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Executive function: A secret pathway to enter the future of adolescent brain cognitive development (ABCD)

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ABSTRACT

Objectives In this systematic literature review, we aim to investigate the research designs of studies on adolescent brain executive function (EF) over the past decade to deduce a potential approach for future studies.
Methods We performed literature searches on PubMed, Science Direct, and Google Scholar including studies that investigate adolescent brain development, specifically empirical studies between the years of 2012 and 2022 on adolescent EF using neuroimaging techniques. We then set up inclusion and exclusion criteria and performed study selection, data extraction, and data analysis.
Results Our findings illustrated that while there was a remarkable rise in adolescent EF studies over the past decade, there were few interventional studies that aimed at advancing the neural developmental opportunities of the adolescent years.
Conclusion These findings suggest that in order to define best practices for advancing adolescent EF, developmental cognitive neuroscience and the field of education need to form a stronger partnership to design more creative and appropriate interventions.
Keywords adolescence, executive function, neuroimaging, developmental cognitive neuroscience, education, partnership

Highlights

- This is a youth-centered review study. Youth researchers were a vital part of active learning and decision making.
- This big-picture review study sets its focus uniquely on the designs and aims of a decade of relevant research. Departing from the findings-oriented approach of typical systematic literature reviews, this study models a novel method for youth researchers who look to expand their horizons beyond their familiar fields.
- Drawing attention to the urgent need for research that advances adolescent brain executive function, this study brings to light the developmental significance of youth leadership.

INTRODUCTION

The adolescent brain, once seen as a burden, is now being recognized as an asset for its flexibility and neuropotential (Abrams, 2022). This change of perspective and the establishment of the interdisciplinary field – developmental cognitive neuroscience – led to a sharp increase in adolescent brain research in the past decade. While a large number of these studies investigated topics that are general to various age groups, some are focused on brain functional and structural changes that are unique to adolescence. Of course, neither the establishment of developmental cognitive neuroscience nor the change in perspective on the adolescent brain would have been possible without the innovations and rapid updates of neuroimaging techniques in the past few decades (Insel, 2011; Vistoli et al., 2015). For example, functional magnetic resonance imaging (fMRI) as an exceptionally useful tool for assessing brain function has already made a great impact on cognitive neuroscience (Ryan & Alexander, 2007).

Characterized by the rapid development of executive function, the adolescent brain is malleable, flexible, and full of possibilities (Crone, 2009; Abrams, 2022). Executive function, an array of brain processes subserved by the prefrontal cortex

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and related subcortical structures, is necessary for the conscious management of thought, emotion, and action (Powell & Voeller, 2004). After examining a multitude of literature on adolescent executive function, we ask the following research question:

To what extent have ABCD research designs over the past decade advanced neural developmental opportunities for adolescent executive function?

LITERATURE REVIEW

Before advanced neuroimaging techniques were made available, the scientific community as well as the general public believed that adolescence was a “troubling time” with the best outcome being “nothing too bad happened” (Ellis, 1979). With neuroimaging evolution in the late 20th century, researchers began to map brain activity and understand the human brain in action (Burunat & Brattico, 2017). New discoveries revealed the true potential of the adolescent brain, especially the wondrous development of executive function.

Myths and the adolescent brain

Several myths about the adolescent brain are, to date, held as societal beliefs. The work of neuroscientists and psychologists in the first half of the 20th century had contributed to these myths. For a long time, scientists believed that brain growth is mostly complete before a child starts school. Because of this, the adolescent brain was seen as the same as the adult brain (McMillan, 1919; Dobbing & Sands, 1973; & Cabana et al., 1993). Other myths include: it is the surging hormones during the teenage years that make teenagers impulsive and emotional (Buchanan et al., 1992; Buitelaar, 2012; & Dahl, 2003), and teenagers want to be difficult because of the rebellious nature of this challenging time (Levin, 1982; Abramson et al, 1979; & Maigallo, et al., 2015). The myth about a child’s IQ and talents was likely the most damaging as it claimed that IQ and talents do not change throughout life (Smith, 2009; Blinkhorn, 1997; & Kotkin, 1978).

Neuroimaging

Marked by the advent of advanced neuroimaging techniques including magnetic resonance imaging (MRI) with the capacity to provide highly accurate images of brain anatomy, ABCD research entered a new era (Giedd, 2008). Neuroimaging is a discipline that uses computer techniques and imaging technology to study the structure and function of the nervous system (Zhang et al., 2020). There are generally two types of neuroimaging techniques: one measures the electric activity of brain cell groups, such as electroencephalography (EEG) and magnetoencephalography (MEG), and the other measures the change in blood flow associated with brain activity, such as functional magnetic resonance imaging (fMRI), near-infrared spectroscopy (NIRS), diffusion tensor imaging (DTI), and positron emission tomography (PET) (Morita et al., 2016). In developmental cognitive neuroscience, neuroimaging tools are often used with performance measures and structured questionnaires (Faridi, et al., 2014).

New discoveries of the adolescent brain

On account of the neuroimaging innovations, researchers began to combat the myths about the adolescent brain. Contrary to the popular belief, brain development continues throughout childhood and adolescence, and the maturation can go well into the third and even fourth decade of life (Johnson et al., 2009; Sekartini, R., 2021; & Counotte, D. S., 2010). This protracted process of brain development is like stacking building blocks – from the bottom up and inside out, with the frontal lobe developing at a later time (Giedd, 2008; Talukdar & Gohain, 2018). One of the most profound changes of brain growth during adolescence is the development of the prefrontal cortex with its executive functioning or EF, which is assumed to be associated with abilities such as response inhibition, attention, regulation of emotion, organization, and long-term planning (Goldfus & Karny-Tagger, 2017). Because of this, researchers recognized that many of the “problematic” behaviors of adolescents are indeed connected with the structural and functional state of the adolescent brain. When a lack of inhibition control and long-term planning is coupled with heightened reward seeking tendencies, the adolescent brain is bound to create turbulence for teens and young adults. On the other hand, because of the drastic neural reorganization, adolescence is also a period that is full of possibilities, especially its potential for learning and EF advancement (Dow-Edwards et al., 2019). Researchers have also discovered that because the brain is changing so much during adolescence, its organization can be influenced by experiences, which makes leaps in intellectual and emotional development during adolescence possible (Mills & Anandakumar, 2020).

Executive function

Executive function or EF is an umbrella term that encompasses a range of cognitive operations including goal-setting, big-picture thinking, planning, working memory, impulse control, task switching, and inhibition, all of which require coordinated neural activation in the prefrontal cortex and a number of other brain regions (Rudolph et al., 2006; Riggs et al., 2006; Brown, 2014). Adolescence is characterized by rapid EF development (Satterthwaite et al., 2013).

For the purpose of this review, we chose the three-factor EF framework proposed by Miyake et al. (2000), because it has been influential to developmental cognitive neuroscience (Anderson & Reidy, 2012). The framework is composed of three interrelated, yet distinguishable EF processes: inhibition, switching, and working memory (Harmon et al., 2020). Inhibition or inhibitory control is the ability to override the dominant responses (Mittal et al., 2015). Switching is the ability to shift attention between tasks or strategies (Peng et al., 2012). Working memory is the ability to retain accurate information in the face of distraction and manipulate the information over a brief period of time (Kapa & Plante, 2015; Yowler, 2019).

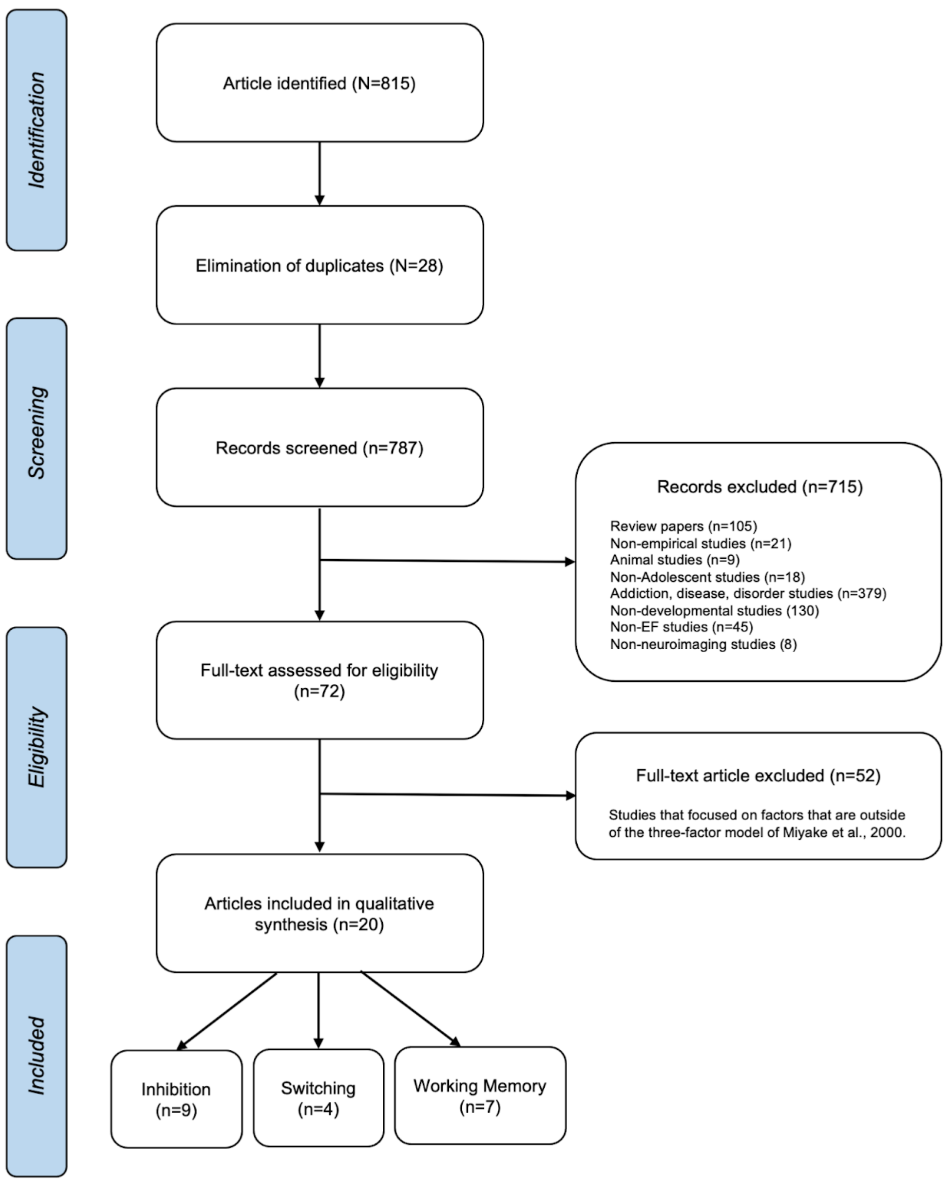

Figure 1 PRISMA flowchart of article selection

METHODS

Literature search

Our search strategy was designed to identify empirical studies that investigated the development of adolescent EF using neuroimaging techniques. The literature search was performed in the databases of PubMed, Science Direct, and Google Scholar. We used the following search terms: "Adolescent brain development" AND "executive function" AND "neuroimaging," and included all studies published between 2012 and 2022.

Inclusion and exclusion criteria

The inclusion criteria were: (i) empirical studies; (ii) studies among adolescent human subjects; (iii) studies that investigate adolescent EF; (iv) studies conducted from a developmental perspective; (v) studies that employ neuroimaging techniques.

The exclusion criteria were: (i) studies that focus on addiction, diseases, and disorders; (ii) studies that investigate the associations between EF and issues such as abuse, bullying, crime, injury, digital media, diet, physical exercise, sleep, and socio-economic status; (iii) genetic studies; (iv) studies that employ self-reported questionnaires and/or cognitive tasks as the only measurements of brain development; (v) studies that investigate issues that are outside of the three-factor EF framework by Miyake et al. (2000).

Study selection

Two reviewers performed literature selection independently according to the inclusion and exclusion criteria. Discrepancies among the reviewers were resolved through discussion and consensus. To determine eligibility, the titles and abstracts of all non-duplicate articles were screened.

Data extraction

Two reviewers independently collected the following data from articles included in qualitative synthesis: (1) author and year of publication, (2) participant info including sample size, age group, and gender ratio, (3) study design including type of the design, EF focus, neuroimaging technique, assessment task, and comparison criteria, (4) outcome and main findings. Discrepancies among the reviewers were resolved through discussion and consensus. All information extracted is presented in the Description and Main Results Table.

RESULTS

Participants

Of the 20 studies included in the qualitative synthesis, eight studies had more than 100 participants, with the largest study having 951 participants. Regarding the age range of the participants, there were four studies comparing two different age groups and one study comparing three different age groups. In one study, Mennigen et al. (2014), all participants were 14 years old. The rest of the studies included participants from childhood to late adolescence and early adulthood. Eight of the 20 studies did not provide data regarding the gender ratio of the participants.

Study designs

In this systematic literature review, we recognized two broad categories of study design: observational and interventional. There were a total of three interventional studies and 17 observational studies. Regarding the EF focus, there were nine studies on inhibition, four studies on switching, and seven studies on working memory. As for the neuroimaging technique, besides four studies that employed DTI and MEG, all other studies relied solely on fMRI. EF assessment tasks used in inhibition studies include the following: Go/No-Go, antisaccade & prosaccade, Dimensional Change Card Sort, Flanker, Stroop, Stop Signal and Simon, Attention Network, Trail Making, N-Back, Emotional Stroop, and NEPSY-II. Studies on switching involved WASI estimate of IQ, Digit Span and Coding, Woodcock-Johnson III Cross-Out, and Stroop Color and Word task. Working-memory studies employed WebNeuro, Behavioral Rating Inventory of Executive Function (BRIEF), Wechsler Scale of Intelligence for Children-III Digit Span, Cambridge Neuropsychological Test Battery Spatial Working Memory (CANTAB SWM), N-Back, and memory guided saccade.

The Description and Main Results Table below shows detailed comparisons and synthesis of the 20 studies.

Author (year)	Participants			Study Design				Outcome
	Sample (n)	Age	Gender ratio (% of males)	Type	EF Focus	Neuroimaging Technique	Assessment Task	Main Findings
Chung et al. (2020)	130	12-25	51%	Observational	Inhibition	fMRI	Go/No-Go Tasks	Functional connectivity sex differences were observed in several subcortical regions (amygdala, caudate, thalamus, etc.) and cortical regions including inferior frontal gyrus engaged most strongly during successful response inhibition and/or error processing; adolescent boys and girls exhibited different normative profiles of age-related changes in several default mode networks of regions and anterior cingulate cortex.
Hwang et al. (2016)	37	14-16, 20-30	49%	Observational	Inhibition	MEG	Antisaccade task, prosaccade task	Adults' AS was associated with increased beta-band power in the dorsolateral prefrontal cortex (DLPFC), enhanced alpha- to low beta-band power in the frontal eye field (FEF) that predicted performance, and increased cross-frequency alpha-beta amplitude coupling between the DLPFC and the FEF; developmental comparisons between adults and adolescents revealed similar engagement of DLPFC beta-band power but weaker FEF alpha-band power, and lower cross-frequency coupling between the DLPFC and the FEF in adolescents.
Kryza-Lacombe et al. (2020)	43	10-17	46.50%	Observational	Inhibition	fMRI	Dimensional Change Card Sort task, Flanker task	Executive functioning moderated youths' neural responses during both reward anticipation and performance feedback, predominantly with respect to amygdala connectivity with prefrontal/frontal and temporal structures; youths with worse executive functioning had more pronounced differences in neural activation and connectivity between task conditions compared to youths with better executive functioning.
Menu et al. (2022)	137	9-10, 15-17	N/A	Interventional	Inhibition	fMRI	Stroop task, Stop Signal and Simon task, Attention Network Task, Trail Making Test, N-back task	Quantitative and qualitative changes were detected in the EF network structure with age and with cognitive training; the EF network structure in children after training was more similar to adolescents' network than before training.
Ordaz et al. (2013)	123	9-26	48%	Observational	Inhibition	fMRI	Antisaccade task, visually guided saccade task	Distinct developmental trajectories for regions within each circuit; mean growth curves of activation in motor response control regions revealed no changes with age; activation in certain executive control regions decreased with age until adolescence, and variability was stable across development; error-processing activation in the dorsal anterior cingulate cortex showed continued increases into adulthood.
Salvia et al. (2019)	60	16-17	35%	Interventional	Inhibition	fMRI	Color-Word Stroop task, Emotional Stroop task	Regional Homogeneity (ReHo) and fractional Amplitude of Low Frequency Fluctuations (fALFF) signals were sensitive markers to detect and monitor changes after Inhibitory Control (IC) training; ReHo and fALFF signals in IC areas were associated with IC efficiency at baseline; the association was different for Cool and Hot IC.

Author (year)	Participants			Study Design				Outcome
	Sample (n)	Age	Gender ratio (% of males)	Type	EF Focus	Neuroimaging Technique	Assessment Task	Main Findings
Treit et al. (2014)	49	5-16	59%	Observational	Inhibition	DTI	NEPSY-II Inhibition test	Several clusters in the frontal projections of the corpus callosum, where higher FA was associated with worse inhibitory performance; several clusters in posterior brain regions and one in the brainstem where higher FA was associated with better cognitive flexibility.
Vara et al. (2014)	30	13-17, 20-25	77%	Observational	Inhibition	MEG, MRI	Go/No-Go Task	Recruitment of the right inferior frontal gyrus in adults , but delayed recruitment of the left inferior frontal gyri in adolescents; left anticipatory-related activity near the hand motor region was present in both adolescents and adults, but for a longer duration in adults; adolescents additionally recruited the right middle and superior temporal gyri , while adults engaged the right temporal gyrus but for a much briefer duration.
Vink et al. (2014)	60	10-25	42%	Observational	Inhibition	fMRI	Stop-signal anticipation task	Older subjects were faster in reactive inhibition with a paralleled increase in motor cortex suppression; older subjects' level of proactive inhibition increased; activation increased in the right striatum, right ventral and dorsal inferior frontal gyrus, and supplementary motor area; functional connectivity during proactive inhibition increased between striatum and frontal regions with age.
Church et al. (2017)	58	9-15, 21-30	N/A	Observational	Switching	fMRI	Two-test WASI estimate of IQ, the Digit Span and Coding task from the WISC-IV and WAIS-III, the Woodcock-Johnson III Cross-Out task, the Stroop Color and Word task	Children performed more slowly with less accuracy and exhibited weaker Cue period activation in a number of putative cognitive control regions; children exhibited greater activity in sensorimotor areas; children who activated cognitive control-related regions more during the Cue period tended to activate the Target signal age-related regions less.
Mennigen et al. (2014)	185	14	N/A	Observational	Switching	fMRI	combined response interference switching task	An overlapping cognitive control network is recruited by conflicts arising from task switching and response incongruence; higher blood oxygenation level dependent (BOLD) responses calculated as the reaction time differences between incongruent and congruent trials; increased activation of the default mode network was only observed in congruent trials.
Seghete et al. (2014)	84	10-16	46%	Observational	Switching	DTI	Color-word interference task of the Delis-Kaplan Executive Function System	Better inhibition was associated with greater fractional anisotropy (FA) in the anterior corona radiata (ACR), independent of age; better task-switching, regardless of age, was associated with greater FA in the superior corona radiata (SCR); the association between FA in the ACR and task-switching was dependent on age.

Author (year)	Participants			Study Design				Outcome
	Sample (n)	Age	Gender ratio (% of males)	Type	EF Focus	Neuroimaging Technique	Assessment Task	Main Findings
Ward et al. (2019)	30	18-25	N/A	Observational	Switching	fMRI	Block-design task Patterns of frontoparietal activation	Task-switching was associated with activation of left premotor and inferior parietal regions; dual-tasking was associated with activation in regions of right prefrontal and inferior parietal cortex; a distributed bilateral pattern of activation across the areas associated with each demand in isolation was observed in the interaction condition.
Breukelaar et al. (2018)	69	18-38	N/A	Observational	WM	fMRI	WebNeuro	During the WM task, increased connectivity of frontoparietal network regions was associated with improved WM and EF; age, gender, or baseline performance do not have an impact on the association.
Faridi et al. (2015)	347	6-16	46.7%	Observational	WM	MRI	Behavioral Rating Inventory of Executive Function (BRIEF), Wechsler Scale of Intelligence for Children-III Digit Span, Cambridge Neuropsychological Test Battery Spatial Working Memory (CANTAB SWM)	BRIEF WM was correlated with CANTAB SWM; BRIEF WM and emotional control were both correlated with cortical thickness of the posterior parahippocampal gyrus; performance measures of WM were associated with volumes of hippocampus and amygdala.
Huang et al. (2016)	39	9-12	N/A	Observational	WM	fMRI	Spatial 1-back task with two memory load conditions	Load-dependent deactivation in default network regions predicted individual differences in task performance; increased prefrontal-parietal coupling was associated with better performance.
Moisala et al. (2018)	167	13-14, 16-17, 20-24	N/A	Observational	WM	fMRI	Attention task, *n*-back task	Older participants performed better in all tasks; older participants showed less task-specific functional connectivity between frontoparietal regions
Satterthwaite et al. (2013)	951	8-22	N/A	Observational	WM	fMRI	Fractal *n*-back task	Limited associations between WM and age; robust associations between WM performance and activation of the EF network and deactivation of the default mode network.
Simmonds et al. (2017)	129	8-30	49%	Observational	WM	fMRI	Memory guided saccade task	From childhood to early adolescence, increased sensorimotor-related activity in visual cortex was associated with WM accuracy; decreased sustained activity in executive regions was associated with response latency.
Takeuchi et al. (2014)	81	18-26	73%	Interventional	WM	fMRI	Regional gray matter volume, functional connectivity during rest	The multitasking training was associated with increased regional gray matter volume and decreased resting-functional connectivity in certain regions of the brain.

DISCUSSION

Despite the influx of research articles on adolescent brain development in the past decade, many aspects of the adolescent brain remain unexplored. We conducted this systematic review to answer the question of "how various ABCD research designs have advanced neural developmental opportunities for adolescent executive function." Our data extraction and synthesis showed that despite the overwhelming consensus on the great potential of the adolescent brain, only a diminutive number of studies aimed at "advancing opportunities." Below we discuss this phenomenon in a decade of ABCD research as well as its possible causes.

Preventing problems vs. advancing opportunities

By investigating the body of literature from the past decade, we hoped to establish an understanding on the ways in which researchers create opportunities to take advantage of the unique development window of adolescent EF. After eliminating irrelevant articles such as reviews, non-empirical studies, animal studies, and non-adolescent studies, we found that almost 70% of the literature was on addiction, disease, and disorder. Though some of these studies employed a developmental perspective, the aims of these studies were generally on treatments and prevention of health issues, not creating opportunities to advance adolescent EF. It indicates that research on adolescent brain development is currently established as a sub-branch of neuroscience and medicine, rather than an interdisciplinary field that involves education, psychology, and neuroscience.

Intervention vs. observation

Of the 20 studies included in the qualitative synthesis, there were only three interventional studies, and the remaining 17 studies were all observational studies. As Thiese (2014) pointed out, observational studies are often retrospective while interventional studies are prospective; and as Birnbaum et al. (2017) explained, observational studies add knowledge and understanding to the situation while interventional studies are used to define the best practices. In comparison to observational designs, interventional designs require more financial and human resources, but the shortage in interventional studies is also a reflection of the lack of capacity for producing well defined EF interventions of which the outcome and impact can be quantified (Corner, 2012). On one hand, to increase the capacity for designing EF interventions, researchers should draw elements from educational practices. On the other hand, however, it is the input of neuroscience that ensures quantifiable outcomes. This means that a partnership between education and neuroscience will likely generate interventional designs that are sound and applicable.

EF development in relation to age

Adolescent EF development involves both structural and functional changes. Our literature screening showed that a significant amount of adolescent EF studies use reference maps of the adult brain to analyze the adolescent brain structure and function. This is a common practice among developmental fMRI studies. In recent years, however, this practice has been challenged, reasoning that the approach may limit the characterization of functional activity patterns that are particular to adolescents (Kundo et al., 2018). Besides using the adult brain as the "gold standard," researchers have also been seeking associations between adolescent EF and age. Studies that investigate EF in relation to age, such as Satterthwaite et al. (2013) and Marschark et al. (2021), have produced limited and conflicting results. This lack of association between EF and age combined with the diminishing gold standard of the adult brain indicate that compared to other brain functions, EF development may be associated more closely with individual experiences rather than age. This notion strengthens the findings of previous studies: adolescent EF can be influenced by experience and therefore makes leaps in intellectual and emotional development possible (Mills & Anandakumar, 2020).

EF & education

When it comes to adolescent EF, educators are, by and large, strong believers of influence and individual experiences. When an adolescent shows signs of low executive function, the adolescent may be considered as "immature," but this consideration seldom stops educators from trying various ways to help. Rather than simply waiting for the adolescent brain to "mature," educators choose to influence the adolescent EF development by implementing various approaches. And they continue to do so year after year because their first-hand experience tells them that it can work. With the establishment of developmental cognitive neuroscience, it is now possible to translate educators' day-to-day approaches to purposeful interventional designs with added quantifiable neuroimaging measures. For a long time, neuroscience was expected to inform educational practices (Brandt, 1999; Diamond & Amso, 2008; Dubinsky, 2010; & Zambo & Zambo, 2012). Recently, however, researchers began to recognize the seemingly obvious: neuroscience cannot be expected to provide direct educational applications, but the applicability of developmental neuroscience lies in creating a deeper understanding of the underlying cognitive mechanisms of learning processes (Stubenrauch et al., 2014).

CONCLUSION

Adolescent executive function is an exciting field that is yet to be fully explored. Our systematic investigation of the mountain of relevant literature concludes that: (1) the need for research that advances adolescent EF is urgent, (2) the shortage in interventional research designs is apparent, and (3) the association between adolescent EF development and interventions is observable. We therefore present a potential framework for a partnership between developmental cognitive neuroscience and the field of education. This partnership will be poised to generate creative and appropriate EF interventions that are rooted in effective educational practices with quantifiable neuro-outcomes, which will address the need and the shortage in interventional research designs that aim to advance adolescent EF; and this in turn, will create a space as well as a demand for educators to be involved in adolescent EF research.

As a design focused systematic literature review, we were unable to perform a deeper examination of the findings of the chosen studies. Meanwhile, the three search engines that we employed meant that relevant literature outside of these three engines was not included. We also recognize that there is criticism of the three-factor EF framework that we adopted to identify eligible articles. In addition to addressing these limitations, we recommend future researchers to explore the proposed partnership by conducting theoretical as well as empirical studies.

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