Concussions and the Developing Adolescent Brain

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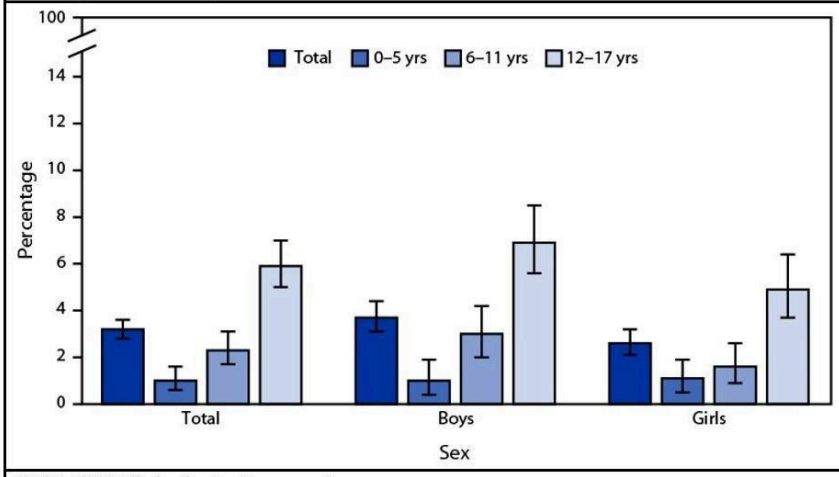
Abstract

Concussions are mild traumatic brain injuries that interfere with normal brain function. According to national data, the prevalence of concussion among adolescents increased by 5.1% between 2016 and 2020. Adolescence is characterized by physiological and social changes. During this period, the brain undergoes growth and reorganization in regions of the brain responsible for cognition, emotional regulation, and behavior; at the same time, adolescents are increasingly taking part in organized sports and experiencing evolving social behaviors. Understanding these changes is important because they provide a biological basis for examining how concussion can affect cognitive function and emotional regulation. This makes the brain particularly susceptible to the short- and long-term effects of brain injury. A review of the literature that included systematic reviews, meta-analyses, and biomedical and social behavioral studies examined the effects of concussion on the developing adolescent brain, emotional regulation in adolescents, and the relationship between cognitive function and emotional regulation. Results suggest that because the adolescent brain is still developing cognitive abilities essential for learning, decision-making, and daily functioning, concussions can disrupt academic and social activities as well as ongoing cognitive development and cognitive function and emotional regulation should be viewed as interconnected consequences of concussion rather than as separate outcomes. The findings suggest that executive function and emotional regulation are interconnected. Given the increasing prevalence of concussion among adolescents and its potential impact on neurodevelopment, continued empirical research on brain function and psychosocial behavior is needed to address this important public health concern and inform evidence-based standards of care for assessment, treatment, and recovery.

Introduction

A concussion is a mild traumatic brain injury (mTBI) that temporarily disrupts normal brain function (Plummer & Abramson, 2024). Concussions can result from a direct blow to the head or a strong impact to the body that causes the brain to move rapidly within the skull. Common causes include falls, motor vehicle accidents, sports-related injuries, and physical violence (Haarbauer-Krupa et al., 2021). Symptoms vary in type and severity and can be classified into three main categories: physical, cognitive, and emotional. Physical symptoms include headaches, dizziness, and blurred vision, while cognitive symptoms may involve difficulties with memory, attention, concentration, and processing speed. Emotional symptoms can include anxiety, irritability, mood changes, and depression (Lima Santos et al., 2023). These symptoms can interfere with brain development, academic performance, behavior, and overall quality of life.

Figure 1. Percentage* of Children and Adolescents Aged ≤17 Years Who Had Ever Received a Diagnosis of Concussion or Brain Injury, by Sex and Age Group – National Health Interview Survey, § United States, 2022



*With 95% Cis indicated by error bars.
Source: National Center for Health Statistics, National Health Interview Survey, 2022.
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Concussions represent an increasingly important public health issue among adolescents, especially those involved in sports, with lifetime diagnosed concussion rates among U.S. middle and high school students rising from 19.5% in 2016 to 24.6% in 2020 ((Black & Zablotsky, 2021); Veliz et al., 2021). The incidence of sports-related concussions generally increases throughout childhood and peaks during adolescence, when participation in organized athletics becomes more common. According to a 2022 report from the Centers for Disease Control and Prevention (QuickStats, 2022), concussion or brain injury diagnoses among children and adolescents generally increased with age (0-≤ 17yrs). Figure 1 also shows that these diagnoses were more common among boys than girls, although the difference was smaller among children aged five and younger.

A recent systematic review and meta-analysis examined sports-related concussion across 28 sports and highlighted the differences in risk between athletic activities (Ingram et al, 2025). Collision sports, including rugby, tackle football, and ice hockey, were associated with a greater risk of concussion than sports involving less physical contact. Together, the 2023 CDC report and the findings of Ingram et al., 2025 demonstrate that due to the high prevalence of adolescents in sports they are significantly more prone to concussions. Due to the nature that their brains are still developing, short- and long-term studies of the effects of concussion on the adolescent brain are needed to understand the consequences of concussion, specifically in adolescents, on academic performance, behavior, family relationships, and continued participation in sports.

Adolescence is a stage of human development that encompasses the transition between childhood and adulthood from 11 through 21 years of age. It is a critical period of brain development characterized by continued growth and reorganization of brain regions responsible for cognition, emotional regulation, and behavior. Two important areas involved in these processes are the prefrontal cortex and the limbic system. The prefrontal cortex supports

higher-level cognitive functions, including attention, planning, decision-making, impulse control, and emotional regulation. The limbic system plays an important role in emotion, learning, and memory. Within this system, the amygdala processes emotionally significant stimuli and contributes to emotional responses, while the hippocampus supports learning and the formation and retrieval of memories.

These brain regions work together to coordinate thinking, emotions, and behavior. During development, the brain is uniquely sensitive to external cues, allowing for a highly adaptable period for neuroplasticity and learning. Once the developmental period ends, the brain is less sensitive to these cues and the changes that occurred during development are more “locked” and less adaptable. A concussion during the adolescent developmental period could leave long lasting alterations in the brain that wouldn’t be observed in adults (Burma et al., 2024). A concussion can disrupt normal brain functioning and potentially affect processes that are still developing, including attention, memory, decision-making, and emotional control (Lima Santos et al., 2023). Understanding how these effects interact is essential because difficulties with cognition and emotional regulation may influence one another, potentially affecting adolescents' daily functioning and recovery.

This narrative review examines research on the effects of concussion on adolescent brain functioning, with particular attention to the relationship between cognitive function and emotional regulation. It seeks to answer the following research question: How does a sports-related concussion affect the relationship between cognitive function and emotional regulation in adolescents? The review focuses on how concussions may affect attention, memory, processing speed, executive function, and emotional regulation during this critical stage of development. It also explores how changes in cognitive and emotional functioning may be interconnected and how these effects can influence adolescents' behavior, academic performance, and overall quality of life.

Concussions and the Developing Adolescent Brain

Concussion and Brain Function

A concussion is a mild traumatic brain injury that temporarily disrupts normal brain function. It can occur after a direct blow to the head or from a force that causes the head and brain to move rapidly. Concussions can affect several areas of brain function, including thinking, memory, attention, and emotional regulation (Lumba-Brown et al., 2018). Adolescents may experience different effects from concussion because their brains are still developing, meaning that an injury can affect brain systems that have not yet fully matured.

The effects of a concussion are not always visible on a traditional brain scan, such as a computed tomography (CT) scan or structural magnetic resonance imaging (MRI). These scans primarily show the brain's physical structure and help identify visible abnormalities which is important to rule out severe damage, but a concussion can disrupt how brain cells communicate and how different parts of the brain function without causing obvious structural damage (Giza & Hovda, 2014). When the brain is injured, mechanical forces can stretch and disrupt neurons,

while changes in brain chemistry and metabolism can interfere with normal communication between brain cells (Giza & Hovda, 2014). These changes help explain why an adolescent may experience cognitive or emotional symptoms even when a CT scan or structural MRI does not show visible damage.

Adolescent Brain Development and Vulnerability

Adolescence is a particularly important period for studying concussion because the brain is still developing and the observed acute effects differ from those of children and adults (Podolak, et al. 2021). Brain development during adolescence involves changes in the structure, organization, and connections between different brain regions. One of the most important areas still developing is the prefrontal cortex, which is involved in attention, planning, decision-making, impulse control, and emotional regulation (Blakemore & Choudhury, 2006). At the same time, areas of the limbic system involved in emotion and memory, including the amygdala and hippocampus, continue to develop (Casey et al., 2008). As these areas develop, the connections between them also become refined and more organized. The prefrontal cortex helps regulate emotional responses from areas such as the amygdala, allowing adolescents to gradually improve their ability to control emotions and make decisions (Luciana, 2013). This development does not happen all at once. Instead, the brain continues to mature throughout adolescence and into early adulthood. The progression of this development is often categorized into critical periods, or limited windows of time where a certain brain region is maximally sensitive to specific external inputs. When a critical period ends, the neuroplasticity of the region returns to its baseline, reducing the ease of plasticity changes.

Altering these critical periods may be why adolescents are uniquely vulnerable to the effects of concussions. An injury during this period can disrupt communication between brain regions that are still developing. Differences in the activity of pre-frontal cortex networks in nonconcussed and concussed adolescents were observed using functional MRI (fMRI) and showed abnormal communication patterns in brain networks of concussed adolescents involved with processing daydreaming, executive function, and attention (Borich et al., 2015). This is especially important for the prefrontal cortex because many of the abilities it supports, such as attention, decision-making, and emotional regulation, are still developing during adolescence. Disruption to developing networks involved in memory and emotional processing may contribute to the cognitive and emotional symptoms that can occur after concussion (Borich et al., 2015). The developing brain may also respond differently to injury than a fully mature brain, making age an important factor when studying concussion and recovery. Therefore, the effects of concussion in adolescents cannot be understood only by looking at the injury itself; researchers must also consider the stage of brain development when the injury occurs (Moser, et al., 2018). Studying adolescents can help researchers understand how concussion may interfere with brain systems that are still developing and how these disruptions may affect cognitive and emotional functioning.

Functional Changes After Concussion

Researchers have found evidence that concussion can produce measurable changes in how the adolescent brain functions. One method used to study these changes is electroencephalography (EEG), which records the brain's electrical activity through sensors placed on the scalp. EEG allows researchers to examine patterns of electrical brain activity and how the brain responds to different types of information. A study examining neurophysiological markers of concussions found measurable changes in brain activity related to cognitive processing and recovery following concussion (Ruiter et al., 2020). These findings provide evidence that concussion can affect brain function even when structural damage is not visible on a traditional CT scan or structural MRI. Researchers have also used functional magnetic resonance imaging (fMRI) to study changes in brain activity and communication between brain regions. Unlike a structural MRI, which produces images of the brain's physical structure, fMRI measures changes in blood flow associated with brain activity. Changes in functional brain networks in adolescents following sports-related concussion (Virji-Babul et al., 2015). These networks involve communication between multiple brain regions, meaning that a concussion may affect not only individual areas of the brain but also the connections between them. This is important because cognitive abilities and emotional regulation depend on several brain regions working together.

Research using EEG, fMRI, and other neurophysiological measures has provided evidence that functional changes can be detected after concussion, although findings have not been completely consistent across studies. A systematic review of adolescent sport-related concussion found that most of the studies reviewed reported differences in brain activity between adolescents with concussion and healthy comparison groups (Burma et al., 2024). However, the studies differed in their methods, measurements, and findings, making it difficult to identify one consistent pattern of brain changes. Differences in the timing of testing, severity of injury, and individual characteristics may contribute to these inconsistent results. However, it is not surprising that the overall evidence suggests that concussion can affect the developing adolescent brain at a functional level. Despite the heterogeneity of the studies, the results support a biological basis for how concussion can affect both cognitive function and emotional regulation.

Cognitive Effects of Concussion in Adolescents

A concussion, or mild traumatic brain injury (mTBI), can affect several cognitive functions that are especially important during adolescence. Cognitive function refers to the brain’s ability to carry out mental processes such as thinking, learning, remembering, and making decisions. Important parts of cognitive function include memory, attention, processing speed, and executive function (Harvey, 2019). Memory allows a person to store and retrieve information, while attention controls how much sensory information the brain processes. Processing speed refers to how quickly the brain can understand information and respond accurately. Executive function involves higher-level skills such as planning, problem-solving, decision-making, organization, self-control, and reasoning. These abilities are particularly important during adolescence because the brain is still developing and adolescents are also using these cognitive abilities constantly as they manage increasing academic demands, sports, social

interactions, and greater independence. As a result, disruption to these functions following a concussion can interfere with important parts of an adolescent's daily life and development.

Effects on Attention, Executive Function, and Working Memory

Research shows that concussions can temporarily interfere with these cognitive processes in adolescents. The executive function of 40 fifteen-year-old adolescents studied over a period of two months involved 20 participants who had experienced a mild traumatic brain injury, while the other 20 served as a control group. Researchers tested the participants' attention and executive function at one week, two weeks, one month, and two months after the injury. The concussed group had difficulty focusing and ignoring irrelevant or conflicting information even two months after the injury, while the participants who had recovered did not. Difficulty controlling attention may make it harder for an adolescent to follow a lesson, complete assignments, or switch between different tasks at school. Therefore, even when an adolescent appears physically recovered, a concussion may continue to affect cognitive abilities that are still developing (Howell et al., 2013).

The effects of concussion can extend beyond cognitive testing and affect an adolescent's ability to learn in school. Learning requires attention, organization, processing speed, and the ability to connect new information with information already stored in long-term memory. Because concussions can interfere with these functions, adolescents may have difficulty completing normal academic tasks after an injury. Research on high school and college students found that concussion-related symptoms such as difficulty concentrating and feeling slowed down can negatively affect academic well-being and lead to frustration and academic setbacks (Holmes et al., 2020). Students who have not fully recovered may also spend more time completing homework, while symptoms such as headaches can interfere with learning. This can be particularly significant for adolescents because high school is a period of increasing academic expectations and preparation for future education. For this reason, students recovering from concussion may need temporary academic accommodations and support while their cognitive functions recover (Holmes, 2020; Pei et al., 2023).

Working memory can also be affected by concussions during adolescence. Working memory allows a person to temporarily hold and use information while completing complex tasks such as learning and reasoning (Quentin, 2019). Students use working memory when following multiple-step instructions, solving problems, reading, taking notes, and connecting new information to what they already know. Manelis et al. (2024) studied adolescents recovering from head injuries and found that concussed adolescents were slower and less accurate during the subacute recovery period than they were six months after the concussion. The study also found that working memory depends heavily on attention and focus, which can be disrupted after a concussion. These findings demonstrate how a concussion can interfere with cognitive processes that adolescents rely on every day while their brains are still developing. Difficulties with working memory may make normal academic tasks more challenging during the recovery period.

Evidence of Cognitive Impairment After Concussion

Evidence from a larger group of studies also supports a connection between sports-related concussion and impaired cognitive function in adolescents. A systematic review of 47 studies and a meta-analysis of 31 studies examining cognitive function after sports-related concussion revealed impairments in areas such as attention, working memory, processing speed, reaction time, and executive function (Hou et al. (2023). Compared with baseline performance in cognitive function, concussed adolescents performed worse in reaction time, visual memory, verbal memory, and processing speed seven days after injury. Some measures improved between seven and fourteen days, showing that many cognitive effects decrease as the brain recovers. However, the review found that some impairments, particularly visual memory, could still be observed one to six months after the injury. The researchers also found that adolescents with a history of multiple concussions generally performed worse than those without a concussion history. Although these findings are not unique to adolescents and can occur in all age groups (McCrory, 2004), they are significant because adolescents may experience repeated concussions while participating in sports during a period when their cognitive abilities are still developing. Repeated disruption of attention, memory, and processing speed may therefore have greater implications for an adolescent who is still developing these skills.

Overall, research demonstrates that concussions can affect several areas of cognitive function in adolescents, including memory, attention, processing speed, and executive function. These effects are often strongest shortly after the injury and tend to improve over time, although research is less consistent about whether some cognitive effects persist long-term. Because of the brain's ongoing development, the effects of a concussion can interfere not only with an adolescent's current academic and social activities but also with important cognitive processes that are still developing. Understanding these effects is therefore important for determining how adolescents can be properly supported while recovering and when they can safely return to school, sports, and other activities.

Emotional Regulation and Concussion in Adolescents

Emotional Regulation and the Adolescent Brain

Emotion is a complex reaction that involves experiential, behavioral, and physiological responses to personally significant events. Emotional regulation refers to the brain's ability to control these responses and adjust their intensity or duration. This process requires communication between several areas of the brain, including the limbic system and the prefrontal cortex. A concussion can temporarily interfere with normal brain functioning, which may affect the neural pathways involved in emotional regulation. Although most adolescents recover from a concussion within approximately four weeks, about 21–35% continue to experience symptoms beyond the expected recovery period, which can interfere with social activities, academic performance, and emotional functioning (Lima Santos et al., 2023).

The limbic system plays an important role in processing emotions, memory, behavior, and information from the environment. When an individual encounters a stimulus, the thalamus receives the information and sends signals to the amygdala, which evaluates the emotional significance of the stimulus based on previous experiences. The amygdala can then activate the hypothalamus, which helps produce the physiological response associated with the emotion. The prefrontal cortex works with these regions to regulate the response by supporting higher-order functions such as planning, decision-making, and social behavior. Together, these brain regions allow an individual to recognize an emotional situation and determine an appropriate behavioral response.

Adolescent Development and Emotional Regulation

External and internal environmental stimuli, under the influence of hormonal changes experienced in adolescence, promote brain development. This interaction is depicted in Figure 2. Hormonal changes contribute to ongoing brain maturation, by influencing the structural development of neural regions involved in cognitive, emotional, and behavioral functioning (Curtis et al., 2024).

Experiential learning and repeated activities support the reorganization of neural networks and increase myelinization of frequently used neural networks. During this period, the prefrontal cortex undergoes changes that support increasingly complex cognitive abilities, including decision-making, social behavior, and emotional regulation. At the same time, the limbic regions involved in emotional processing develop more rapidly than the prefrontal cortex. This difference in developmental timing may contribute to the stronger and sometimes less controlled emotional responses commonly seen during adolescence (Casey, 2008). Because the adolescent brain is still developing, a concussion may interfere with the communication between brain regions that are responsible for controlling emotional responses. Brain plasticity allows the developing brain to adapt to changes and learn new skills, but it may also leave these developing neural pathways vulnerable to disruption following a head injury.

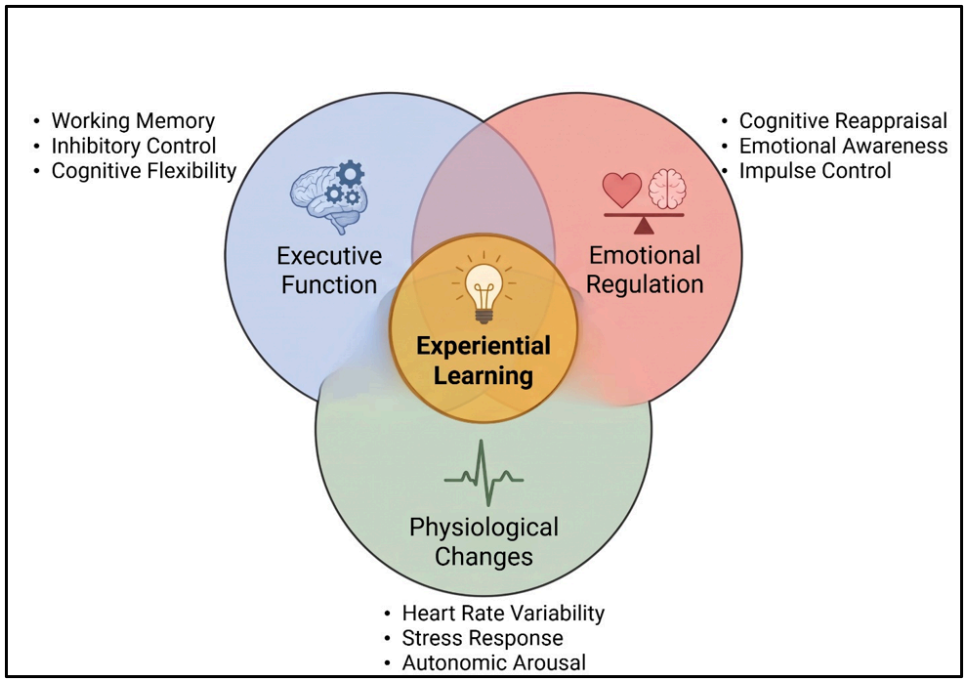


Figure 2. Tripartite integration of physiological changes, executive function, and emotional regulation in experiential learning. Conceptual Venn diagram illustrating the convergence of three foundational domains underlying experiential learning. Physiological Changes (green, bottom) encompass stress responses, autonomic arousal, and heart rate variability that signal and modulate body states during an experience. Executive Function (blue, top-left) provides top-down cognitive control through working memory, inhibitory control, and cognitive flexibility. Emotional Regulation (red, top-right) modulates subjective experience via cognitive reappraisal, emotion awareness, and impulse control. The central three-way intersection, Experiential Learning, (lightbulb) denotes the synergistic synthesis of internal physiological feedback, cognitive processing, and affective modulation required to acquire, reflect upon, and integrate a lived experience. Created in https://BioRender.com

Emotional Changes Following Concussion

Emotional dysregulation following a concussion can occur for several reasons. A concussion may disrupt neural pathways involved in emotional processing, making it more difficult for the brain to control an emotional response. However, emotional changes may also be influenced by the circumstances surrounding the injury. For adolescent athletes, being unable to participate in sports can lead to frustration, isolation, or changes in daily routines. Preexisting emotional or developmental difficulties may also contribute to symptoms after a concussion. Therefore, emotional changes following a concussion cannot always be attributed to the injury alone. Neuroimaging research may help researchers identify changes in brain activity or structure associated with concussion and distinguish these changes from normal patterns of adolescent brain development.

One area of concern is the development or worsening of anxiety and depression following a concussion. The World Health Organization estimates that anxiety disorders affect approximately 4.1% of adolescents ages 10–14 and 5.3% of adolescents ages 15–19, while

depression affects approximately 1.3% of those ages 10–14 and 3.4% of those ages 15–19. Anxiety and depression can involve symptoms such as irritability, changes in mood, fatigue, difficulty concentrating, and difficulty making decisions, which can overlap with common concussion symptoms. This overlap makes it difficult to determine whether emotional symptoms are caused directly by a concussion, normal adolescent development, or other factors. Consideration of the psychosocial effects of the inability to participate in sport-related activities such as practice and tournaments provides an alternative reason for symptoms of depression in concussed adolescents. Isolation, loneliness, and lack of physical activity have been reported as factors leading to depression in adolescents (Recchia, et al., 2023). Results of a systematic review focused on the relationship between sport participation and psychological and/or social outcomes in 5–17-year-olds aligned with better mental health, including reduced depression. Data also supported the positive role of sports participation in improving health-related quality of life in both children and adolescents (Callahan, 2022; Master et al., 2024; Voormolen et al., 2019; Wade et al., 2019).

Research on Mood and Emotional Symptoms

Fish et al. (2023) examined this issue by comparing anxiety and depression symptoms in 111 adolescents who had experienced a concussion with 171 adolescents who had not. The researchers used the Patient-Reported Outcomes Measurement Information System (PROMIS) Anxiety and Depressive Symptoms pediatric questionnaire, a standardized tool developed by the National Institutes of Health to evaluate physical, mental, and social health in children and adolescents. A greater proportion of concussed participants had depression scores above the normal range compared with nonconcussed participants. However, when participants with a previous history of anxiety or depression were excluded, the difference in anxiety and depression scores between the two groups was not statistically significant. These findings suggest that a concussion may be associated with increased emotional symptoms in some adolescents, but the relationship is complex and may be influenced by preexisting mental health conditions.

Review of 12 studies involving 3761 participants to investigate the association of a medical history of mental health problems and the clinical outcome from sport-related concussion. Nine of the 12 studies showed that the participants with a medical history of mental health problems were at greater risk of having prolonged symptoms or worse outcomes. Some factors that may be relevant to clinical outcomes of mild brain trauma injury include genetic and family-environmental risk factors for mood and anxiety disorders, greater life stressors, less effective coping skills, less emotional awareness, and changing or decreasing daily activities because of physical illness or injury (Iverson et al., 2020; Iverson et al., 2017)

The effects of concussion on mood can also change over time. A longitudinal study of 2,160 high school athletes examined mood following sport-related concussion using the Patient Health Questionnaire-9 (PHQ-9), a nine-item questionnaire used to measure symptoms of depression. Concussed athletes completed the questionnaire at several points after injury, including within 24–72 hours, seven days, at return to sport, and three, six, and twelve months after the concussion. The study found that mood deteriorated slightly after the injury but generally returned to baseline by the time athletes returned to sports and remained at similar

levels through at least twelve months. The findings suggest that although emotional symptoms can occur after a sport-related concussion, they do not necessarily result in long-term changes in depressed mood for most high school athletes (Hammer et al., 2021).

Overall, concussion can temporarily affect the brain systems responsible for emotional regulation, which may lead to changes in mood, anxiety, behavior, and social functioning. Adolescents may be particularly important to study because their prefrontal cortex and other neural systems involved in emotional control are still developing. At the same time, research indicates that emotional symptoms following concussion often improve as the brain recovers. Understanding the interaction between concussion, adolescent brain development, and emotional regulation is therefore important for determining which symptoms are directly related to the injury and which may be influenced by normal development or other factors.

The Relationship Between Cognitive Function and Emotional Regulation

Interaction Between Cognition and Emotion

Cognitive function and emotional regulation are closely connected because the brain systems responsible for thinking, attention, memory, and decision-making also interact with the systems responsible for processing and regulating emotions. This connection is especially important during adolescence, when the brain is still developing and reorganizing the neural networks that control these functions. Research on the interaction between the prefrontal cortex and the limbic system shows that cognition and emotion do not operate independently. Instead, emotional regulation involves neural networks associated with executive function, working memory, and attention (Okon-Singer et al., 2015). Because these cognitive abilities are also affected by concussion, an injury can potentially disrupt both cognitive and emotional functioning at the same time.

The prefrontal cortex and limbic system are important parts of this connection. The prefrontal cortex supports attention, planning, working memory, decision-making, and the expression of appropriate emotions and social behaviors. The limbic system includes structures such as the amygdala and hippocampus that are involved in emotional processing and memory. When an individual experiences an emotionally significant event, the amygdala helps evaluate the emotional importance of the stimulus, while other cortical regions provide information about the body's internal state, and the hippocampus provides information about the time and place associated with the experience (Etkin et al., 2015). The prefrontal cortex then helps regulate the emotional response and determine an appropriate behavior. As shown in Figure 3, these systems must communicate effectively for an adolescent to manage emotions while also paying attention, remembering information, and making decisions. Injury or disruption to these networks following a concussion may therefore affect both emotional regulation and cognitive function.

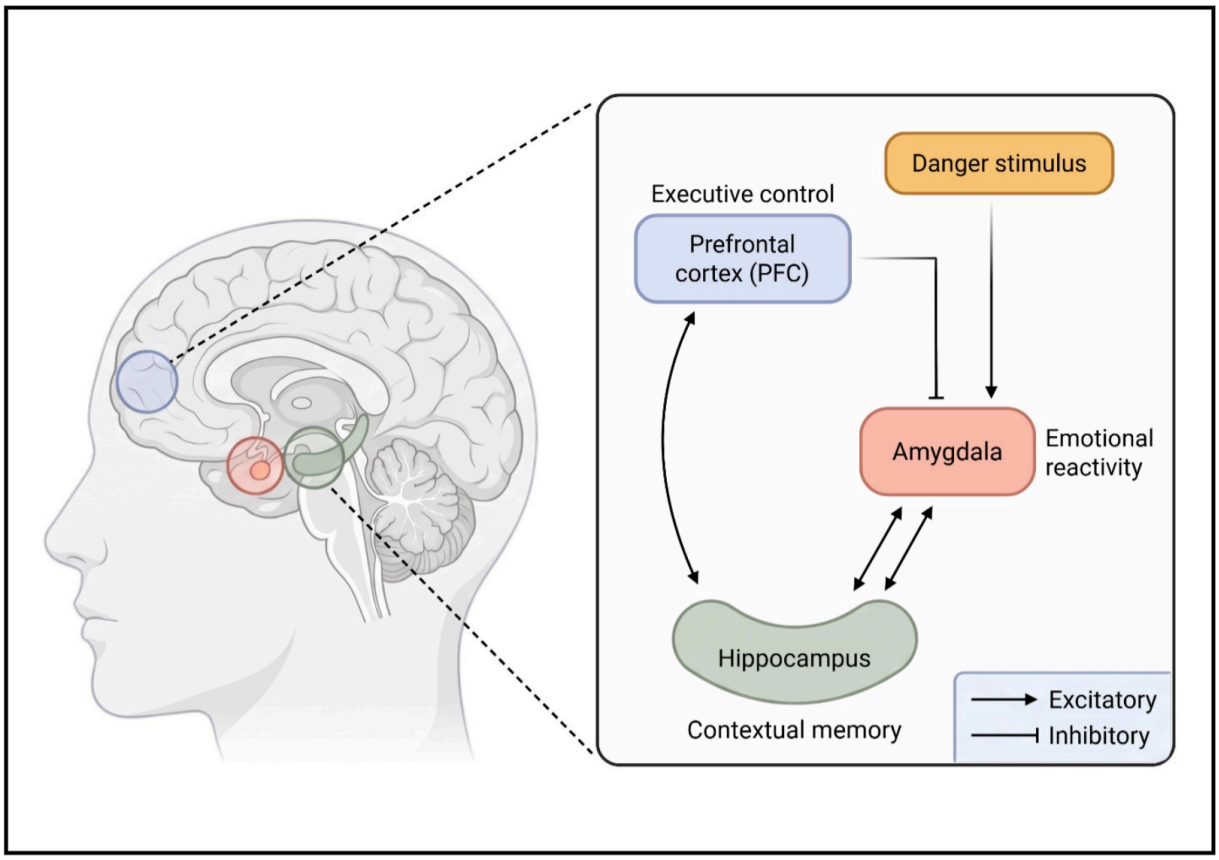


Figure 3. Prefrontal-limbic circuit mediating executive control and emotional reactivity. Schematic representation of top-down emotional regulation and contextual modulation during threat processing. (Left) Medial sagittal anatomical locator highlighting the prefrontal cortex (PFC, blue), amygdala (red), and hippocampus (green). (Right) Functional circuit mechanism. An incoming danger stimulus directly activates the amygdala to elicit emotional reactivity. The prefrontal cortex exerts top- down inhibitory control (flat-end connector) over the amygdala to dampen reactivity. The hippocampus engages in reciprocal bidirectional signaling with both the amygdala and PFC, providing contextual memory to guide emotional appraisal and executive regulation. Created in https://BioRender.com.

Cognitive Difficulties and Emotional Effects

The relationship between cognition and emotion can also be seen in the way cognitive difficulties following concussion may contribute to emotional changes. Adolescents experiencing problems with attention, memory, or processing speed may have greater difficulty completing schoolwork, participating in sports, or maintaining their normal routines. These difficulties can create frustration and affect an adolescent's overall quality of life. Howell et al. (2019) examined the relationship between concussion symptoms and quality of life in children and adolescents. The researchers found that participants who experienced more severe concussion symptoms during the first month after injury reported lower quality of life 30 days after the concussion,

regardless of age. This finding demonstrates that the effects of concussion are not limited to performance on cognitive tests. When cognitive and physical symptoms make everyday activities more difficult, they may also affect an adolescent's emotional well-being and ability to participate in normal activities.

Emotional Difficulties and Cognitive Effects

The connection can also work in the opposite direction, with emotional difficulties affecting cognitive performance. Emotional processing and cognitive control rely on overlapping brain systems, meaning that anxiety, depression, or low mood can interfere with attention and executive function. Chiu et al. (2016) found that anxiety can impair executive function and, as a result, interfere with learning. This is particularly relevant during adolescence because students rely heavily on attention, working memory, and executive function to learn new information and complete increasingly complex academic tasks. When an adolescent is experiencing anxiety or low mood after a concussion, the emotional symptoms may make it more difficult to concentrate, remember information, or control attention. In this way, emotional symptoms may add to the cognitive difficulties already caused by the concussion.

Research involving a large group of adolescents provides additional evidence of this relationship. Roberts et al. (2023) examined data from the Adolescent Brain Cognitive Development cohort, which included 11,876 adolescents. The researchers found that adolescents experiencing moderate to severe anxiety or low mood also demonstrated difficulties with attention regulation. These findings are important when considering adolescents recovering from concussion because attention is already a cognitive function that can be disrupted by a head injury. Emotional symptoms may therefore make existing attention difficulties more noticeable or more difficult to manage. An adolescent who is struggling emotionally may have greater difficulty focusing in class, completing assignments, or maintaining attention during everyday activities.

Brain-Based Evidence of the Connection

Brain imaging research also provides evidence that emotional symptoms can be associated with differences in the brain systems responsible for cognitive control following concussion. Functional magnetic resonance imaging (fMRI) is a technique that measures changes in blood flow to identify areas of the brain that are active during specific tasks. Ho et al. (2018) used fMRI to examine the relationship between depressive symptoms and inhibitory control in adolescents who had experienced a concussion. The participants completed the Children's Depression Inventory and were separated into groups based on their level of depressive symptoms. They then completed an Emotional Go/No-Go task involving angry and neutral facial expressions while undergoing fMRI. Adolescents with elevated depressive symptoms showed activity in regions involved in facial and cognitive processing, but they did not show the same activation in frontal regions associated with inhibitory control as adolescents with average depressive symptoms (Ho et al., 2018). This suggests that emotional symptoms

following concussion may be associated with differences in the brain networks used to control behavior and respond appropriately to emotional information.

Bidirectional Effects and Adolescent Development

These findings demonstrate that the relationship between cognitive function and emotional regulation is not simply a one-way process. Cognitive difficulties can contribute to emotional problems, while emotional difficulties can further interfere with cognitive abilities. For example, an adolescent who has difficulty with working memory after a concussion may struggle to complete an assignment. This difficulty could lead to frustration or anxiety, which may then make it harder to concentrate and complete future assignments. Similarly, an adolescent experiencing anxiety may have difficulty maintaining attention in class, which can make learning more difficult and increase frustration. The two sets of symptoms can therefore reinforce each other rather than occurring independently.

This interaction is particularly important during adolescence because the adolescent brain is undergoing significant structural and functional changes. Neural networks are being reorganized while adolescents are simultaneously adapting to changing academic, social, and emotional demands. This developmental plasticity allows the brain to adapt to new experiences and develop increasingly complex abilities, but it may also make the developing brain vulnerable to disruption from a mild traumatic brain injury. At the same time, this plasticity may contribute to the brain's ability to recover following injury. Christensen et al. (2021) emphasize that understanding concussion in adolescents requires considering the interaction between the physical effects of the injury, changes in neural and biological processes, cognitive functioning, psychosocial factors, and decision-making during adolescence.

Overall, cognitive function and emotional regulation should be viewed as interconnected consequences of concussion rather than as separate outcomes. The same developing neural networks that allow adolescents to control attention, working memory, and decision-making also contribute to their ability to regulate emotions and behavior. A concussion can disrupt these systems, while emotional symptoms can further interfere with cognitive performance. The evidence therefore supports a bidirectional relationship in which cognitive and emotional symptoms can influence one another. Understanding this relationship is especially important in adolescents because they are still developing the cognitive and emotional skills needed for academic success, social relationships, and independent decision-making. Examining both sides of this relationship provides a more complete understanding of how concussion can affect the developing adolescent brain.

Conclusion

The research reviewed in this paper demonstrates that concussion can affect multiple aspects of adolescent brain function, including cognition, emotional regulation, and the

interaction between the two. Because the adolescent brain is still developing, a concussion may temporarily disrupt processes involved in attention, working memory, processing speed, executive control, and emotional regulation. Although many adolescents recover within several weeks, research suggests that some cognitive and emotional effects may persist beyond clinical recovery.

Cognitive effects are among the most consistently documented consequences of concussion in adolescents. Studies have reported difficulties with attention, working memory, information-processing speed, and executive functioning, with the greatest impairments generally occurring shortly after injury (Manelis et al., 2024). Slower reaction times and reduced processing speed are particularly common during the early stages of recovery and generally improve over time. However, some deficits may remain detectable for months after injury. A meta-analysis by Hou et al. (2023) found that disturbances in executive functioning can persist for one to six months following sport-related concussion in some adolescents. Neuroimaging research has also identified changes in activation within frontal brain regions involved in working memory, even among adolescents who appear clinically recovered. These findings suggest that the absence of noticeable symptoms does not necessarily indicate a complete return to normal brain functioning.

Concussion can also affect emotional functioning. Because brain systems involved in cognition and emotion are closely connected, disruptions caused by concussion may contribute to anxiety, depression, frustration, mood changes, and difficulties with emotional regulation. These symptoms may occur even as physical symptoms begin to improve and, in some cases, can continue for weeks or months. Emotional symptoms can influence an adolescent's academic performance, social relationships, daily activities, and overall quality of life (Lowry, 2019). Therefore, evaluating concussion recovery requires attention to both cognitive and emotional changes rather than focusing solely on physical symptoms.

The relationship between cognition and emotion matters especially during adolescence. Cognitive and emotional processes do not operate as completely separate systems; instead, they interact to influence attention, memory, decision-making, behavior, and responses to emotional experiences. Because the adolescent brain is undergoing significant development, disruptions to these interconnected systems may affect multiple areas of functioning at the same time. For example, difficulties with attention and executive control may make it more difficult for an adolescent to regulate emotions, while emotional difficulties may further interfere with concentration, learning, and decision-making. This interaction highlights why the effects of concussion should be considered across cognitive, emotional, and behavioral domains.

The effects of concussion can also differ between the short and long term. In the short term, adolescents may experience headaches, dizziness, fatigue, memory difficulties, reduced concentration, mood changes, and sleep disturbances. These symptoms can interfere with school, daily activities, and sports participation during the typical two- to four-week recovery period. Although many adolescents recover during this period, some research suggests that

changes in brain functioning may remain after clinical symptoms have been resolved. Dolman et al. (2024), for example, found that adolescents with a history of concussion were less efficient at filtering and prioritizing sensory information than adolescents without a concussion history. Similarly, Adams et al. (2020) reported reduced efficiency in filtering irrelevant sensory information and greater difficulty performing tasks in the presence of distractions. Together, these findings suggest that some effects of concussion may persist beyond the period of noticeable symptoms.

Despite the growing body of research, several gaps remain. Differences in study designs, participant populations, assessment methods, and interpretation of results make it difficult to establish consistent conclusions about the long-term effects of adolescent concussions. Future research should focus on identifying reliable biomarkers that can improve the diagnosis, prognosis, and monitoring of concussion recovery (Bishay, 2025). Additional research is also needed to better understand differences in concussion outcomes between males and females. Finally, advanced neuroimaging techniques such as magnetic resonance spectroscopy (MRS) may provide additional information about microscopic changes in brain chemistry that are not visible on standard MRI scans (Esopenko et al., 2023).

Research suggests that adolescents may experience longer and more variable concussion recovery periods than adults, particularly in cognitive functioning (Davis et al., 2017). In a study comparing high school and college athletes, high school athletes demonstrated prolonged memory difficulties, performing significantly worse than their age-matched controls seven days after injury, while college athletes returned to comparable performance levels by day three (J.Pediatrics, 2003). Similarly, Davis et al. (2017) reviewed 134 studies that concluded that children and adolescents should follow age-specific concussion management guidelines, with symptoms generally expected to resolve within four weeks. What makes these findings unique is that age appears to influence the speed of cognitive recovery. Even with these results, there is not sufficient evidence to establish with certainty that adolescent concussions result in greater long-term neurological damage than adult concussions.

Overall, the evidence indicates that concussion during adolescence can affect cognition and emotion in interconnected ways. While many adolescents experience substantial recovery within weeks, some may continue to demonstrate cognitive, emotional, or neurological changes after clinical symptoms have improved. The body of research in this review suggests that adolescence may be a period of greater vulnerability to concussions but there is no direct evidence comparing if the symptoms are significantly worse or different from those seen in adults. Continued research into these effects, particularly through longitudinal studies and more sensitive measures of brain function, is necessary to better understand adolescent concussion and improve the assessment and management of recovery.

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