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Adolescent Brain Development

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Abstract

This paper reviews recent research on the factors that impact adolescent brain development. Numerous research studies have analyzed the biological and psychological changes that underlie this transitional period within the lifespan. Nevertheless, many remain at a level that can be difficult for the general public to understand, causing the public to associate adolescence with only danger and risk and not providing adolescents with the opportunity for exploration. Therefore, this literature review aims to compile research on the main factors that affect adolescent development in a comprehensible paper to provide a more accurate depiction of adolescence. This paper will begin with a discussion on adolescence and a background on the current adolescent research. The paper will then be divided into six sections describing the most extensively researched and critical factors influencing the adolescent brain. This includes the effects of puberty, emotional development, risk-taking, social environments, sleep, and learning and decision-making on the developing adolescent. Finally, this paper will conclude with key findings to broaden the understanding of adolescence beyond a time of 'storm and stress' to help shift the adolescent narrative and how society can best support them by giving adolescents the space to navigate through hardships and complete their goals as they define the future.

Keywords: Adolescence, Brain development, Adolescent growth, Brain growth, Neuroscience, Psychology

1. Introduction

Over the years, 100,000 research papers have been published on adolescent development, giving more light to understanding adolescence. Adolescence is the phase marked by the start of pubertal maturation between childhood and adulthood, around ages 9 to 25 (Wierengai et al., 2017). It is a critical transitional period defined mainly by the development of essential neural networks that, together with social, emotional, and hormonal changes, set the stage for adult life. Recent studies have explored adolescents' biological and psychological changes to understand this transitional period. Studies have also focused on the effects of adolescent changes on mental health, contributing to internalizing disorders like depression and externalizing disorders like substance abuse (Crone and Dahl, 2012). However, despite increasing research on adolescents, public understanding of adolescents is declining, resulting in a negative public perception as seen through the stigmatization and discrimination against adolescents in the social world and media (Lau, A. S. et al. 2016). This paper aims to provide an accessible overview of critical factors in adolescent brain development to help facilitate society to support opportunities that will give adolescents the environment to take healthy risks and explore themselves to promote a positive transition not defined by negative consequences that can help build a stable future ("Exploration & Risk Taking", n.d.).

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2. Puberty

Puberty a phase marked by the increase in sex-specific hormonal changes that give rise to physical and biological attributes. These neurobiological changes that occur at puberty onset are critical for the social, emotional, and cognitive maturation necessary for the ability to achieve reproductive success (Piekarski et al., 2017). Before puberty, postnatal (the period before childhood) brain development causes a shift within sensitive periods in which plasticity is enhanced (Piekarski et al., 2017). Researchers denote this as the sensitive period because it is the most critical time for adolescents to acquire a particular skill rapidly. However, as puberty progresses, adolescents' plasticity declines to stabilize already learned skills that can impact our academic, cognitive, and long-term memory-keeping abilities. This is due to the changes in hormone levels that may have reorganizing effects on human brain development (Wierengai et al., 2017). According to Wierengai (2017), as our abilities become more specialized, the volume in an adolescent's brain loses its ratio of gray matter to white matter. Gray matter serves to process information in the brain to white matter, which then passes messages between different areas of gray matter within the central nervous system. During the period before puberty, gray matter reaches its peak before being encroached by white matter that increases and stabilizes into adulthood, meaning that cognitive functions and behaviors are fine-tuned (Suleiman et al., 2017).

Additionally, gonadal hormones are enhanced during puberty, which is involved in how people experience romantic love, including oxytocin (role in childbirth and nursing), vasopressin (role in maintaining blood flow to vital organs), dopamine (role in how we feel pleasure), serotonin (role in regulating our emotions), and cortisol (role in helping our body respond to stress) (Suleiman et al., 2017). The development of sex hormones causes adolescents to stimulate neural signals in their brains that affect the dopamine system. This unique reward-seeking system facilitates goal- seeking behavior in adolescence. For example, an adolescent will use this system to seek out relationships for romantic love and sex. Furthermore, changes in hormones during pubertal onset are essential to understand as they can cause more activation and sensitivity in regions of adolescents' brains that may intensify emotional reactivity (mood swings), impulsivity (fast driving), and novelty-seeking behaviors (developing relationships), as well as poorer sleep regulation. (Lee et al., 2014). Social and cultural aspects also play a vital role in framing the sexuality of youth. Parents, peers, and the media can all activate adolescents' neural reward circuitry and risk-taking behavior. Though maternal relationships in adolescents' early life play a part in adolescents' brain development, adolescents tend to communicate their stress more with their peers when faced with scenarios of anxiety due to the heavy amount of time adolescents spend with their peers going to school than their parents. Thus, the buffer of stress shifts from parents to friends, making adolescents want to be more independent from their parents and be more strong-willed against them.

3. Emotional Development

Adolescence is a time marked by profound hormonal changes that can fine-tune critical neural networks that work to produce and manage emotions. Thus, adolescence is characterized by a time of extreme sensitivity in one's emotional life to both desirous and non-desirous emotional experiences. Compared to adults and children, adolescents are known to have hyper-emotionality (the state of being extremely emotional), being happier or more depressed in response to events like talking to friends (Guyer et al., 2016). Unlike adults, adolescents' positive feelings do not last as long and generally have a more challenging time regulating their emotions, causing adolescents to experience disorders like mood swings and depression. Throughout adolescence, youth slowly develop the emerging ability to exert greater self-directed control over behaviors and emotions. According to Guyer and researchers (2016), learning to manage one's emotional reactions is a principal task of adolescence because discovering new emotional experiences, like jealousy and acceptance, can cause heightened emotions that should be managed. However, experiences of early life adversity, like separation from biological parents or exposure to violence, may stump this growth of emotional development in the brain. Two categories of early life adversities that youth experience are threat (risk of being potentially harmed) and deprivation (suffering a lack of a substantial benefit) (Hein et al., 2020). These types of adversities may change the processing of an adolescent's brain by impacting the adolescent's mental health, stress responses, and emotional processing. As reported in Hein's study, adolescents without violence exposure started with

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a higher level of amygdala activation (the stimulation of the cerebral cortex into a state of general wakefulness or attention) to a threatening image in the scanner but eventually habituated to it. In contrast, youth who experienced early life adversity started with less activation but did not habituate. Overall, violence exposure and social deprivation were related to factors of anxiety and depression. Given all these changes in the neurodevelopment of emotionality, adolescence is the critical window for the emergence of internalizing (keeping your feelings or issues inside and not sharing your concerns with others) disorders like depression, anxiety, or self-harm. Girls have been shown to be at a higher risk for the emergence of internalizing disorders 2-3 times more than boys due to their earlier puberty onset and more rapid pubertal tempo (developmental change over time) due to the fact that girls tend to have close-knit friend groups (Pfeifer et al., 2020). One out of five adolescents have a mental illness that persists into adulthood (Lee et al., 2014). According to Pfeifer et al. (2020), peer relations (including peer rejection, close friendships, and romantic or sexual relationships) significantly determine well-being and mental health in childhood and adolescence. Youths increasingly report friends as an essential source of social and emotional support as they age (Fuligni, 2019). The central relationship stressor that causes mental health problems is the experience of being rejected. Increased neural sensitivity to peer rejection naturally increases across pubertal development but is exacerbated among adolescents with depression. Though researchers know little about how brain development relates to positive aspects of social connections, like close friendships, with this data, researchers can help pinpoint and decrease the symptoms of adolescents showing the emergence of internalizing disorders and help adolescents gain a stronger sense of their emotions.

4. Risk-Taking

Adolescents display heightened attraction to adventurous and thrilling experiences despite their evident risk relative to children and adults. This is because adolescence is crucial for explorative learning, risk-taking, and sensation-seeking (Braams et al., 2015). Increased risk-taking in adolescents results from dopamine systems gaining heightened sensitivity to rewards, which leads to an overactive reward system in the brain, causing adolescents to make risky decisions. According to Chien and colleagues (2015), peer presence may encourage adolescent risk- taking by sensitizing brain regions associated with reward sensitivity (Figure 2). Greater adolescent risk-taking in peer presence can be explained by the fact that youth spend more of their social life with friends than adults. Greater risk-taking in the company of peers is consistent with a group polarization (when a group makes a more drastic decision than its members would have made if acting on their own) effect of peer influence. Chien's study demonstrated that adolescents took greater risks in a simulated driving task than adults when observed by peers.

Risky behavior reflects the contribution of two brain systems when decision-making. The first is an incentive processing system that biases decision-making based on the valuation and prediction of potential rewards and punishments. The presence of peers may sensitize this incentive system to respond to cues signaling the potential rewards of risky behavior. The second is a cognitive control system that aids goal-oriented decision-making by keeping impulses in check and providing the brain with the machinery to make alternative decisions. Thus, it is likely that youth with reasonable executive control and peer groups with similar interests will be able to experiment with risky behavior without causing severe results (Chein et al., 2011).

Although negative risk-taking has been commonly associated with adolescents, positive risk-taking is just as used. Positive risks can include trying a new sport or activity or trying public speaking for the first time. Risks can be categorized as more than just negative by assessing the benefit it has to an adolescent's well-being, the rigor of the potential consequences, and the relative social appropriateness of the behavior. Positive and negative risk- taking are disparate but are influenced by some of the same underlying characteristics (e.g., participation in team sports is associated with a higher rate of substance use). According to Duell and Steinberg (2020), sensation-seeking and reward sensitivity are associated with greater positive and negative risk-taking, showing that positive and negative risk-taking were significantly and positively correlated. Though there are many correlations between the two types of risk, there are also many differentiating factors. Harmful risk-taking was associated with the psychological aspects of impulsivity, high reward sensitivity, and punishment, while those did not seem to characterize positive risk-taking. Positive risk-taking is associated with greater school engagement, whereas negative risk-taking is associated with lower school engagement. There are also gender differences in risk-taking, the main difference being that adolescent girls are less likely to take adverse risks than boys, as seen in (Figure 1) (Romer et al., 2017). This may have to do with early maturation seen in girls around the start of adolescence. Not only do adolescent girls experience bodily maturation faster than adolescent boys, but they also reach a greater cognitive level. Young adults who perform fatal risk-taking tendencies show brain responses with weak cognitive control. High sensation seekers may be more inclined towards risk-taking behaviors that can lead to harmful outcomes. However, they appear to learn from these experiences as they age, compared to adolescents with impulse control problems. According to Romer's study (2017), many adolescents can be described as "hyper-rational" as they rely on the risks and benefits of their behavior even more than adults do. Therefore, adolescents are prone to more risk-taking than adults and children, though it can also have many positive outcomes.

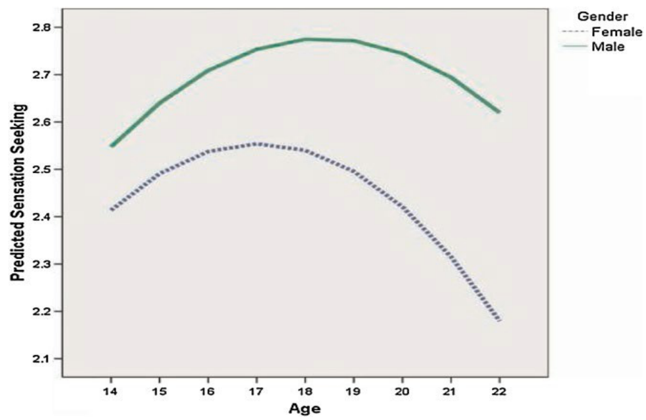

Figure 1. U.S. Survey of 1800 adolescents shows trends in sensation seeking (exhibiting heightened attraction to novel and exciting experiences despite their evident risk) from females and males in the United States. The x-axis indicates the age of participants, and the y-axis indicates the peak of sensation seeking. Image from (Romer et al., 2010).

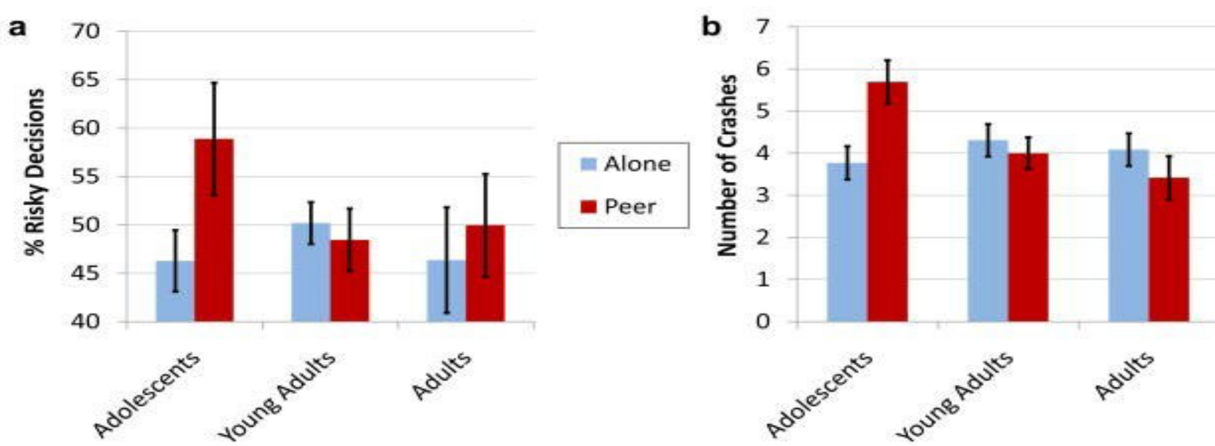

Figure 2. Car-driving scanner, in which all 40 participants from different age groups took more risk-taking decisions in the context of peers. The x-axis represents the different age groups, the y-axis in Figure 2a is the mean percent of risky behavior, and in Figure 2b is the number of crashes when playing car simulation. Error bars indicate the standard error of the mean. Image from (Chein et al., 2011).

5. Social Environment

Another major shift that occurs alongside adolescent brain development is the experience of extensive changes in adolescents' social behavior and environments. The development of the social brain, a neural network of the brain involved in social perception and cognition, allows adolescents to form more complex, hierarchical relations and have more sensitivity to the acceptance and rejection of their peers (Kilford et al., 2012). According to Kilford and colleagues (2012), adolescents can now make better sense of the world through processing signals (the understanding, analyzing, modifying, and synthesizing of signals such as sound and images) and encompassing a wide range of cognitive processes to interact with one another. This allows adolescents to be more equipped in motivational processing and decision-making. Young adults have increased activation in the posterior superior temporal sulcus (pSTS), involved in interpreting complex social gestures, and other engagement of the dorsomedial prefrontal cortex

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(dmPFC), engaged in inferring another's mental states compared to adults (Kilford et al., 2012). Thus, greater engagement of the dmPFC reflects the increased use of the social brain to understand others better, even when unnecessary. As adolescents develop an increased sensitivity to others' perceptions of themselves, they are also more prone to social anxiety than any other anxiety disorder (Kilford et al., 2012). This is because youth become increasingly self-conscious as they develop a better ability to evaluate themselves and others, causing them to believe in an imaginary audience (the phenomenon that others constantly criticize them) (van Hoorn et al., 2019). While adolescents are motivated by reward and dopamine-seeking goals such as social affiliation, many struggle with social anxiety and experience approach-avoidance due to fear of rejection or humiliation, which is associated with greater cortisol responses (Muscatell et al., 2012). Another factor that can cause social reluctance among adolescents is their carefulness when choosing their friends due to the profound influence friends may have on their performance (Kilford et al., 2012). Following the development of the social brain, adolescent decision-making often occurs in the context of peers, parents, or other critical social agents. When adolescents decide based on social context, they observe the social influence of their decision and the social outcome (van Hoorn et al., 2019). According to the van Hoorn paper (2019), the best way to make decisions is to consider the role of neural systems involved in effect (the ability to make inferences about others' emotions and feelings), cognitive (the ability to make inferences about others' thoughts and beliefs) control, and social information processing (how individuals and groups interact and establish social relationships).

As these extensive changes in adolescents' social behavior unfold alongside the development of the social brain, adolescence can also be characterized as a time when youth gain the ability to consider the needs, concerns, and perspectives of others (Fuligni, 2019). Understanding the scenarios of others better allows adolescents to feel the need to help and positively impact others. Thus, showing signs of prosocial behavior is defined as voluntary behavior intended to benefit others. Prosocial behavior can be in the form of sharing, giving, and making decisions involving outcomes for oneself and others (Güroğlu and Crone, 2014). Two main processes correlating with prosocial behavior are social cognitive perspective-taking and empathic concern (Blankenstein et al., 2020). Social cognitive perspective-taking involves understanding one's mental state by observing their social situation (Freschmann et al., 2019). While empathy focuses on understanding (cognitive empathy) and relating to one's situation (affective empathy). For an adolescent to perform prosocial behavior, they must have both of these two processes. For example, empathy can cause others distress when faced with specific scenarios (exc. a homeless man begging for money), causing them to avoid the situation rather than help. When researching prosocial behavior, researchers cannot take observations from a random group of benefactors of prosocial behavior. This is due to adolescents having favorability towards certain groups of people when making contributions (Figure 3). Researchers determine adolescents' longitudinal change in prosocial behavior by examining their behavior towards strangers, friends, and family. According to Padilla-Walker and colleagues (2018), adolescents are more likely to help

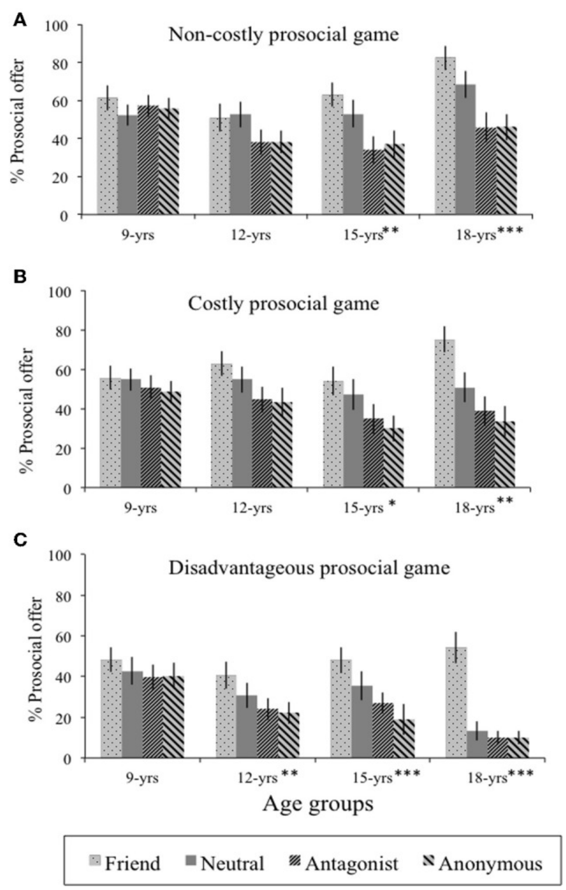

Figure 3. Assigned games to 125 participants from four age groups to evaluate favorability in prosocial behavior based on relational status. The x-axis is the different age groups, and the y-axis is the mean frequency and standard errors of prosocial offers. Each figure is distributed into A) non-costly prosocial game, B) costly prosocial game C) disadvantageous prosocial game (Güroğlu and Crone, 2014).

someone they know (exc. friends, family) than a stranger, in large part because they are motivated to help by relationship quality and norms that are a part of relationships they have with friends and family. However, friends tend to be the common target for youth making contributions due to adolescents being surrounded by peers. When gifting, adolescents' prosocial behavior toward their family is more likely motivated by their desire to maintain the relationship rather than wholly from a moral sense of self. Prosocial behavior toward peers increased steadily among adolescents, in contrast to prosocial behavior toward the family, which was reasonably stable across adolescence and peaked. In comparison, prosocial behavior toward strangers increased across early to mid-adolescence and then flattened out during adulthood. There are sex-specific differences in prosocial behavior between girls and boys. Girls' perspective-taking increased between mid-adolescence, but boys' perspective-taking increased in late adolescence (Figure 4). Researchers suggest this may have to do with girls' faster maturation in cerebral cortical development from early adolescence to mid-adolescence, causing girls to be about two years ahead of boys in intellectual and social cognitive functioning as an adolescent. According to Van der Graaf and team (2014), boys may lack empathetic concern because of pubertal maturation that increases testosterone, inducing competitive behavior and thereby reducing empathy. As one can see, factors that affect adolescents' prosocial behaviors are dispositional (empathy, perspective-taking), relational (mother and father warmth, friend connections) behaviors, and demographics (child, gender, family structure, ethnicity).

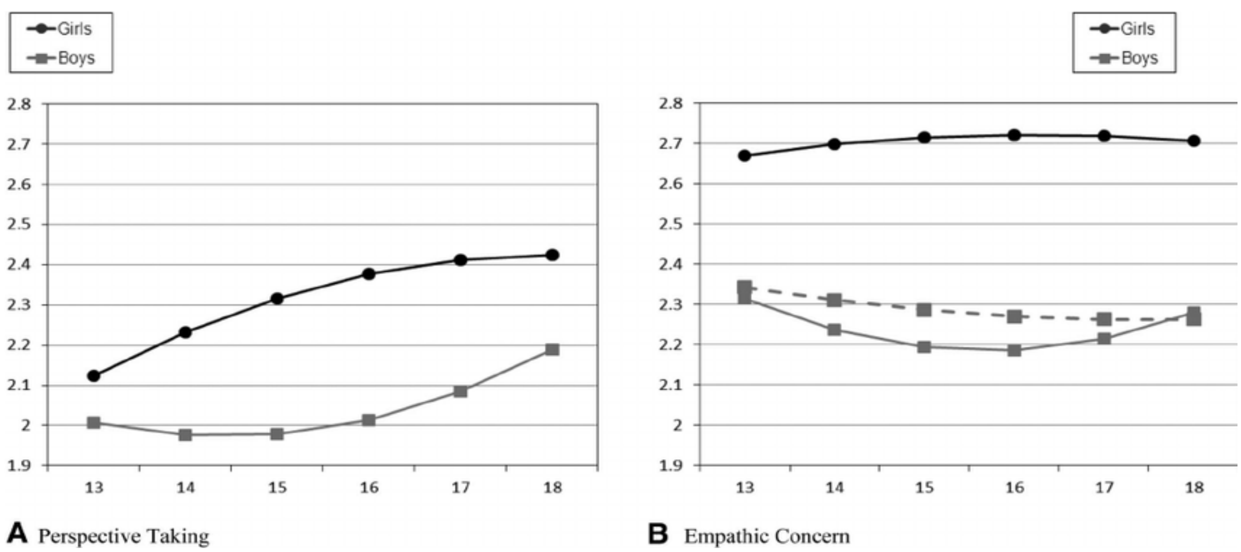

Figure 4. Development of prosocial behavioral skills between girls and boys. 497 participants were observed, with 214 of them being girls. The x-axis is the age of the participants, and the y-axis is the comparative fit index of A) perspective-taking and B) empathic concern. The solid lines represent the best-fitting models for developing A) perspective-taking and B) empathic concern. The dashed line in Figure 1B represents the boys' development of empathic concern corrected for differences in pubertal status from ages 13 to 16. (Van der Graaf et., 2014)

6. Sleep

Sleep is the body's essential cycle to rejuvenate. It is vital for memory consolidation, learning, and academic performance (Galván, 2020). The Galván et al. (2020) paper elaborates on sleep's ability to deepen cognitive sophistication, improve emotion regulation, and intensify social cognition during adolescence.

Nonetheless, sleep deprivation among adolescents is common. According to Hagenauer and Lee (2012), growing adolescents require, on average, as much as 9–10 hours of sleep per night. However, over 45% of adolescents in the United States report obtaining less than 8 hours of sleep on school nights. Inadequate sleep may amplify the neural imbalance between affective and cognitive control systems in adolescents by diminishing their ability to control their impulses while increasing their reactivity to rewarding activity (Telzer et al., 2013). Therefore, a lack of sleep can

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impair cognitive control by inhibiting activation of the dorsolateral prefrontal cortex (DLPFC), a brain region known for predicting an action's consequences (Telzer et al., 2013). According to Telzer and colleagues, adolescents who experienced inferior sleep quality have reported less self-esteem and more indifference in their behavior when making decisions and socializing. Thus, a lack of sleep can negatively impact adolescents' mental health, leading to symptoms of depression and suicidal thoughts. The root cause of adolescents' vast sleep deprivation is their tendency to stay up late. Three primary components are essential in determining the timing of sleeping and waking. They are the circadian system ("internal 24-hour clock"), homeostatic sleep pressure (drive for sleep), and other external factors (such as stress, medication, and environment) (Hagenauer and Lee, 2012). The circadian system generates daily rhythms and is entrained by external time cues (or "zeitgebers," such as sunlight) to maintain a periodicity that matches environmental rhythms, such as the 24-hour day. Due to adolescents' circadian rhythm associating with zeitgebers, it may be harder for an adolescent's body to fall asleep during the daytime when light is around than at night as the daily rhythms' main goal is to align the circadian system to the solar day. During pubertal onset, adolescents undergo biological alterations in their circadian and homeostatic systems that alter adolescents capacity to fall asleep faster (Galaván, 2020). Adolescents take longer to build up sleep pressure (the biological process that causes the brain to feel the need to sleep), which means older adolescents do not feel the need to sleep until later in the night (Figure 5). The reduced need for sleep is one of the many reasons youth are encouraged to do activities like outdoor sports to build their sleep pressure. To help, parents can create parent-set earlier bedtimes, which not only provide a regular schedule and encourage adolescents to spend sufficient time in bed but may advance the circadian rhythm phase by reducing light exposure in the evenings and increasing light exposure in the morning (Telzer et al., 2013).

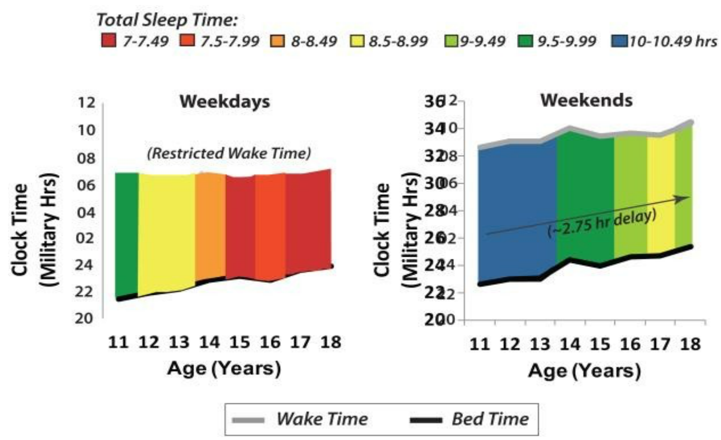

Figure 5. The trend of adolescents' timing of sleep decreases with age. The x-axis is the different countries' participants' ages in years, and the y-axis is the clock hours in military hours. The average bedtimes (black line) and wake times (gray line) are shown for both weekdays (left graph) and weekends (right graph). The total sleep time is indicated by color (key at the top of the figure). The arrow in the right graph demonstrates the change in color, indicating that adolescents were not getting the recommended sleep of 9-10 hours (Hagenauer and Lee, 2012).

7. Learning and decision-making

Adolescence is marked by a sensitive period when learning and decision-making are accelerated and emphasized. As adolescents reach adulthood, they begin to feel the burden of more responsibilities to successfully transition to complete independence as an adult. A major component in decision-making is temporal discounting, which is the process of evaluating the value of waiting for a future reward depending on the vastness of the reward and the delayed time (Sullivan-Toole et al., 2019). Temporal discounting involves three cognitive processes: valuation (the value placed on a specific outcome), cognitive control (engaging in goal-directed cognitive processes), and prospection (thinking about the future) (Anandakumar et al., 2018). With these three cognitive abilities, individuals will vary in preference for a more minor vs. significant reward and vice versa. According to Anandakumar and colleagues (2018), individual variability in temporal discounting selection could be explained by differences in functional brain organization that develop throughout adolescence, like the shifting gray matter in our brains. According to Anandakumar and colleagues (2018), the sensitivity to rewards in young adults relates to how that individual values the proposed reward or how well that individual can inhibit reflexive urges or the ability to think about the future. Anandakumar's longitudinal neuroimaging study on temporal discounting showed that there is indeed an age-related increase in the preference for waiting for the more immense rewards. On average, younger adolescents weigh delay costs heavily in their decisions, but as they grow older, they become increasingly tolerant of delays to wait for higher-

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value rewards (Sullivan-Toole et al., 2019). This suggests that age and individual differences in neural circuitry are related to an individual's preference for immediate versus delayed rewards (Anandakumar et al., 2018). Reward sensitivity is also essential in promoting learning, though a critical behavior that declines with age (Davidow et., 2016). The negative implications of reward sensitivity in adolescents have been well documented, but much less is known about the possible adaptive side for learning (Hauser et., 2015). Adolescent learning far exceeds adults' learning capabilities due to adolescence being associated with quick- changing environmental demands, which require excellent adaptive skills and high cognitive flexibility (Figure 6) (Davidow et al., 2016). According to Hauser and team (2015), youth show improved learning from reinforcement outcomes (rewarding desired behaviors and/or punishing undesired ones) and enhanced episodic memory (the ability to recall and mentally re-experience specific episodes from one's past). This suggests a solid link between reinforcement learning and episodic memory for rewarding outcomes. According to Hauser and colleagues (2015), learning from reinforcement is linked to how episodic memories are shaped and how they are seen as more good than bad. The hippocampus is a region of the brain that supports this reinforcement learning, as it is known for its role in learning and memory, particularly episodic memory, which contributes to reward-related behaviors like reinforcement learning, reward-guided motivation, and value-based decision-making. Adolescence is when potent and positive memories are formed, emphasizing the importance of learning from experiences to cement an adolescent’s ability to learn from errors and make better future decisions.

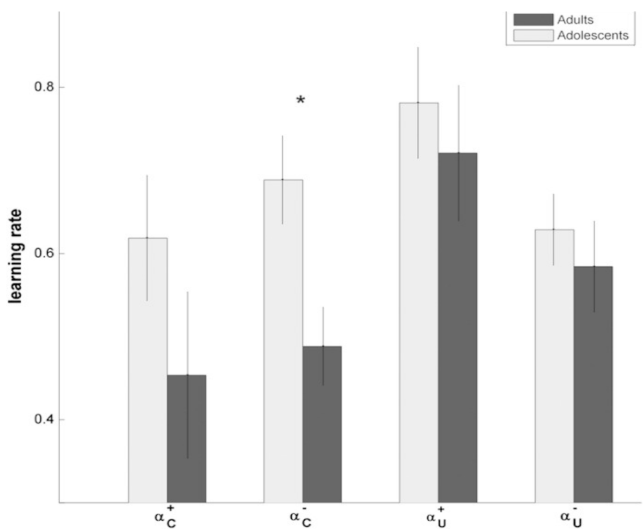

Figure 6. Differences between adolescents and adults in learning. The x-axis represents the different learning stimuli being compared between age groups of 36 participants, and the y-axis represents the rate at which the participants learned their chosen object. The asterisk indicates that p < .05 (data significant) to show multiple comparisons corrected (Hauser et., 2015).

8. Conclusion

This paper reviews recent research on the various factors that impact adolescent brain development. Adolescence is one of the most crucial life stages in which individuals grow and adapt to form their identities, interests, and goals. Through reviewing several studies on adolescence, it can be concluded that encouraging parents to understand the underlying reasons for their child’s behavior is crucial in helping adolescents stay on the right track by providing them with a supportive and understanding environment. Additionally, adolescents who take the time to understand the social implications of their actions recognize the rationale behind their choices and make more informed decisions. Society can fundamentally transform its approach by ensuring a comprehensive understanding of adolescent developmental research to support the development of policies and programs to give adolescents the chance for healthy exploration and positive risk-taking. Further developmental neuroscience and psychology exploration could be conducted to support future youth who will impact our communities' social and economic prosperity in our nation and our world (“Exploration & Risk Taking", n.d.). Studying adolescents’ physiological and neural development will challenge and change society’s negative perception of adolescence and construct an optimistic trajectory for adolescents and the future.

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