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Review Article

The Adolescent Brain: Neurocognitive Risks and Educational Opportunities

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Abstract

This review of adolescent brain neurobiological and cognitive development begins with a summary of current research on adolescent structure-function development. The aim is to summarize the current research on how neuroanatomical changes relate to cognitive function, and which cognitive factors may contribute to academic struggle and associated social/emotional or behavioral issues. The neuroscience review is followed by a description of intervention research including physical exercise, computerized cognitive training, and digital educational programs that have been shown, through independent review, to demonstrate positive educational, cognitive and/or social-emotional outcomes. The review concludes with promising educational initiatives and directions for further investigation.

Introduction

Adolescence represents the neuropsychological transition from childhood to adulthood, and is now viewed as a second sensitive period of brain development. This period is full of both opportunities and risks for the developing individual. The opportunities include dramatic growth in cognitive and self-regulatory executive functions, while the risks include serious social-emotional and behavioral challenges, which may be exacerbated by poverty and other types of adversity. Neuroscience-based educational initiatives, focused on building cognitive and self-regulation skills, may ameliorate adolescent neurobehavioral risks and enhance the maturation of executive functions.

Complex Interplay Between Affective and Cognitive/Emotional Domains

Adolescence, the developmental period from 10 to 24 years, is recognized as a period of increased maturation of the prefrontal cortex and of the cognitive regulatory skills specifically associated with that region of the brain. [1,2]. However, during this period there is a complex interplay between improved self-regulation and potentially conflicting cognitive, behavioral, emotional, and motivational changes. The latter include a proclivity toward risk-taking, heightened reward motivation and social-affective inclinations, which increase adolescent risk of substance dependency and mental illness [3,4]. Two models have been proposed [5] to explain this complex interplay between affective and cognitive/executive processes:

- Dual Systems Model [6,7]
- Maturational Imbalance Model [8]

Both models attribute adolescent novelty-seeking, reward motivation, and risk-taking to a temporary imbalance between two neurological systems: the subcortical social/emotional system that responds to reward, novelty, and emotion, and the cortical cognitive/executive system that supports planning, impulse control, and decision making. Both models cite research indicating that the social/emotional system matures earlier than the cognitive/executive system, to explain why early and middle adolescents (ages 14 until 17) are more reward motivated and thereby especially vulnerable to risk taking, substance abuse, and related issues. Both models further predict reduced novelty-seeking and reward motivation during late adolescence due to increasingly mature cognitive control [5].

Neurobiology

Delineating the major neuroanatomical changes of cortical maturation and brain network organization represents a natural step toward understanding cognitive development and verifying the Dual Systems and Maturational Imbalance Models [9]. To date, brain imaging studies have shown that the development of structural and functional distributed association network connectivity is related to improvements in higher-order cognitive control processes [10].

Early, post-mortem investigations of adolescent neuroanatomy revealed that synaptic pruning within the gray matter is a dominant developmental process during this period. Cortical connections fine-tune and specify, while redundant or unnecessary synapses are eliminated. This fine-tuning leads to decreases in gray-matter volume, as verified through later imaging research [11,12]. However, according to research by Sarah-Jayne Blakemore [13], the gray matter volume reductions observed through structural imaging of adolescents were greater than what would be expected based on synaptic pruning alone. A second factor, the expansion of white matter within the cranial vault due to intracortical myelination, results in a thinner appearing cortex. Prefrontal cortex maturation during adolescence then, appears to be associated with increases in white matter volume through expansion of network interconnections. Thus, imaging research in adolescence has moved toward identifying structure-function connectivity patterns associated with this maturation [13].

Smith and colleagues [14] conducted one of the earlier studies of the interplay of demographics, cognitive skills and structural connectivity, utilizing the unique data set of the Human Connectome Project (HCP, www.humanconnectome.org). They delineated the covariation matrix between behavioral variables and resting-state connectivity measures in 461 HCP participants, finding the strongest correlations between the quality of functional connectomes and strength of higher-order cognitive abilities such as attention, vocabulary, and fluid intelligence.

Modabbernia *et al.*, in a 2021 review of diffusion-weighted imaging (DWI) research on the adolescent brain [15], summarized the preponderance of data indicating a prolonged, experience-dependent developmental trajectory of intracortical myelination. The experience-dependent changes occur primarily within prefrontal and other association regions which, in turn, facilitate dynamic maturation of cognitive systems [16-18]. In a large, longitudinal tractography study Lebel *et al.* [19] found reduced axial and radial water diffusivity and increased fractional anisotropy, indicative of developmental increases in the diameter and myelination of axons as well as the fiber density of white matter tracts. They found that the association tracts, which are critical for cognitive control, were the latest to develop, with changes continuing even beyond adolescence. White matter tract development is part of the dynamic maturation of network modules, including modules for higher order cognitive skills. How these modules develop has implications for both cognitive development and psychopathology [20].

Graph theory tools, which are used to analyze the architecture of brain networks and map structural and functional brain connectivity, have revealed groups of densely interconnected nodes that form network modules. These modules are considered the basis for specialized components of information processing [21]. In a large-scale DWI study with 882 participants, ages 8–22, from the Philadelphia Neurodevelopmental Cohort, Baum *et al.* [22], found that structural network modules become more segregated with age. As modules segregate, their connections to other modules get weaker, while connections within the module get stronger. This age-related segregation increases brain network efficiency and is associated with improvement of executive functioning in children and adolescents. Wang *et al.* [23] found support for this association in a functional magnetic resonance imaging (fMRI) study with 88 Chinese children, ages 7-12, performing a Dots task, which taps working memory, inhibition, and task-switching skills. The results indicated that task-dependent brain networks became increasingly segregated during this age range, with the modular segregation significantly mediating the relationship between age and executive function. A large cross-sectional study, with 727 participants, ages 8-23, that included a smaller longitudinal component (n = 294), was conducted by Baum *et al.* [24] to further investigate this type of structure-function coupling. The investigators collected DWI and fMRI data from individuals performing an N-back task, which taps working memory, attention, and interference processing skills. They found that higher structure–function coupling in the rostrolateral prefrontal cortex was associated with higher executive performance, partially mediating age-related executive function improvements. All of this research indicates that increased functional specialization and the remodeling of structural connectivity are critical for the development of cognitive and executive skills in the adolescent.

Connectionist models of cognition also emphasize the importance of viewing brain function in terms of networks, rather than individual neurons [25]. Neural network models may effectively delineate the architecture of cognitive functions. Deep neural networks add structured neural connectivity units, serving as "hidden" layers between input and output, to improve performance. This approach to network models potentially provides a more specific method to explain how gains in cognitive performance are possible through neuroplastic refinement of the brain connectivity architecture.

Factors that Contribute to Academic and Behavioral Issues

Many researchers are working to identify factors that contribute to variability in brain structure-function maturation. Understanding this variability is critical for identifying adolescents who are at behavioral and academic risk because of lags in executive function development. It is also essential for designing effective educational and intervention approaches for those at risk [10].

4.1 General Psychosocial and Environmental Factors

One of the largest efforts in this area is a collaboration among 21 institutions known as the Adolescent Brain and Cognitive Development (ABCD) study. The studies described in this section, drawing on ABCD data, have illuminated complex relationships between socioeconomic status (SES), brain structure, and cognitive function. This body of research points to a number of related factors that influence risk as well as resilience during cognitive development. While these studies have been correlational, many of the reported associations are likely underpinned by biological factors, and thus are considered likely causative.

In one large cohort study, Modabbernia *et al*. [26] investigated the covariation of psychosocial and environmental factors with measures of brain organization to identify distinct association patterns in a U.S. nationally representative sample of 9,623 individuals (aged 9-10 years, 49% female). The analyses identified seven advantage/adversity factors that were consistently associated with multiple positive or negative features of brain organization: neighborhood environment, parental characteristics, quality of family life, perinatal history, cardiometabolic health, cognition, and psychopathology. The brain structure and function differences observed were global and cross-modal. The highest positive correlations were seen between cortical thickness and physical fitness, SES, cognitive skills, and (lower) psychopathology.

Gonzalez *et al*. [27] took a closer look at the impact of SES on total brain surface area and cognitive skills. They found negative impacts in both children from low income families (<200% Income to Needs Ratio INR) and those from mid-income families (200%-400% Income to Needs Ratio INR). However, they found that resource access and social factors also influenced outcomes by enhancing resilience and/or decreasing risks. Regardless of family income or physical adversity, youth who reported having social support or access to resources had higher cognitive scores and greater brain surface area.

Taylor *et al*. [28] looked beyond household poverty level to consider the potential impact of broader, neighborhood poverty. They looked specifically at the development of the prefrontal cortex because of its role in executive functions like attention and impulse control, as well as the hippocampus, essential for memory and learning. Neighborhood poverty level was assessed by such factors as unemployment rate, average educational level, and percent in poverty. They found that children living in high poverty neighborhoods exhibited lower cognitive scores and brain structure volumes, independent of the income level of the child's household.

Further studies have also looked at the impact of neighborhood poverty. Rakesh *et al.* [29] used existing MRI brain scans from 7,618 children, aged 9-10, to correlate functional connection (FC) patterns with neighborhood disadvantage measures, including crime rates, lower quality educational and healthcare options, and higher environmental pollution levels. Their analysis revealed that more disadvantaged children exhibited widespread reduced functional connectivity within and between several brain networks associated with higher-order cognitive skills and sensorimotor systems. They also looked at the role of other psychosocial factors including positive home and school environments. They found that these protective factors were associated with reduction in the harmful effects of neighborhood disadvantage. In a related study [30] they found that neighborhood poverty is generally linked to reductions in the cortical thickness of both frontoparietal and visual regions; however, high income-to-needs ratios may serve a protective role.

The good news from all of these SES studies is that changes in educational and community factors could potentially improve the developmental trajectory of low SES adolescents. Neighborhood poverty is often associated with higher crime levels, fewer avenues for cognitive and social stimulation, reduced internet access, and lower school quality. Addressing these demographic variables through public policy and other political or community initiatives might significantly enhance educational and psychosocial outcomes.

4.2 Social Deprivation and The COVID-19 Pandemic

Mental health and brain maturation are also affected by adolescents' increased need for peer interaction and their enhanced sensitivity to social stimuli. Social deprivation, such as that experienced by adolescents during the COVID-19 pandemic, may have profound consequences. At the time of this writing, an understanding of the full neurobiological impact from the pandemic-related reductions in educational and social access is unknown. According to Orben *et al.* [2], most of the research on social isolation has been conducted with animal models. Rodent 'adolescent' studies have shown substantial and potentially long-term effects from social deprivation and isolation on neurochemistry, structural brain development, and behaviors associated with mental health problems. However, social deprivation effects on human development are not as well understood.

The COVID 19 pandemic experience for adolescents often included abrupt withdrawal from school, the cancellation of athletic events, clubs, extracurricular activities, and loss of in-person access to friends and extended family. In addition, some adolescents had to face family stresses ranging from job loss, to illness, to domestic violence. These stressors can impact adolescents' mental health. Studies of adolescents during the pandemic have found increased rates of post-traumatic stress disorder, depression, and anxiety [31]. Furthermore, negative coping mechanisms, such as adopting a high-fat diet, or excessive use of social media, can have major repercussions [32]. Withdrawal from outdoor and organized activities in many cases significantly decreased physical activity among adolescents during the pandemic. Nagata *et al.* [33] reveal data indicating that only 8.9% of adolescents studied met physical activity guidelines during the pandemic compared to 16.1% before. Reduced physical activity has significant impacts on both physical and mental health.

It is also important to consider the direct neuropathological sequelae associated with the COVID-19 virus itself. Some patients, even young adults, have presented with cognitive and attention deficits ("brain fog"), new-onset anxiety, depression, and psychosis [34]. These have occurred independently of respiratory symptoms and not secondary to respiratory insufficiency, suggesting that the virus can directly cause brain damage. Follow-up data from Germany and the United Kingdom found post-COVID-19 neurological symptoms in 20% to 70% of patients, including young adults, that persisted for months after other symptoms resolved [34].

Educational and Remedial Approaches

The neuroscience revelation that adolescence represents a second critical period of brain development has sparked a new interest in educational and remedial initiatives that can take advantage of this neurologically formative stage. Accordingly, the wealth of cross-sectional adolescent research, as reviewed in this paper, has prompted a search for viable approaches to address and ameliorate negative brain maturation processes. The evidence indicates that it is possible to identify behavioral and academic risk factors prior to and during early adolescence, before they have a permanent impact on brain function and mental health [10,25] The next sections summarize the research on approaches to cognitive skill building that improve working memory and self-regulation, approaches to literacy instruction that foster metacognitive skills, and approaches to math instruction that foster cognitive domain capacities. Combining these with educational and community environments that enhance the emotional domain could have profound impacts on cognitive and mental health outcomes for all adolescents.

Figure 1 is a schematic overview of risk factors described above and evidence-based educational initiatives and remedial approaches described in more detail below.

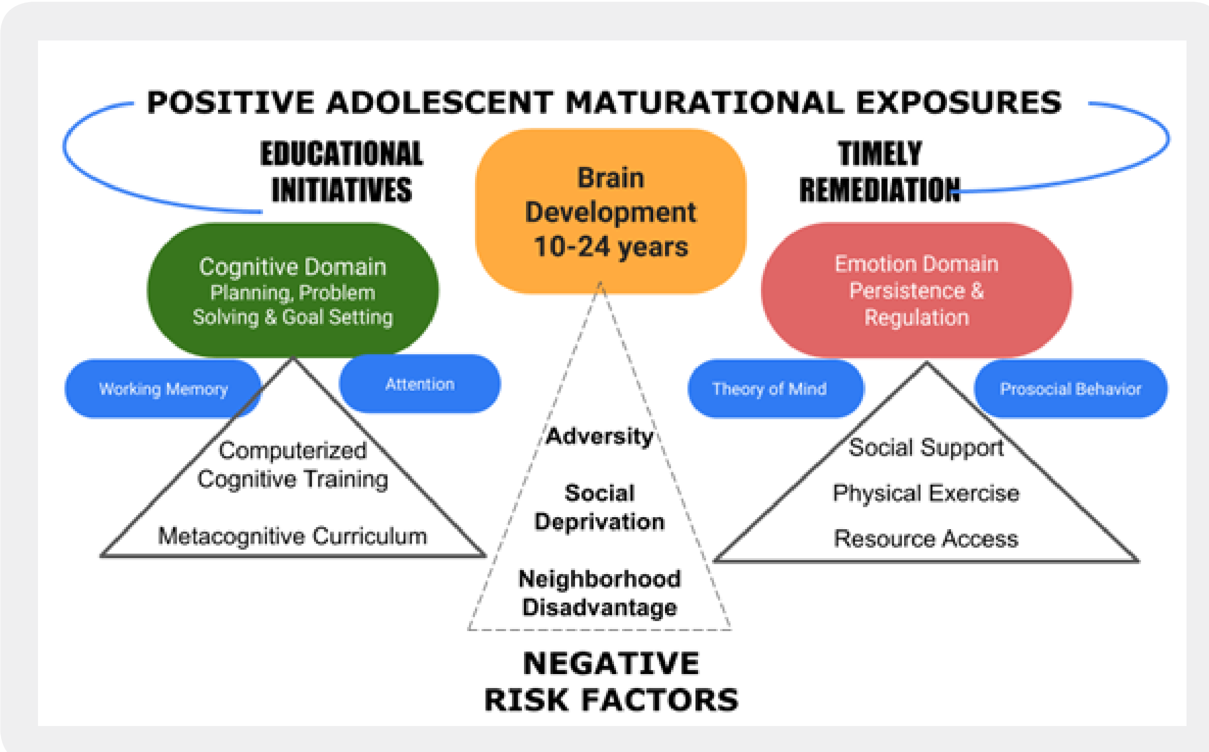

Figure 1: *Brain maturational risks and positive exposures. The adolescent brain is still actively developing, influenced by the complex interactions between positive exposures and negative risk factors that especially impact the cognitive and emotional domains. For all adolescents, but especially those with negative risk factors, both cognitive and emotional domain support are essential. Educational initiatives and/or timely remediation including quality curriculum and cognitive training can positively impact the cognitive domain. Provision of social support and access to resources can positively impact the emotion domain. (Adapted and updated from [10, 26].)*

Although many promising practical and scalable methodologies are on the horizon, some of the most effective educational and remedial approaches identified at this time are those shown to foster executive functions and associated brain maturation. In a review of longitudinal research on the relationship between academic achievement and cognitive skills, Best *et al.* [35] note that the research has generally confirmed that executive functions contribute to academic achievement rather than vice versa. Performance on inhibition and working memory tasks, in particular, has been shown to consistently correlate with mathematics and reading achievement.

Working Memory and Fluid Intelligence

Moser *et al.* [36] used the unique data set from 823 healthy participants in the HCP to investigate the brain-behavior relationship of working memory (WM) capacity - an executive function especially important to learning that requires cognitive control to actively maintain information. They employed sparse canonical correlation analysis (sCCAs) to determine the covariation between brain imaging metrics of WM-network activation and connectivity as well as nonimaging measures relating to lifestyle characteristics, affective and nonaffective cognition, mental and physical health. Their data indicated that fluid intelligence shows a strong correlation with WM-network functional integrity, even when multiple other variables are considered. They view these data as corroborative of other research that has examined individual variability in functional brain connectivity, and conclude that there are common neural mechanisms that support both WM and fluid intelligence. In a recent review of process-oriented intelligence research, Frischkorn *et al*. [37] stated that there is a general consensus that WM is strongly linked to fluid intelligence, and that differences in intelligence may arise from processes limiting WM.

Attentional Self-Regulatory Remediation

Research on attentional problems has largely been conducted on clinical populations, but issues with attention and impulsivity can affect many adolescents. Defoe *et al*. [38] tracked 364 urban U.S. youth, (median-age 13.5) over a five year period, and saw a complex trajectory that connected impulsivity during pre-and early adolescence years to alcohol use and antisocial behavior in later adolescence. The risks posed by self-regulatory issues in adolescents underscore the importance of effective interventions.

Based on a meta-analyses of fMRI studies investigating Attention Deficit and Hyperactivity Disorder (ADHD), Westwood *et al*. [39] noted patterns of underactivation across the cognitive-domain-dependent frontostriatal and fronto-cerebellar systems during cognitive control tasks. Reduced activation was seen in the right dorsolateral prefrontal cortex and striatal and parietal regions during attentional tasks, bilateral superior prefrontal regions during working memory tasks, and inferior frontal, parietal, and cerebellar regions during tasks with high rapid processing demands. The ventromedial frontostriatal areas were shown to be under-activated when reward-related functions were involved.

The most effective short-term medical treatment for adolescents with an ADHD diagnosis is the use of psychostimulant medications, but these can cause side effects and have limited longer-term efficacy. Noninvasive brain stimulation treatments, such as repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS), have been deemed relatively safe and have minimal side effects. They have also been shown to induce neuroplasticity, a benefit not associated with medications [39]. Unfortunately, these technologies are inaccessible in many communities, especially those in rural or remote areas or living in high poverty regions or neighborhoods.

Cognitive Remediation Reviews and Meta-Analyses

Physical Exercise. For youth at risk of cognitive and behavioral issues there are inexpensive, physical exercise interventions as well as readily available community-based dietary, meditation, and cognitive exercise interventions. With respect to the former, there are several controlled research studies that have shown the benefits of physical exercise on cognition and attention. Liang *et al*. [40] conducted a systematic review and meta-analysis of intervention studies using physical exercise to improve the executive functions of children and adolescents with ADHD. They found that physical exercise interventions had a moderate-to-large positive effect on inhibitory control as well as cognitive flexibility. A subgroup analysis compared two exercise types: cognitively engaging exercises (i.e., ball games, yoga, exergaming) and aerobic exercises (i.e., swimming, running, jumping). While both exercise types were found to be effective, intervention intensity and frequency had a significant impact on outcomes. The authors concluded that to improve executive functions, exercise interventions need not be cognitively engaging, but should have moderate intensity and "chronic" duration (6-12 weeks).

Instructional Approaches. In addition to physical exercise, educational cognitive neuroscience now offers a wealth of information for building and designing effective instructional approaches for at-risk adolescents. Many educational neuroscientists consider this especially important now, because of academic losses among adolescents nationwide associated with over two years of COVID-19 pandemic restrictions. Throughout the school years, but especially during middle and high-school years, executive functions are essential for achievement in academic tasks that require problem solving, integrating multiple subskills, and metacognition. This includes not only domain-area competence in higher level literacy, writing, and mathematics, but also general academic skills such as goal-directed studying, test taking, and long-term projects [10,41]. Executive function strategies can also be specifically embedded within curricular content [41, see also the Digital Promise Learner Variability Navigator https://lvp.digitalpromiseglobal.org/content-area/literacy-7-12; https://lvp.digitalpromiseglobal.org/content-area/math-7-10]

Of specific importance are educational approaches that provide not only carefully designed and scientifically evaluated curricular content but those that also provide just-in-time cognitive remediation for students who present as at risk for academic failure.

Table 1: *Summary of Evidence-Based Program Reviews*

EVIDENCE REVIEW	*Brain Fitness and Executive Function* Brainfutures.org	*Exercise Interventions* Liang *et al.*, 2021	*Research-Based Certified Products* *Learner Variability Certified Products* Digital Promise.org
CONTENT	Cognitive Training Mindfulness Executive Function Skills Curricula	Cognitively engaging exercises (e.g., yoga) Aerobic exercises, (e.g., swimming)	Edtech product certification to ensure that products are research focused.
OUTCOMES	Significant increases in proficiency for math, reading, and core subjects Reduced disruptive behavior Increased prosocial behavior	Moderate-to-large positive effects on inhibitory control and cognitive flexibility	Product design is 1. research-informed 2. grounded in theory 3. the research basis is publicly accessible

Open Access Reviews

● BrainFutures, a nonprofit citizen advocacy organization, has developed a detailed review of evidence-based, affordable interventions shown to improve executive function skills and prosocial behavior [42 BrainFutures - Brain Fitness and Executive Function Report]. The independent review includes outcomes of ten programs, including cognitive training, mindfulness, and executive function skills curricula shown to increase proficiency on state-mandated tests for math and reading, reduce disruptive classroom behaviors, increase prosocial behaviors, and/or improve executive functions. Among the relevant outcomes they report are benefits from computerized cognitive training. On state standardized test data, elementary students who received cognitive training achieved 4 times greater math proficiency and 3 times greater reading proficiency, compared to students who did not receive the training [43, p.20-25].

● Digital Promise is a non-profit organization focused on spurring innovation in education. They offer product certifications for research-based products, as well as products that target individual learning needs.

Summary and Future Directions

Adolescence represents a second sensitive period of brain maturation. This period of rapid change provides a window of opportunity for schools and communities to foster the brain capacities essential for productive adulthood. The current review has emphasized the importance of cognitive skill development, the risks posed by demographics, adversities, and reduced access to social and emotional support, and the potential exacerbation of these risks during the recent COVID-19 pandemic restrictions. An upside of this research has been to spur a movement toward readily available and affordable evidence-based educational and remedial initiatives with positive psychological and cognitive impacts.

Future Directions

In addition to remediation, the research also points to the need to continue to design, develop, and refine middle and high-school curriculum based on the accumulating scientific data. As knowledge regarding adolescent brain development and learning has grown exponentially, opportunities to shape more effective educational practices, especially at the secondary level, have also grown. Insights gleaned over the past decade from many scientific disciplines, including neuroscience, cognitive science, and psychology, are converging as a new "science of learning" that can transform educational curriculum and methodology [43-45]. The foundational knowledge provided through these scientific inquiries, combined with the accumulated knowledge from decades of educational research, provides a framework for supporting adolescents' learning and welfare across the educational spectrum. Future directions need to be predicated on the importance of rethinking educational approaches and institutions designed decades ago. Schools and curricula can be organized around developmentally-supportive relationships as well as carefully scaffolded, evidence-based personalized instruction, tuned to the assets and needs of each student [46]. In secondary mathematics instruction, for example, advances in technology and artificial intelligence can formatively shape content, provide students with on-demand assistance, and assist teachers in identifying each student's unique strengths and learning challenges [47-49].

Secondary curriculum also needs to align with the research on the importance of executive functions, not just as an aspect of learning, but also as an essential component of brain maturation during the critical adolescent period. Many efforts are already underway in this regard. In literacy instruction, for example, Duke and Cartwright [50] have proposed an "Active View of Reading" that expands Scarborough's Simple View of Reading by adding regulatory executive functions with examples of the critical role cognitive skills play in literacy instruction.

At the secondary level, metacognitive skills are also an area of focus [46]. The metacognitive capacity known as Theory of Mind (ToM) is the ability to understand and take into account one's own and others' mental states. In a review, Weimer *et al.* [51] summarized the research on ToM as an important component of psychosocial development in adolescents, emphasizing the need for additional research to investigate its acquisition and application. The objective is to clarify whether ToM interventions can foster prosocial behavior in youth at risk of social-emotional difficulties. ToM is now recognized as especially relevant in the context of literacy instruction because of the social-emotional demands required to understand the perspective of an author or a literary character. Through exposure to high quality literature adolescents can build this understanding as well as learn to comprehend social cognitive constructs such as irony, sarcasm, and humor [51]. Secondary literacy curriculum and instruction provides another promising avenue for enhancement of self-regulation [52,53].

Conclusion

In conclusion, educational neuroscience research offers profound opportunities to provide and increase positive exposures for adolescents worldwide who are at risk of cognitive, behavioral and mental health issues. The research is providing a practical through-way for the learning sciences to refine educational practices and identify students at risk of cognitive or social-emotional issues before they fail academically or present with mental illness. The research literature should be actively applied to continue designing and scientifically evaluating sound instructional content and remediation methodologies.

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