to impaired attention, memory, and cognitive flexibility, as demonstrated by

increased error rates in standard neuropsychological tests (25). Studies utilized cognitive tests such as the stroop test (testing selective attention and cognitive flexibility), Go/No-Go task (testing response inhibition and impulse control) and the spatial span test (testing working memory and spatial memory) to assess the impact of these structural changes (26, 27). It was found that adolescents who smoke made 30% more errors on the Go/No-Go task, suggesting impaired impulse control. Adolescents who use nicotine were also found to perform worse than the control group on tasks especially related to memory and attention (22). Nicotine has also been shown to lead to reductions in hippocampal cell density and dendritic complexity in adolescents.

These structural changes have been found to manifest in negative impacts on memory as well (28). In particular, adolescents who smoke have been found to perform worse on verbal and spatial memory tasks compared to their non-smoking peers. There is also evidence that these deficits persist years after cessation, potentially meaning permanent alterations in hippocampal function (22). Behavioral studies have also consistently demonstrated that these cognitive disruptions among adolescents using nicotine may lead to behaviors, such as increased impulsivity and risk-taking behaviors, that could result in heightened likelihood of continued substance use in the future (29).

In summary, nicotine use during adolescence disrupts key neurodevelopmental processes in the prefrontal cortex and hippocampus, leading to lasting structural, cognitive, and functional impairments. These disruptions contribute to deficits in attention, memory, and impulse control that can persist even after nicotine use stops. As a result, much like alcohol and marijuana use, adolescents may face long-term challenges in academic performance, emotional regulation, and an increased risk of continued substance dependence.

LIMITATIONS

There are limitations to this research paper. The literature review was not fully systematic, as not every available title was analyzed, which could have led to the exclusion of additional relevant studies.

Additionally, self reported substance use in adolescents research participants may be unreliable due to fear of legal or parental consequences, affecting the accuracy of numerical data presented. This could potentially understate the true impact substance use has on adolescent brain development.

PREVENTION AND INTERVENTION STRATEGIES

Preventing adolescent substance use is essential in order to avoid future substance use disorder development. Things like school based education programs can raise awareness of the long term effects of the most commonly used or exposed to substances among adolescents like alcohol, marijuana, and nicotine. Education on the importance of physical exercise may also reduce substance use, as staying active is a way to avoid situations exposed to substances.

CONCLUSION

In conclusion, adolescent substance use, particularly alcohol, marijuana, and nicotine consumption, can have substantial and lasting impacts on brain structure and everyday functioning. The substances specifically interfere with critical brain regions including the prefrontal cortex and hippocampus. This interference has been found to result in deficits in memory, attention, decision making, and impulse control. Neuroimaging highlights these structural and functional impacts. Adolescence being a vulnerable period of brain development, early prevention and intervention is necessary. With a large number of adolescents reportedly using alcohol, marijuana, or nicotine before graduating high school, prevention and education is essential. By addressing these issues early on, potential to reduce long term consequences is possible.

Future research is needed to better understand how substance use affects different stages of adolescent brain development, respectively. Tracking adolescents over time could provide deeper insights into the structural and functional brain changes associated with alcohol, marijuana and nicotine use. Additional studies could also further explore the effectiveness of prevention and intervention programs to determine what is most effective.

DECLARATION OF CONFLICT OF INTERESTS

The author states that there are no conflicts of interest regarding the publication of this article.

REFERENCES

1. Whitford TJ, Rennie CJ, Grieve SM, Clark CR, Gordon E, Williams LM. Brain maturation in adolescence: concurrent changes in neuroanatomy and neurophysiology. *Human brain mapping*. 2007 Mar; 28 (3): 228-37. https://

doi.org/10.1002/hbm.20273
2. Blakemore SJ, Mills KL. Is adolescence a sensitive period for sociocultural processing?. *Annual review of psychology.* 2014 Jan 3; 65 (1): 187-207. https://doi.org/10.1146/annurev-psych-010213-115202
3. Bava S, Tapert SF. Adolescent brain development and the risk for alcohol and other drug problems. *Neuropsychology review*. 2010 Dec; 20: 398-413. https://doi.org/10.1007/s11065-010-9146-6
4. Subbaraman MS, Kerr WC. Simultaneous versus concurrent use of alcohol and cannabis in the National Alcohol Survey. *Alcoholism: clinical and experimental research*. 2015 May; 39 (5): 872-9. https://doi.org/10.1111/acer.12698
5. Clark DB, Chung T, Pajtek S, Zhai Z, Long E, Hasler B. Neuroimaging methods for adolescent substance use disorder prevention science. *Prevention science*. 2013 Jun; 14 (3): 300-9. https://doi.org/10.1007/s11121-012-0323-0
6. Dahl RE. Adolescent brain development: a period of vulnerabilities and opportunities. Keynote address. *Annals of the new York Academy of Sciences*. 2004 Jun; 1021 (1): 1-22. https://doi.org/10.1196/annals.1308.001
7. Kolb B, Mychasiuk R, Muhammad A, Li Y, Frost DO, Gibb R. Experience and the developing prefrontal cortex. *Proceedings of the National Academy of Sciences*. 2012 Oct 16; 109 (supplement_2): 17186-93. https://doi.org/10.1073/pnas.1121251109
8. Fortier CB, Leritz EC, Salat DH, Lindemer E, Maksimovskiy AL, Shepel J, Williams V, Venne JR, Milberg WP, McGlinchey RE. Widespread effects of alcohol on white matter microstructure. *Alcoholism: Clinical and Experimental Research*. 2014 Dec; 38 (12): 2925-33. https://doi.org/10.1111/acer.12568
9. Squeglia LM, Tapert SF, Sullivan EV, Jacobus J, Meloy MJ, Rohlfing T, Pfefferbaum A. Brain development in heavy-drinking adolescents. *American journal of psychiatry.* 2015 Jun 1; 172 (6): 531-42. https://doi.org/10.1176/appi.ajp.2015.14101249
10. Guerri C, Pascual M. Mechanisms involved in the neurotoxic, cognitive, and neurobehavioral effects of alcohol consumption during adolescence. *Alcohol*. 2010 Jan 1; 44 (1): 15-26. https://doi.org/10.1176/appi.ajp.2015.14101249
11. Weafer J, Gallo DA, de Wit H. Effect of alcohol on encoding and consolidation of memory for alcohol-related images. *Alcoholism: clinical and experimental research*. 2016 Jul; 40 (7): 1540-7. https://doi.org/10.1111/acer.13103
12. De Bellis MD, Clark DB, Beers SR, Soloff PH, Boring AM, Hall J, Kersh A, Keshavan MS. Hippocampal volume in adolescent-onset alcohol use disorders. *American Journal of Psychiatry*. 2000 May 1; 157 (5): 737-44. https://doi.org/10.1176/appi.ajp.157.5.737
13. Hall W, Leung J, Lynskey M. The effects of cannabis use on the development of adolescents and young adults. *Annual Review of Developmental Psychology*. 2020 Dec 15; 2 (1): 461-83. https://doi.org/10.1146/annurev-devpsych-040320-084904
14. Banister SD, Arnold JC, Connor M, Glass M, McGregor IS. Dark classics in chemical neuroscience: Δ9-tetrahydrocannabinol. *ACS chemical neuroscience*. 2019 Jan 28; 10 (5): 2160-75. https://doi.org/10.1021/acschemneuro.8b00651
15. Subramaniam P, Yurgelun-Todd D. Neural and behavioral correlates associated with adolescent marijuana use. *Current addiction reports*. 2020 Dec; 7: 475-85. https://doi.org/10.1007/s40429-020-00335-7
16. Filbey FM, Aslan S, Calhoun VD, Spence JS, Damaraju E, Caprihan A, Segall J. Long-term effects of marijuana use on the brain. *Proceedings of the national academy of sciences*. 2014 Nov 25; 111 (47): 16913-8. https://doi.org/10.1073/pnas.1415297111
17. Price JS, McQueeny T, Shollenbarger S, Browning EL, Wieser J, Lisdahl KM. Effects of marijuana use on prefrontal and parietal volumes and cognition in emerging adults. *Psychopharmacology*. 2015 Aug; 232: 2939-50. https://doi.org/10.1007/s00213-015-3931-0
18. Chye Y, Suo C, Yücel M, Den Ouden L, Solowij N, Lorenzetti V. Cannabis-related hippocampal volumetric abnormalities specific to subregions in dependent users. *Psychopharmacology*. 2017 Jul; 234: 2149-57. https://doi.org/10.1007/s00213-017-4620-y
19. Wu M, Di Y, Diao Z, Yan C, Cheng Q, Huang H, Liu Y, Wei C, Zheng Q, Fan J, Han J. Acute cannabinoids impair association learning via selectively enhancing synaptic transmission in striatonigral neurons. *BMC biology.* 2022 May 13; 20 (1): 108. https://doi.org/10.1186/s12915-022-01307-1
20. Meier MH, Caspi A, R. Knodt A, Hall W, Ambler A, Harrington H, Hogan S, M. Houts R, Poulton R, Ramrakha S, Hariri AR. Long-term cannabis use and cognitive reserves and hippocampal volume in midlife. *American Journal of Psychiatry*. 2022 May 1; 179 (5): 362-74. https://doi.org/10.1176/appi.ajp.2021.21060664
21. Lopez-Larson MP, Bogorodzki P, Rogowska J, McGlade E, King JB, Terry J, Yurgelun-Todd D. Altered prefrontal and insular cortical thickness in adolescent marijuana users. *Behavioural brain research*. 2011 Jun 20; 220 (1): 164-72. https://doi.org/10.1016/j.bbr.2011.02.001
22. Holliday ED, Logue SF, Oliver C, Bangasser DA, Gould TJ. Stress and nicotine during adolescence disrupts adult hippocampal-dependent learning and alters stress reactivity. *Addiction biology*. 2020 May; 25 (3): e12769. https://doi.org/10.1111/adb.12769
23. Dwyer JB, Broide RS, Leslie FM. Nicotine and brain development. *Birth Defects Research Part C: Embryo Today: Reviews*. 2008 Mar; 84 (1): 30-44. https://doi.org/10.1002/bdrc.20118
24. Chung DW, Wills ZP, Fish KN, Lewis DA. Developmental

pruning of excitatory synaptic inputs to parvalbumin interneurons in monkey prefrontal cortex. *Proceedings of the National Academy of Sciences*. 2017 Jan 24; 114 (4): E629-37. https://doi.org/10.1073/pnas.1610077114

25. Yu D, Yuan K, Zhang B, Liu J, Dong M, Jin C, Luo L, Zhai J, Zhao L, Zhao Y, Gu Y. White matter integrity in young smokers: a tract-based spatial statistics study. *Addiction biology*. 2016 May; 21 (3): 679-87. https://doi.org/10.1111/adb.12237
26. Cerezo García M, Martín Plasencia P, Aladro Benito Y. Alteration profile of executive functions in multiple sclerosis. *Acta Neurologica Scandinavica*. 2015 May; 131 (5): 313-20. https://doi.org/10.1111/ane.12345
27. Rangel-Pacheco A, Lew BJ, Schantell MD, Frenzel MR, Eastman JA, Wiesman AI, Wilson TW. Altered fronto-occipital connectivity during visual selective attention in regular cannabis users. *Psychopharmacology*. 2021 May; 238: 1351-61. https://doi.org/10.1007/s00213-020-05717-3
28. Shariq M, Sahasrabuddhe V, Krishna S, Radha S, Nruthyathi N, Bellampalli R, Dwivedi A, Cheramangalam R, Reizis B, Hébert J, Ghosh HS. Adult neural stem cells have latent inflammatory potential that is kept suppressed by Tcf4 to facilitate adult neurogenesis. *Science Advances*. 2021 May 21; 7 (21): eabf5606. https://doi.org/10.1126/sciadv.abf5606
29. Hanlon CA, Owens MM, Joseph JE, Zhu X, George MS, Brady KT, Hartwell KJ. Lower subcortical gray matter volume in both younger smokers and established smokers relative to non-smokers. *Addiction biology*. 2016 Jan; 21 (1): 185-95. https://doi.org/10.1111/adb.12171