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for every child

The Adolescent Brain: **A second window of opportunity**

A Compendium

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Office of Research-Innocenti

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UNICEF is most grateful to Todd Siler and to Ronald Feldman Fine Arts, New York for the rights to use the works of art reproduced in this publication.

Todd Siler, PhD, is an American multimedia artist, author, educator, and inventor, equally well known for his art and for his work in creativity research. He describes his philosophy as “Realizing human potential. That’s my life’s work. Those three words sum up everything I live for and aspire to accomplish through my art.” Many of his works are inspired by the brain and its functioning and his interest in its power and flexibility.

COVER
Todd Siler
Below the Clouds of Consciousness, 1989
Mixed media on paper
4 x 12 ft
Courtesy Ronald Feldman Fine Arts, New York

Pages 6-7
Todd Siler
Crossing the Primordial Bridges between Art
Science Technology in Human Nervous Systems,
1989
Courtesy Ronald Feldman Fine Arts, New York

Pages 18-19
Todd Siler
What Are All the Dimensions of Consciousness?
1988-1989
Courtesy Ronald Feldman Fine Arts, New York

Pages 26-27
Todd Siler
Humanature – A Turbulent Integration, 1991
Courtesy Ronald Feldman Fine Arts, New York

Pages 36-37
Todd Siler
Evolution of Abstract Realism, 2010-2011
Mixed media on paper
22 x 35 inches
Photo: Bill Orcutt
Courtesy Ronald Feldman Fine Arts, New York

Pages 46-47
Todd Siler
Mind Icon No.7 (Metaphorming Conscience), 1991
Multi-colored serigraph on Arches 300gm paper
40 x 60 cm
Courtesy of Ronald Feldman Fine Arts, New York

Pages 54-55
Todd Siler
Metaphorming Civilizations, 1992-1993
Courtesy of Ronald Feldman Fine Arts, New York

Pages 62-63
Todd Siler
Metaphorming Humanature. Humankind's
Integration with Nature, 1989
Courtesy of Ronald Feldman Fine Arts, New York

Pages 72-73
Todd Siler
Envisioning a Cornucopia of All-purpose
Nanomaterials (2014)
Mixed media on synthetic canvas
6 x 12 ft
Courtesy of Ronald Feldman Fine Arts, New York

Pages 80-81
Mind Icon No.8 (Questioning Our Evolution), 1991
Multi-colored serigraph on Arches 300gm paper
40 x 60 cm
Courtesy of Ronald Feldman Fine Arts, New York

CONTENTS

THE ADOLESCENT BRAIN: A SECOND WINDOW OF OPPORTUNITY

A Compendium

FOREWORD

UNICEF Executive Director, Anthony Lake

Few things irritate adolescents more than being told what to do – or how to think. Their need for independence is not only emotional. Adolescence is a critical developmental phase of life, a time during which children acquire the social skills they need to thrive as adults.

Just as critically, it is also the time in which their brains develop – or fail to develop – in a way that enables them to reach their full potential in life.

We already know that in the earliest years of childhood, children's brains form neural connections at a rate never to be repeated. This is the first window of opportunity to influence the development of children's brains through nutrition, stimulation and protection from violence and other harms.

But a growing body of scientific knowledge shows that experience and environment also combine with genetics to shape the brains of adolescents. This presents a second, crucially important window of opportunity to influence the development of children's brains – and thus, their futures.

In 2016, UNICEF hosted *The Adolescent Brain: A second window of opportunity*, a symposium that brought together experts in adolescent neuroscience to discuss this emerging science and how we can apply it to support *all* adolescents – but especially those already facing risks to their well-being, including poverty, deprivation, conflict and crisis.

The articles in this compendium elaborate on some of the ideas shared at the symposium. Together, they provide a broad view of the dynamic interactions among physical, sexual and brain development that take place during adolescence. They highlight some of the risks to optimal development – including toxic stress, which can interfere with the formation of brain connections, and other vulnerabilities unique to the onset of puberty and independence.

They also point to the opportunities for developing interventions that can build on earlier investments in child development – consolidating gains and even offsetting the effects of deficits and traumas experienced earlier in childhood. Evidence shows that practical approaches – including safe and secure environments, or the presence of a caring adult – can help counteract the effects of trauma and lay a better foundation for optimal development.

The symposium also highlighted the importance of greater collaboration between the scientific research community and development professionals to develop and implement policies and programmes that apply the new science – something we at UNICEF will explore more concretely with partners in the months and years ahead.

With 1.2 billion adolescents in the world today, all of us have a stake in helping them to reach their full potential. For today's independence-seeking adolescent is tomorrow's doctor. Tomorrow's teacher. Tomorrow's worker. Tomorrow's leader.

Their future is the future of our world.

Anthony Lake
Executive Director, UNICEF

INTRODUCTION

Crossing the Primordial Bridges between Art Science Technology in Human Nervous Systems (1989)

INTRODUCTION

Scientific advances over the past decade have contributed to a much greater understanding of the growth of the human brain from birth to adulthood. Latest evidence illuminates the adolescent brain as a ‘work in progress’, and adolescence as a critical period to build on early investments, offering a second chance for those who have not fared well in early childhood. Neuroscientific research in particular is integral to improving our understanding of the cerebral transformations that take place during this time and how they are influenced by interactions between the evolving adolescent brain and the environment in which it develops. In the field of early childhood development (ECD), neuroscientific evidence featured prominently in galvanizing positive change for children through changes in policy and programming and more of this type of evidence is needed to also provide answers regarding critical intervention junctures and approaches during adolescence. In this compendium, eight experts in adolescent neuroscience and development summarize scientific and programmatic evidence from their work, offering an insight into how to maximize the potential of adolescents during this period of opportunity, but also vulnerability. It builds on the discussions initiated at a one-day symposium entitled *The Adolescent Brain: A second window of opportunity*, held on 4 May 2016 at UNICEF headquarters in New York. The event brought together specialists to review the state of science related to the adolescent brain, specifically focusing on how to guide future responses to programming and policy and providing directions for research to further advance these aims.

Experience from the early 1990s brought scientific thinking and biological evidence on ECD into the mainstream of programmes for young children (Shonkoff and Phillips, 2000) and catalysed a critical turning point in inter-sectoral programming approaches from the neonatal period through infancy into toddlerhood. Early childhood neuroscience has been formative in programme development for children in that age category, informing programmes and advocacy around nutrition, protection, play and many other areas; but the field has not adequately examined the continuum of development into adolescence.

The advances and investments made in ECD must be continued for children in their second decade of life. Adolescence is a time of both opportunity and vulnerability. Many problematic and risky behaviours are activated in adolescence, including substance abuse, and behaviours that can lead to sexually transmitted diseases (STIs), HIV/AIDS, road injuries, drowning and other negative outcomes (Mokdad, 2016). It is a time when mental illness and the incidence of suicide sharply increases (Petroni, Patel and Patton, 2016) and when experiences of bullying, inter-personal violence and exclusion often leave a long-term mark on the individual (Lupien, 2012). The vulnerability of adolescents is significantly exacerbated by growing up in environments of chronic stress, such as armed conflict, violence and extreme poverty. Organizations working in humanitarian and resource-poor settings desperately need science to provide answers regarding the most cost-effective interventions that can maximize the potential of adolescents and provide them with the opportunity to develop into healthy and successful young adults.

Advances in technology and scientific methods, such as Magnetic Resonance Imaging (MRI), have gradually made it possible for scientists to better understand the nature of the changing adolescent brain and the underlying motivations for different behavioural outcomes during this pivotal period of development. These advances in knowledge have leapt from laboratories and academic journals, and can now be found in mainstream newspapers and magazines. Countless books have appeared on the topic, explaining why adolescents behave the way they do – some of them bestsellers. The wide interest is prompting a global community of researchers, practitioners, scientists, service deliverers and parents to ask the question: How can we use this information to enhance policy and programme responses that improve outcomes for adolescents?

The commentaries in this compendium together summarize the state of adolescent neuroscience, reflecting on what is known about positive and negative impacts on brain development, including the effects of poverty, violence, stress, technology, but also socio-emotional learning, meditation, nutrition, counselling and positive relationships. They go beyond the science to discuss its application for maximizing the potential of adolescents.

This compendium is designed to encourage further dialogue stimulated by new thinking grounded in adolescent neuroscience research and its application. It aims to challenge readers to bring science to bear on programme interventions and public policies for adolescents. An improved understanding from neuroscience is well-placed to strengthen behavioural evidence and provide a more complete picture of adolescent behaviour and development, while also stimulating fresh thinking and approaches that can be tested.[1]

1 For an in-depth discussion of how neuroscientific thinking could support public policies that address adolescents, see Steinberg, 2012; 2014.

Key themes from expert commentaries

The key themes summarized in the commentaries reflect many of the challenges and opportunities identified in the broader neuro- and social-science literature on adolescent development – or in the words of Dahl and Suleiman (see pages 19-23), the positive and negative 'spirals' that begin and continue through this period of rapid change.

Unsurprisingly, the theme of **transitions** experienced during adolescence is strongly present in several of the commentaries. At the individual level, the adolescent is transitioning physiologically from child to adult and is subject not only to pubertal changes which lead to sexual maturity, but also to structural remodelling and neuronal reconfiguring of the brain, resulting in increased ability for adult-level reasoning. As these physical, sexual and cerebral changes transpire, the adolescent is at the same time finding her or his place in social hierarchies; a process accompanied by enhanced emotions of wanting to belong, be accepted and admired by peers.[2] Another transition is that of societal expectations of adolescents, which tend to change during this period, with the adolescent enjoying more respect, but also having more responsibility. Social transitions during this period may include those between primary and secondary school, tertiary education and the workplace. They are not always linear, with many adolescents not having the opportunity to complete all of these stages or completing them in a different order. Another life-changing social transition experienced by some adolescents, particularly those living in low- and middle-income countries is that of marriage and parenthood, requiring them to take on adult roles. All of these experiences require new and increased levels of responsibility and can result in increased levels of stress for the adolescent (Lupien et al. 2001). From a global perspective, the period of adolescence itself is undergoing a transition. Demographic and epidemiological shifts at the population level – such as lower fertility and mortality, longer life expectancy, and reductions in infectious disease (UNFPA, 2014; UNICEF, 2016) – have resulted not only in the largest cohort of adolescents inhabiting the world today, but in many contexts also in an earlier onset and later conclusion of adolescence (Reavley and Sawyer, 2017). Choudhury (pages 39-45) points out that a transitional period of adolescence occurs in most cultures, but the duration, expression and salience of particular developmental traits may differ across cultures. Several commentaries (Choudhury, Noble, Ward) examine the joint influence of the **environment** and **individual experience** on how the brain is sculpted.

Choudhury introduces the concept of the '**situated brain**' which incorporates the influence of culture into the study of adolescent brain development and argues that lived experience, developmental histories, dynamic interactions, and cultural contexts

2 For details see commentary by Dahl and Suleiman in this compendium.

interact with biological processes to influence the making of the adolescent individual. Noble's commentary (pages 49-53) focuses on the role of external factors such as **poverty,** highlighting the greater risks to mental and physical health that are associated with living in low-income settings. She cites a study which found that in a sample of 66 US families from a range of socio-economic backgrounds, socio-economic differences had no effect on an infant's brain function at birth (Brito et al. 2016), but contrasts this with a study with an older sample, which showed that later in life parental educational attainment and family income is related to differences in the size of the cerebral cortex (Noble et al. 2015). The studies suggest that while there is general similarity in the functioning of infants' brains regardless of family socio-economic status, these external factors are influential in sculpting the developing brain later in life.

While socio-economic status influences adolescent outcomes in the long-term, at the inter-personal level, a more immediate influence is that of **peers** and potential romantic partners. Several commentaries (Dahl and Suleiman, Ward, Lupien, Luna) highlight the strong motivation of adolescents to engage in **social learning** and their desire for acceptance, belonging, respect and admiration. They are also highly driven by the promise of obtaining **immediate rewards** – a tendency associated with sensation-seeking and risk-taking. Luna's commentary (pages 29-35) unpacks how adolescents' newly developed abilities to reason can be engaged in the context of reward-seeking to facilitate positive outcomes and reduce risk-taking behaviours that undermine survival.

What works?

Epidemiological research suggests that population stressors, including war and famine, experienced in early adolescence (10-14 years of age) are more strongly associated with a decrease in total life span than stressors experienced at any other age of childhood. This makes early adolescence a crucial time for certain types of intervention.

Responding to UNICEF's request to guide future discussions on policy and programming to fulfil the potential of adolescents, a number of authors dedicated their commentaries to answering the question of "What works?" to maximize positive opportunities and reduce the impacts of negative stressors during this rapid stage of development. Dahl and Suleiman (pages 21-25) put forth a strong argument that early adolescence presents a unique window of opportunity for prevention and early intervention, as it is during this time that many negative physical and mental health outcomes first begin to manifest themselves. As the onset of puberty interacts with intensified neurological development, this group also experiences a sharp increase in accidents, suicides, substance use, and eating disorders, mental disorders, unwanted pregnancies and other negative outcomes. When exposed to stressors such as war and famine during early adolescence, the effects are more negative and lasting than when experienced during any other developmental phase. The authors make a case for specialized learning which appeals to adolescent motivations, such as engagement in social roles with peers and potential romantic partners, while remaining mindful of adolescents' strong desire for acceptance, belonging, respect and admiration.

Elizabeth Ward (pages 65-70) writes about a comprehensive **resiliency programme** in Jamaica called BALANCE. The programme guides adolescents through the process of learning positive and unlearning negative behaviours, minimizing risks and building life skills. Its architecture is based on an understanding of how the adolescent brain functions, 'putting the brakes on' risk-taking behaviours and promoting maturity in decision-making. The multi-faceted programme includes components of therapy, relaxation, nutrition, academic achievement, parenting attachment enhancement, spirituality and sexuality, mindfulness and counselling, and in line with the recommendations made by Choudhury, takes into account the contextual stressors and opportunities in which the brain is developing.

Another example of a resiliency programme for adolescents is **DeStress for Success**, developed and executed by Sonia Lupien's team from the University of Montreal in Canada. In her commentary (pages 57-61), Lupien describes how the developing adolescent brain is extremely sensitive to stress, with a chronic production of stress hormones affecting learning, memory, emotional processing and mental health. The intervention her team developed recognizes and deconstructs stress based on four situational determinants captured in the acronym 'NUTS': novelty (N), unpredictability (U), threat to personality (T) and a sense of low control (S). The programme equips adolescents with skills for managing and coping with stress and is also available as a web-based platform (*Stress Inc*©) and a mobile phone application (*iSMART*©) able to detect chronic stress, making its benefits available in settings where face-to-face delivery may not be possible.

Yi-Yuan Tang dedicates his commentary (pages 75-78) to the benefits of mindfulness, which is also one of the components of the BALANCE programme in Jamaica. Tang's **mindfulness meditation** includes at least three components that interact to enhance self-regulation: enhanced attention control, improved emotion regulation and altered self-awareness. His research suggests that mindfulness training is highly advantageous to the growth and sculpting of the adolescent brain and general well-being, showing positive effects on attention, emotion, immune function and a reduction in stress. This low-cost intervention was shown to be more effective than other relaxation trainings and could be used to enhance self-control of cognitive, affective and social capacities in adolescents.

Offering a different perspective on an 'intervention' which could both improve and harm adolescent brain development, Melina Uncapher (pages 83-88) shares her research on **action video games** and other interactions with technology. She reports findings that adolescents who frequently engage in playing action video games have different brains to non-gamers, with the former performing better on: perceptual decision making, speed of processing, ability to overcome attention capture, memorizing visually presented information, multi-tasking and rapidly switching between two tasks (Bejjanki et al. 2014; Mishra et al. 2011; Bavelier et al. 2012). The downside of such games is that they often include violent content which has been linked to increased aggression in players. Uncapher's recommendation for policy and practice is to promote a sensible 'technology diet', where balanced and thoughtful use of technology during adolescence maximizes the benefits and minimizes the risks.

The commentaries emphasize that interventions targeting adolescents would do well to capitalize on their emergent adult-level reasoning and heightened motivation towards immediate rewards. Depending on the desired outcomes, interventions can be: at the policy level, such as cash transfers to mitigate the negative effects of poverty on adolescent brain development; at the community level, such as the multi-faceted BALANCE programme; or at the individual level, such as well-designed action video games that improve cognitive functioning.

Challenges for the future

As the field of adolescent neuroscience develops, the application of findings to interventions will face an important challenge of how to understand the complex relationships between developmental biology and the environments in which adolescents live. Much of the neuroscientific evidence is developed in the global North, and more information is needed to reflect the diverse experiences of adolescents around the world, including in harsh situations of war, conflict, chronic stress and malnutrition. An inter-disciplinary effort is needed to fill knowledge gaps, situate evidence from brain research within a larger body of science,[3] and consider a range of biological, behavioural, socio-economic, and contextual factors to build a broader and more inclusive understanding of developmental processes.[4]

That is not to say that laboratory research cannot be applied in the real world. Lupien's *DeStress for Success Program* has a theoretical framework rooted in psychoneuroendocrinology and was built on laboratory results which were transferred

3 See commentaries by Dahl and Suleiman, and by Choudhury, in this compendium.

4 Ibid.

to real world settings, resulting in improved physiology and mental health among adolescent participants.

When exploring the potential for research on the adolescent brain to inform policy and programme responses, a few limitations must be kept in mind. More research is needed to understand the sculpting of the adolescent brain is low- and middle-income country contexts, particularly those where individuals experience high levels of stress due to poverty, conflict, famine and other stressors. It is also important to remember that neuroscientific research methods deserve the same scrutiny regarding their rigour as any other method to ensure that the results are reliable and applicable across different settings. Varying definitions of adolescence – in terms of age range and pubertal status – found across studies, also make it difficult to draw conclusions about impacts and outcomes.

As Choudhury points out, a vast amount of laboratory research on the adolescent brain revolves around functional neuro-imaging studies which are correlational in nature and cannot determine the direction of causality. From this perspective, the plans by Noble and colleagues to examine causal connections between poverty and brain development are truly exciting. Working across disciplines and across the life course, the longitidinal study aims to look at low-income mothers of newborns and examine the effects of various monthly supplements on the child's cognitive and brain development. Studies such as this are important not only for improved understanding of how poverty affects brain dvelopment, but also from a practical perspective to understand effective interventions that have the potential to facilitate the positive spirals during adolescence. Finally, it is crucial not to compartmentalize children and their brain development according to age group, but to take an integrated life-course approach in which evidence and programming knowledge from one stage of life is used and built upon in another, supporting the infant, child, adolescent and young adult through each phase and transition that she or he faces.

With 1.2 billion adolescents under its global mandate, UNICEF is looking forward to continuing a discussion with the scientific community and together making an investment case for adolescents. It is crucial to identify the right periods or 'windows of opportunity' to intervene and design appropriately matched interventions which are cost-efficient, scalable, and sustainable and can improve adolescents' well-being for the rest of their lives.

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ADOLESCENT BRAIN DEVELOPMENT: WINDOWS OF OPPORTUNITY

What Are All the Dimensions of Consciousness? (1988-1989)

ADOLESCENT BRAIN DEVELOPMENT: WINDOWS OF OPPORTUNITY

Ron Dahl and Ahna Suleiman
University of California Berkeley
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Two important framing issues are relevant to the perspective expressed in this brief summary. The first point focuses on the ways that neuroscience can best contribute to complex real-world issues relevant to adolescents. We believe that advances in understanding adolescent brain development should be considered as one component within a larger *developmental science perspective.* That is, while neuroscience is providing unique insights into several aspects of adolescent development, the greatest translational opportunities (to inform complex real-world problems in areas like adolescent health and education) may be best served by an approach that emphasizes a broader more integrative understanding of developmental processes – one that includes a range of biological, behavioural, social, and contextual factors (and their interactions). This perspective has important implications for how best to leverage the scientific insights. For example, it highlights the importance of trans-disciplinary teams working together to make translational progress (rather than attempting to make a simple linear translation from the neuroscience to policy or practice).

The second point addresses the broader perspective regarding our emphasis on the transition from childhood into adolescence as a particularly promising focal point for neuroscience-informed contributions to the broader developmental science. On the one hand, we have a very broad life-span view of adolescence – not only as a broad developmental period bridging from childhood into adulthood, but also as part of a trajectory that builds upon developmental processes in infancy and early childhood and extends across the entire adult lifespan. On the other hand, we focus on early adolescence (and more specifically the onset of puberty) as a particularly dynamic and promising window of opportunity for leveraging a deeper understanding of *modifiable* developmental processes. Even though we acknowledge that most of the high-impact adolescent problems tend to emerge later in adolescence and extend into early adulthood, we believe there is a compelling case for focusing on this earlier window, as a key early inflection point for prevention and early intervention – a developmental inflection point when small positive changes in these developing systems may have a larger and more enduring impact (creating better opportunities to leverage change).

Biological and environmental interactions leading to negative behavioural spirals

Early adolescence (9-14 years of age) is a period of rapid physical growth as well as rapid learning (particularly social, emotional, and motivational learning). The onset of puberty creates a cascade of hormonal changes that lead to reproductive maturity *and* stimulate numerous structural and functional changes in the brain. Pubertal hormones play a critical role in reorganizing neural circuitry, with particular impact on neural circuits involved in processing emotions, risks, rewards, and social relationships (Spielberg et al. 2014). These neural changes are strongly associated with tendencies to explore one's independence and to find novel, exciting experiences to be highly rewarding. These neural developmental changes do not occur in a vacuum. That is, biological changes do not determine behaviour; rather the biological changes lead to increased tendencies to behave in particular ways, and the actual behaviours depend to a very large extent upon the particular social context. Moreover, it is the emergence of *patterns of behaviour* that leads to cascading impact, typically involving complex interactions of social, emotional, psychological, behavioural and neuro-developmental processes.

For example, pubertal changes in sleep/wake regulation do not cause adolescents to stay up later and sleep in later; rather, biological changes at puberty lead to a slight tendency to prefer staying up later and sleeping in later. However, over time and with access to electric lights, video screens, and social interactions via cell phones and the Internet, these biological tendencies can lead to large changes in patterns of behaviour – resulting in very late bedtimes, erratic sleep schedules, and social jet-lag when trying to adjust to early school start times. These small biological tendencies can easily spiral – over months to years – into highly problematic and difficult-to-change patterns of behaviour. Yet, the answer is *not* to change the biology (or throw up our hands and say that adolescents are unable to sleep on a regular schedule), but rather to understand how developmental changes in the biology suggest a window for intervention/prevention early in the trajectory of these spiraling patterns of behaviour.

There are many other examples of negative spirals of behavioural and emotional patterns across adolescence. Early adolescence has long been identified as the onset of a myriad of negative physical and mental health outcomes including sharp increases in accidents, suicides, homicide, mental disorders, substance use, eating disorders, sexually transmitted infections, and unwanted pregnancy – all outcomes that can lead to life-long negative trajectories (Castellanos-Ryan, O'Leary-Barrett and Conrod, 2013; Guttmacher Institute, 2014; Kreipe and Birndorf, 2000; Paus, Keshavan and Giedd, 2010). Epidemiological research suggests that population stressors, including war and famine, experienced in early adolescence (10-14 years of age) are more strongly associated with a decrease in total life span than stressors experienced at any other age of childhood (infancy, 1-4 years old, 5-9 years old, or 15-19 years old) (Falconi et al. 2014). Extensive work has gone into trying to ameliorate and minimize these negative trajectories during this sensitive time period.

Opportunities for positive spirals

However, it is crucial to understand that adolescence is also a window of opportunity for positive spirals – establishing healthy patterns of behaviour, and social and emotional learning that can increase positive developmental trajectories. Developmental science, including developmental neuroscience, has helped to expand the focus on the positive opportunities occurring during this time. The potential of the brain is shaped by genetics, biology, and experience. In addition, the brain is highly flexible and normally adapts rapidly to changes and challenges. Providing key positive and learning experience during the period of brain development which occurs at the onset of puberty can significantly influence neural developmental trajectories. These learning experiences require healthy supports and scaffolding from parents, trusted adults, schools, and communities, to shift tendencies away from negative risk-taking trajectories and towards healthy exploration and learning – essential for acquiring skills and knowledge relevant to taking on new roles and responsibilities that lead to adult capabilities. Thus, providing environments that support progress and learning during these periods of rapid growth and development can have great impacts and enduring effects.

The neural flexibility occurring during early adolescence results from shifts in the balance between regions of neural stability and plasticity (Takesian and Hensch, 2013). Neural plasticity can be understood as a window of opportunity for specialized learning – a maturational interval when patterns of experience are shaping patterns of neural connections in the developing brain. Early childhood has been well established as a critical window for intervention but the neural transitions occurring in early adolescence suggest it is not too late for positive intervention, and may in fact be the best time for certain types. Patterns of experience in early adolescence can have many long-term effects on social, emotional, and motivational tendencies that extend across the life span. The neural plasticity that occurs during puberty creates a unique window of opportunity to influence positive and negative behavioural and developmental trajectories. Understanding the *interactions* among these processes provides insights into both diminishing vulnerabilities for difficult-to-change negative spirals *and* enhancing opportunities to establish positive spirals.

This begs the question: What types of specialized learning is the adolescent brain attuned to? The onset of puberty seems to re-orient greater attention and salience toward social and emotional information processing streams. These changes lead to neural flexibility that enhances learning in two specific realms. First, adolescents are highly motivated to engage in learning relevant to social relationships. They experience a profound increase in interest in engaging in social roles with peers and potential romantic partners, and navigating and understanding social hierarchies and sexual and romantic behaviour. Second, learning about oneself and finding one's place in social hierarchies becomes a primary motivator of early adolescent behaviour. This includes an amplified salience of self-conscious emotions including both a strong desire for acceptance, belonging, admiration and respect, as well as increased sensitivity to feelings of rejection, disrespect, embarrassment, and humiliation. From an anthropologic perspective, these transitions coincide with the pubertal transitions resulting in sexual maturity, also preparing adolescents to engage in finding a mate and raising offspring. In the context of modern society, mating and child-bearing tend to occur long after the pubertal transition, pointing to the need for adolescents to have a wide range of other opportunities to engage in high-intensity social activities that ignite passions in other realms such as education, music, sports, or civic engagement.

There are many compelling factors contributing to the need for UNICEF and other organizations to focus on early adolescence. Across the globe, there are significant demographic increases in adolescent populations, particularly in low-resourced countries. There are more 10- to 24-year-olds on the planet today than ever before in human history, comprising almost 25 per cent of the world's population (Patton et al. 2016). In addition, the period of adolescence has continued to expand as the age of puberty declines and the age at which young people assume adult roles continues to increase across the globe (Parent et al. 2003; Sørensen et al. 2012). As the trend to delay marriage and childbearing expands globally, engaging adolescents in other types of developmentally informed learning experiences is critical to maximize this window of opportunity for specialized learning. Lastly, the explosion of access to mobile and digital technology across the globe, with adolescents being the earliest adopters, provides a historically unparalleled opportunity to engage adolescents and requires innovation that encourages positive rather than negative trajectories.

Developmental neuroscience has helped to expand our understanding of early adolescence (9 to 14 years of age) as a dynamic period of rapid changes. On one hand, there is growing excitement about the rapid advances in understanding neuro-developmental processes in adolescence and the insights emanating from this work. On the other hand, it is important to use caution to avoid over-simplifying the translation of these advances into policy and practice. It is essential to establish a high bar for the types of insights developmental neuroscience can offer to improve interventions. It is not sufficient for the neuroscience to merely reaffirm what has already been demonstrated through years of policy and practice; instead neuroscience must be used to transform our intervention strategies. This process is far from straightforward. Leveraging advances in developmental science to inform policy and practice is complicated and will require the work of integrated trans-disciplinary teams who can apply these insights wisely. Although simple solutions do not emerge from developmental science, some key principles hold great promise for translation. Ongoing research is providing more fine-grained understanding regarding how to identify the specific targets, and precise developmental timing for specific types of early intervention and learning, creating significant opportunities for impactful, global change.

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NEUROIMAGING AND THE ADOLESCENT BRAIN: A PERIOD OF PLASTICITY FOR VULNERABILITIES AND OPPORTUNITIES

Humanature - A Turbulent Integration (1991)

NEUROIMAGING AND THE ADOLESCENT BRAIN: A PERIOD OF PLASTICITY FOR VULNERABILITIES AND OPPORTUNITIES

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In the last two decades the study of the adolescent brain has made significant leaps with the advent of scientific methods such as Magnetic Resonance Imaging (MRI) which allow measurement of brain structure (sMRI) and function (fMRI) in a non-invasive manner. Previous knowledge had been obtained primarily from post-mortem brain samples and animal models, limiting our ability to assess dynamic processes in the brain related to behaviour in humans. MRI is a neuroimaging method in which magnetic properties of different tissues of the brain can be measured. *Structural* MRI studies allow us to measure changes in the gray matter of the brain, where neurons, the brain cells that process information and generate responses, reside, and white matter, where the connections between neurons that allow communication across the brain, exists.

In addition, *functional* MRI studies provide precise information at millimetre resolution regarding where oxygen changes resulting from neuronal function during specific tasks takes place, allowing us to characterize the role of different regions and how these are engaged during the adolescent period. A recent addition to functional MRI is *resting-state* fMRI (rsfMRI), which provides information regarding what regions of the brain form networks of communication to support different aspects of behaviour while subjects are *not* involved in a task. Together, these methods have allowed developmental cognitive neuroscientists to begin to characterize which brain processes are on line by adolescence and which are still maturing and how their relative contributions help us understand the unique behavioural profile of adolescence.

Initial post-mortem brain studies, which showed earlier development of visual cortex relative to the rest of the brain, were interpreted to suggest that perhaps the human brain developed first in the most posterior regions where basic sensory function is processed, while the frontal parts of the brain, which support reasoning, were last to mature (Huttenlocher, 1990; Yakovlev, Lecours and Minkowski, 1967). This notion is still pervasive in the popular media and undermines our understanding of the reasoning abilities available in adolescence. Accumulating neuroimaging evidence to support a more nuanced profile of brain maturation reinforces emerging models of adolescent development with access, though sometimes limited, to adult level reasoning (Luna et al. 2015; Shulman et al. 2015).

Structural studies were the first to identify developmental changes in the brain and indicated that while much of the gray matter has reached maturity, regions that support the processing of complex information are still maturing in adolescence (Gogtay et al. 2004; Raznahan et al. 2014). These include the prefrontal cortex, which underlies reasoning, as well as regions throughout the brain which support high levels of integration and process motivation. These changes were evident in the thinning of the gray matter thought to reflect the known loss of neuronal connections (synaptic pruning) (Petanjek et al. 2011), an adaptive process believed to support the sculpting of the brain through adolescence to fit the demands of its environment in order to promote optimal survival.

Recent post mortem studies in prefrontal cortex have shown that synaptic neural connections multiply through childhood, but by adolescence a steep loss of these connections occurs and continues beyond age 30 (Petanjek et al. 2011). Structural MRI studies, in particular Diffusion Tensor Imaging (DTI) which measures the coherence of the motion of water molecules within white matter tracts of the brain, have also identified immaturities in connections in the adolescent brain. These studies have shown that much of the white matter connectivity of the brain is already in place by childhood, however connectivity of regions that support reasoning continues to undergo significant growth and reaches adult levels during adolescence, while the connectivity of regions that support emotional and social processing demonstrates continued change beyond age 30 (Lebel et al. 2012; Simmonds et al. 2013). Together, structural neuroimaging and postmortem studies indicate that brain maturation is characterized by an initial period of brain growth/building in childhood and then shifts into a stage of pruning/sculpting in adolescence, which lasts through young adulthood.

Functional MRI studies add to structural findings by measuring changes in how the brain operates while engaged in cognitive tasks, including reasoning and motivation. Basic aspects of cognition are present early in development but the ability to engage these systems in a controlled and reliable fashion continues to strengthen throughout adolescence. In particular, the systems that support the ability to generate behaviour in a voluntary manner for a planned goal, referred to as Executive Function or Cognitive Control (we will use Cognitive Control here), continue to improve through adolescence into adulthood (Diamond, 2013; Luna et al. 2015). Aspects of cognitive control that are typically measured include:

- the ability to stop an impulsive behaviour (inhibitory control, such as choosing a healthy snack over candy);
- the ability to retain and process information to guide behaviour (working memory,

such as remembering a phone number);
- the ability to flexibly switch between cognitive processes in service of changing task demands; and
- the ability to follow rules and execute optimal reasoning.

Such fMRI studies have predominantly probed functions in the prefrontal cortex and have found varied results depending on ages tested and tasks used (Bunge and Wright, 2007; Luna, Padmanabhan and O'Hearn, 2010).

Recent studies show evidence that brain systems supporting executive control are in place by adolescence, including the engagement of the prefrontal cortex (Ordaz et al. 2013). What continues to strengthen is the ability for the prefrontal cortex to network with other brain regions (Hwang et al. 2016; Hwang, Velanova and Luna, 2010), which is critical to enacting controlled behaviour. Importantly, there is evidence that during adolescence there may be hyper-sensitivity in the brain regions that support motivation when presented with an opportunity to gain a reward (Galvan, 2013; Luna et al. 2013). This hyper-sensitivity can propel brain systems to respond in an impulsive manner in order to obtain that reward (Geier et al. 2010; Padmanabhan et al. 2011). This is in accordance with evidence from animal studies which suggests that during puberty there is a peak in the availability of dopamine, the brain chemical neurotransmitter that supports motivation (Padmanabhan and Luna, 2013; Wahlstrom et al. 2010).

In addition, the heightened drive for rewards is specific to immediate rewards and not those that require a waiting period (Stanger, Budney and Bickel, 2013). Finally, at a whole brain level, resting state fMRI, which is used to characterize brain networks supporting cognitive, sensorimotor, and motivational systems, has revealed that these networks are also well organized early in development. However, the ability for integration between networks increases during adolescence, and facilitates more complex reasoning with a consequent effect on decision-making (Marek et al. 2015). Together these studies suggest that adolescents have access to brain systems that support reasoning, but they are also very much driven by obtaining immediate rewards. The combination of reasoning and rewards may contribute to sensation-seeking and risk-taking that often characterize the adolescent period, but also identify key aspects of how to influence development.

This literature has informed several models of adolescent neurobehavioural functioning that highlight a dual systems approach, indicating that in adolescence motivational systems are predominant over cognitive control systems (Shulman et al. 2015). Some suggest that prefrontal cognitive control systems are distinctly immature in adolescence compared to adults, with the implication that adolescents are not only driven by rewards but are also limited in their reasoning, especially in situations where there is heightened motivation (Casey, Jones and Hare, 2008; Ernst, Pine and Hardin, 2006; Steinberg, 2008; Shulman et al. 2015).

The 'driven dual systems' model is unique in highlighting that by adolescence a critical level of cognitive control has been reached but is affected in the context of increased drive for rewards (Luna and Wright, 2016). The former implies that adolescents are particularly limited in their ability to plan and make decisions while the latter proposes that adolescents do have the ability to reason as adults but cannot yet apply these capabilities consistently and across a wide range of task domains. Considering the extant literature, especially emerging findings, we propose that critical to adolescence is the emergence of adult-level cognitive control that can be engaged in the context of rewards, whether for sub-optimal risk-taking or for responsible decision-making. Thus, this model suggests that adolescents' capability to reason should not be dismissed, but rather be engaged knowing that decision-making is particularly influenced by heightened sensitivity to rewards and new access to adult-level cognition providing new insight into their risky decisions but also on how to engage their optimal development.

Finally, dual systems models of heightened motivation during adolescence agree that while this underlies sensation-seeking that can lead to risk-taking behaviours which may undermine survival, it also serves an adaptive role in development, which encourages experience-gathering in an independent fashion, necessary for reaching adult-level independence. That is, by adolescence, individuals have reached a level of bodily growth and strength, as well as cognitive control that allows them to experiment and explore the world independently from the direction of adults for the first time. This is necessary in order to start forming a path for successful survival when adult support will no longer be available, and includes forming relationships and social circles. Social processing is particularly important at this time and has been found to engage the reward centres of the brain that influence decision-making (Chein et al. 2011). Thus experience-gathering is critical to being able to adjust and fine hone brain systems to fit particularities of the individual's environment.

The hippocampus, a brain region known for its involvement in memory including of specific experiences and events (episodic memory), continues to mature into adolescence (Benes et al. 1994; Lee, Ekstrom and Ghetti, 2014) similarly to the prefrontal cortex. Importantly, their connectivity shows protracted growth into the thirties (Lebel et al. 2012; Simmonds et al. 2013), enhancing the influence of experience on cognition. We propose that in addition to brain changes which balance the cognitive and motivational systems (encouraging experience-gathering) the integration of cognitive and memory systems helps to establish modes of operation that are founded on experience and will be available in adulthood (Murty, Calabro and Luna, 2016). In sum, the emerging brain imaging literature indicates that adolescence is a period of dynamic specialization of established core brain systems within which heightened motivation towards immediate rewards propels the experience-gathering that will formulate the way in which the individual will interact with their environment. As such, this is a critical period where the nature of experiences can establish trajectories but also allows for change in their direction. Several implications emerge. First, the initial formative years can establish the basis from which the brain will specialize and experiences will be sought. Second, this is a period of heightened motivation underlying increased sensation-seeking which then propels the experience-gathering needed for brain systems to fit the requirements of the environment. Increased sensation-seeking can lead to risk-taking behaviours, which undermine survival but are critical for normative maturation.

The particular proclivity of adolescents for immediate rewards and social advantages could inform practices relevant to education and health. Finally, maladaptive experiences during adolescence can disrupt normative trajectories and establish abnormal ones such as criminality. However, this is also a time when trajectories can change based on positive experiences such as rehabilitation and training (Luna and Wright, 2016). Overall, much can be gained by investing in the protection of positive and broadening experiences during adolescence in order to avoid or limit impaired or interrupted development, with effects that endure throughout the lifespan.

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SITUATING THE ADOLESCENT BRAIN: THE DEVELOPING BRAIN IN ITS CULTURAL CONTEXTS

Evolution of Abstract Realism
(2010-2011)

SITUATING THE ADOLESCENT BRAIN: THE DEVELOPING BRAIN IN ITS CULTURAL CONTEXTS

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Adolescence: A sensitive window of development

Scientific developments during the past two decades have ushered in new and widespread interest in the neuroscience of adolescent development, and what has come to be known popularly as the 'teen brain'. Clinicians, policy makers, educators, parents and young people are increasingly informed by these emerging scientific insights into the adolescent brain's malleability and its sensitivity to environmental input from puberty through to early adulthood. These findings have been made possible by the relatively recent availability of non-invasive neuroimaging techniques that have allowed researchers to attempt to identify the 'neural underpinnings' of behavioural differences between adolescents, adults and young children (Choudhury, 2010).[1] The rapid growth of a new research programme dedicated to adolescent brain development has challenged the older assumption in developmental science of brain rigidity after late childhood (Fuhrmann et al. 2015) and has given rise to an increasingly neuroscientifically-informed, and brain-centered, understanding of adolescence (Giedd, 2015) in wider culture. This commentary highlights the central, multiple, and often overlooked roles of culture in our understanding of adolescent behaviours, and in the translation of adolescent brain science to policy and public engagement.

Neuroimaging studies since the early 1990s support earlier, smaller-scale post-mortem studies in the 1970s in suggesting that 'sensitive periods' of development of the human brain may be more protracted than previously thought (Huttenlocher, 1979). The adolescent brain is now frequently described as 'a work in progress' to emphasize the structural remodeling and neuronal reconfiguring that occurs as the child brain transitions to the mature adult structure. This growing body of research, including longitudinal neuroimaging studies that follow large groups of participants

1 UNICEF defines adolescents as those aged 10-19 and children as those aged 0-18. These age demarcations may not correspond with the way these populations are defined in neuroscience experiments.

over time, has shown functional and structural changes in the brain during adolescence hypothesized to correspond with behavioural changes during this period (Furhmann et al. 2015; Crone and Elzinga, 2015).

Synaptic reorganization in the prefrontal cortex is of particular interest – particularly to researchers seeking to apply brain science to evidence-based policy-making and to inform self-understanding of young people – since this part of the brain is implicated in high-level cognitive capacities including the regulation of behaviours and emotions, self-awareness, social understanding and decision-making. The synaptic reorganization that takes place in adolescence is a function of the highly plastic nature of the adolescent cortex. Cortical plasticity refers to the brain's ability to reorganize and adjust its neural connections in response to environmental stimuli. Human studies of sensitive periods have largely focused on early childhood, demonstrating highly plastic periods of language development and sensitive periods that underlie sensory capacities like sound categorization (Blakemore and Choudhury, 2006). Researchers have begun to hypothesize that adolescence is a second interval of intense neuronal plasticity, characterized by experience-expectant periods, specifically sensitive to experiential input affecting executive functions and social cognition (Blakemore and Mills, 2014; Nelson et al. 2016). A close understanding of these windows of opportunity, and how they are shaped by the environment and by experience, can have enormous implications for the ways in which we – in research, policy, advocacy, education, families, mental health and medicine – can provide protective, nurturing and empowering environments for adolescents.

Although empirical research has demonstrated extensive structural and functional changes in the brain during adolescence, there has been much debate over the interpretation and findings of these studies. Discrepancies, in part, arise from difficulties characteristic to the logic of neuroimaging methodology. Functional neuroimaging studies provide correlational information but cannot provide causal certainty, leaving the links between neuroanatomical development and changes in behaviour and brain function unclear (Weber and Thompson-Schill, 2010). In addition, variability of age-range and pubertal status used to denote periods of 'adolescence', 'childhood' and 'adulthood' leads to differing characteristics of samples that, along with varying methodological techniques applied by different laboratories using neuroimaging methods, yield disparate conclusions.

However, these nuances and limitations remain under-debated while the appetite for the science in the public sphere and policy context has become increasingly strong. The appeal is clear: this research offers state-of-the-art scientific investigations into the brain basis of behaviours that are often anecdotally or stereotypically associated with teenagers, particularly in Western societies. For example, neuroimaging studies explain why adolescents make 'poorer' decisions than adults (Baird, Fugelsang and

Bennett, 2005; Braams et al. 2015; Shulman et al. 2016); they reveal the neural correlates of 'high-risk behaviours' associated with adolescence such as increased sensation-seeking behaviour and heightened impulsivity (Brown et al. 2015, Steinberg and Chein, 2015). That the prefrontal cortex is implicated in the most dramatic change during adolescence is of major significance: the prefrontal cortex is associated with capacities for behavioural control including decision-making, working memory and multi-tasking, and also with social cognitive skills including empathy, perspective-taking and emotional recognition – the very capacities at stake in the debates about the relevance of the developing brain for education, law, psychiatry and child-rearing.

Critical neuroscience and the 'situated brain' in adolescence

The social and cultural contexts of a person have historically been overlooked in the neuroscience laboratory given that they are hard to capture and difficult to control in the conditions of an experiment. However, the way we define adolescence is in terms of a social transition, that is, the developmental period between childhood and adulthood. Critical neuroscience is a helpful framework for approaching the adolescent brain as culturally situated, and aims to illuminate these methodological and conceptual challenges of the experimental process in neuroscience, and of the interpretation of the data (Choudhury and Slaby, 2012). Recognizing the relevance of cognitive and neural mechanisms for behaviour and psychiatric symptoms, but taking the embeddedness of the brain seriously, critical neuroscience espouses a view of a 'situated brain' (Choudhury and Gold, 2011) which demands wider exploration of the way in which brain function has to be investigated in the context of an organism's environment (Kirmayer, 2006; Lock, 1995). The brain and nervous system, no less than the mind, is *situated,* which requires an approach that blurs the distinction between nature and culture. This view would depart from those in mainstream cultural and social neuroscience by challenging the primacy of the brain in investigating the mind. It would also maintain room to examine the interaction of scientific culture with the object of study, for example, the categorization of research participants, the 'social'/'cultural', or of disease, which is contingent on the culture of neuroscience.

The premise of this approach is that the culture/brain dichotomy is a false one. Mounting evidence from epigenetics and social neuroscience has fuelled major shifts in the way we conceptualize the relationship between the body, brain and environment, and demonstrates that on the one hand of course, the human brain is a fundamentally social brain and has evolved to have a biological preparedness to negotiate complex social groups and acquire culture. On the other hand, culture and biology interact to create different experiences of what we consider to be 'biological processes' during the lifespan. For example, cross-cultural evidence from cultural anthropologist

Margaret Lock's work on menopause in women suggests that it makes sense to speak of *local biologies;* in other words there are biological effects of culturally determined behaviours such as diet. In line with this, compelling evidence from the work of Michael Meaney and colleagues (Meaney, 2001) demonstrates that early parenting experiences and social adversity alter the regulation of stress response systems for the life of the organism. The notion of *cultural biologies* that Laurence Kirmayer has used (2006), likewise suggests that human biology is variable, plastic and deeply interdependent with cultural practices; that lived experience, developmental histories, dynamic interactions, patterned by cultural contexts, are all fundamentally bound up with biological processes as 'low-level' as brain development and gene expression.

If we understand the brain as a situated brain, we need to ask questions about how cultural differences in child-rearing, education, play, or rites of passage influence adolescent behaviour, and how the brain mediates these differences. While there is a transitional period of adolescence in most cultures, the way it is characterized, the duration, the expression and the salience of particular developmental goals may differ between some cultures (Choudhury, 2010; Schlegel and Barry, 1991; and others). Research in Bangladesh, for example, shows that individuals are considered adults as soon as they start employment, but precisely when an individual needs to start working may depend on his particular economic responsibilities (Blanchet, 1996). We need to consider the different meanings of developmental goals associated with adolescence – these may not be universals.

Cultural significance of the 'teen brain': science and self-understanding

Understanding the cultural significance of the science of the adolescent brain, that is, empirically delineating the influences neuroscience exerts on contemporary society and in particular in the lives and worlds of adolescents, is an important objective. In other words, what are the meanings that get assigned to ideas, images and messages about the developing teenage brain that are delivered to young people through intervention programmes or scientific outreach initiatives? A growing literature in the social studies of neuroscience has speculated that the vast expansion of the neuro-disciplines and related discourses since the 'Decade of the Brain', as well as the many cultural formulations that have arisen as a consequence, from popular science genres to policy texts and commercial projects, are contributing to new ways in which to constitute persons (Vidal and Ortega, 2016; Vrecko, 2006). Indeed, in the social science literature, metaphors such as the 'neurochemical self' (Rose, 2007) and the 'cerebral subject' (Ehrenberg, 2004; Vidal and Ortega, 2007; Vidal, 2009) are becoming familiar shorthand expressions to capture the reduction of 'personhood' to ‘brainhood’ implicit in neuroscientific theories – and their lay interpretations – about cognition and behaviour. Little is known about how young people, a target for current public engagement in neuroscience activities, view neuroscientfic theories of adolescence. Analysis of young people’s engagement with the neuroscience of adolescence is necessary at this moment for two reasons: firstly, to investigate the effects of recent efforts in ‘public engagement’ or ‘knowledge transfer’ in a swiftly developing field within cognitive neuroscience; secondly, given the recent interaction between neuroscience and policy intended to develop evidence-based strategies for restructuring aspects of educational curricula and healthcare programmes, it is necessary to examine the assumptions about adolescence that form the basis of this evidence in an inclusive discussion between young people, academics, and policy makers. This is particularly relevant given the new knowledge transfer or public engagement initiatives that have emerged with a new goal of *speaking to teens themselves* to promote the science and to help individuals develop a kind of ‘neurologic prudence’ or make informed life choices that ‘treat their brains well’.

Summary

An emphasis on social and cultural contexts of the developing brain is crucial to understanding a period of development during the lifespan that is as much defined and shaped by social and cultural transitions as it is by biological maturation. While neuroscientists increasingly assume the understanding of the brain as bathed in its environment at multiple levels, recent research clearly demonstrates that the integral role of the social context is lost in outreach initiatives, ignored by policy-makers and at times insidiously shielded. Establishing an integrative view of the developing brain in which context is key to understanding structure and function has important implications for neuroscientists and researchers involved in knowledge translation in exemplary areas of clinical research, policy applications and public engagement. This commentary summarized one possible critical neuroscientific approach to the adolescent brain as a ‘situated brain’ that takes into account brain, body and environment, in which no process is uni-causal, but all equally mould and modify each other and themselves to a significant degree. The following questions remain essential for researchers working towards socially, culturally and ethically appropriate international development programming:

- How can we combine neurobiological insights with social and economic determinants of health to inform windows of opportunity?
- Can we establish opportunities for participation of adolescents in the science and outreach processes about the teenage brain?
- If neuroscience impacts on identity/self-understanding, can researchers incorporate a view of adolescents as resilient, social actors, into the scientific model of the adolescent brain?

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POVERTY AND THE ADOLESCENT BRAIN

Mind Icon No.7 (Metaphorming Conscience) (1991)

POVERTY AND THE ADOLESCENT BRAIN

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The human brain has been called "the most complex three pounds in the universe" (Asimov, 1970). Its experience-related plasticity is remarkable: it is well understood that neural circuits that are used frequently tend to strengthen, whereas those that are not used are dropped, or pruned. While vigorous growth and pruning occurs early in childhood (Huttenlocher and Dabholkar, 1997), it is becoming increasingly apparent that plasticity is in many cases retained through adolescence and even adulthood (Draganski et al. 2004; Gutchess, 2014; Maguire, Woollett and Spiers, 2006; Neville and Bavelier, 1998; Sowell et al. 2003; White-Schwoch et al. 2013). An individual's experience varies tremendously by family social and economic circumstance (McLoyd, 1998), and so we can use socio-economic factors as a lens through which to understand better neural plasticity and how it relates to key aspects of adolescent development.

Family socio-economic status, or SES, is typically considered to include parental educational attainment, occupational prestige, and income (McLoyd, 1998); subjective social status, or where one sees oneself on the social hierarchy, may also be taken into account (Adler et al. 2000). A large and cross-cultural literature documents that disparities in income and human capital are associated with substantial differences in children's learning and school performance. For example, across these different socio-economic indices, researchers have described marked disparities in a range of important cognitive and achievement measures for children and adolescents, including IQ, literacy, achievement test scores, and high-school graduation rates (Brooks-Gunn and Duncan, 1997). These differences in achievement in turn result in dramatic differences in adult economic well-being and labour market success.

However, although such outcomes are clearly critical for understanding disparities in development and achievement, they tell us little about the underlying neural mechanisms that lead to these differences. Distinct brain circuits support discrete cognitive skills, and differentiating between underlying neural substrates may point to different causal pathways and approaches for intervention (Farah et al. 2006; Hackman and Farah, 2009; Noble, McCandliss and Farah, 2007; Raizada and Kishiyama, 2010). Studies that have used a neuroscience framework to investigate cognitive disparities have documented that children and adolescents from socio-economically disadvantaged backgrounds tend to perform worse than their more advantaged peers on several neurocognitive domains, most notably in language, memory, self-regulation and socio-emotional processing (Hackman, Farah and Meaney, 2010; Hackman and Farah, 2009; Noble, McCandliss and Farah, 2007; Noble, Norman and Farah, 2005; Raizada and Kishiyama, 2010).

More recently, neuroscientists have extended this line of research to examine how family socio-economic circumstances relate to differences in the structure of the brain itself. For example, in the largest study of its kind to date, we recently analyzed the brain structure of 1,099 children and adolescents recruited from socio-economically diverse homes from ten sites across the United States (Noble et al. 2015). We found that both parental educational attainment and family income accounted for differences in the surface area, or size, of the cerebral cortex – the outer layer of brain cells that does most of the cognitive 'heavy lifting'. These associations were found across much of the brain, but were particularly pronounced in areas that support language and self-regulation – two of the very skills that have been repeatedly documented to show large differences along socio-economic lines.

Several points about these findings are worth noting. First, this relationship was similar across the entire age range sampled, from age 3 through to age 20. While these data cannot determine whether adolescents and younger children would benefit equally from interventional approaches, at a minimum it suggests that differences in brain structure did not widen over time. Second, these results held constant for genetic ancestry – essentially a measure of genetically-defined race. Thus, although race and SES tend to be confounded in the United States, we can say that the socio-economic disparities in brain structure that we observed were independent of genetically-defined race. Third, we observed dramatic 'individual differences', or variation from person to person. That is, there were many instances of children and adolescents from disadvantaged homes with larger cortical surface areas, and conversely, many instances of children from more advantaged homes with smaller surface areas.

We might consider the analogous situation with gender and height. In childhood, boys tend to be taller than girls. However, we all know that there are many 6-year-old girls who are taller than many 6-year-old boys. Along the same lines, while children from higher-income homes *tended to* have larger brain surfaces, our research team could in no way predict an individual's brain size simply by knowing his or her family income. Finally, the relationship between family income and surface area was nonlinear, such that the steepest gradient was seen at the lowest end of the income spectrum. That is, each extra dollar in family income was associated with proportionately more surface area for children of disadvantaged families, relative to their more advantaged peers. Of course, we can't determine the direction of causality from these correlational findings. However, as discussed here, future work will aim to disentangle the causal effect of income on brain structure, with direct policy implications for disadvantaged families. Are these socio-economic differences in brain structure clinically meaningful? Early work would suggest so. In the sample discussed previously, differences in surface area partially accounted for links between income and certain executive function skills (inhibitory control and working memory) (Noble et al. 2015). Independent work elsewhere has suggested that differences in brain structure may account for between 15 and 44 per cent of the income-achievement gap in adolescence (Hair et al. 2015; Mackey et al. 2015). This line of research is still in its infancy, however, and several outstanding questions remain to be addressed. For example, are the associations between SES and brain development the result of differences in experience, such as differences in nutrition, housing and neighbourhood quality, parenting style, family stress, and/or education? Certainly, the preponderance of social science evidence would suggest that differences in experience are likely to account at least in part for differences in child and adolescent development (Duncan and Magnuson, 2012).

Few studies, however, have directly examined links among SES, experience and the brain (Luby et al. 2013). A recent report in a sample of 66 families suggested no socio-economic differences in brain function at birth (Brito et al. 2016), but the extent to which experience leads to the emergence of disparities in brain structure and function over the course of childhood and adolescence is unknown. Thus, disentangling links among socio-economic disparities, modifiable experiences and brain development represent a clear priority for future research.

Perhaps most importantly, all of the work to date documenting associations between poverty and brain development has been correlational in nature. While there have been some excellent experimental and quasi-experimental studies in the social sciences (see Duncan and Magnuson, 2012 for a review), the field of neuroscience is silent on the causal connections between poverty and brain development. As such, a team of social scientists and neuroscientists from across the United States are hoping to launch the first-ever randomized experiment testing the causal connections between poverty reduction and brain development. In this study, we plan to recruit low-income mothers at the time of their child's birth to receive a large monthly income supplement or a nominal monthly income supplement. Families will be tracked longitudinally to definitively assess the causal impact of this unconditional cash transfer on cognitive and brain development. It is our hope to ultimately follow these children through adolescence and beyond. We hypothesize that increased family income will trigger a cascade of positive effects throughout the family system. As a result, across development, children will be better positioned to learn foundational skills.

Poverty affects approximately one billion children and adolescents across the globe. To maximize the potential of adolescents with programming, policy and advocacy, UNICEF and other international development stakeholders must invest in rigorous research that has the potential to inform international policies that affect disadvantaged families. For example, if hypotheses are borne out, a randomized trial of poverty reduction would inform social policies that affect the lives of millions of disadvantaged families. One possibility is that governments could choose to implement a child allowance to low-income families. This work will also inform decisions about the generosity of in-kind benefits, such as food stamps or housing vouchers. In either scenario, the disadvantage that many children and adolescents face will be reduced, setting them on a path to having greater opportunities for lifelong success.

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HELPING TEENAGERS DEVELOP RESILIENCE IN THE FACE OF STRESS

Metaphorming Civilizations
(1992-1993)

Figure 1. A) Drawings on stress from children aged between 9 and 11. B) Drawings on stress from adolescents aged between 12 and 15. The drawings were obtained during the validation study of the *DeStress for Success Program* of the Centre for Studies on Human Stress. Other drawings are available at: www.humanstress.ca.

HELPING TEENAGERS DEVELOP RESILIENCE IN THE FACE OF STRESS

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Contrary to popular belief, children and adolescents are just as capable as adults of experiencing stress and the stress-related health outcomes that ensue (Lohman and Jarvis, 2000). When you ask children (see Figure 1a) and teenagers (see Figure 1b) to draw what stress means to them, you see that 1) they understand that stress can be negative and that 2) it is related to psychological distress.

The physiological stress response

Although humans of all ages can easily associate stress with a general state of 'psychological distress', it is the physiological stress response that can have damaging effects on both physical and mental health (McEwen, 1998). Response to stress involves activation of the hypothalamic-pituitary-adrenal (HPA) axis that leads to the secretion of glucocorticoids from the adrenal glands, i.e. the two small glands located on top of the kidneys. Chronic secretion of glucocorticoids can have damaging effects on physical health due to the process of allostatic load, that is, the wear and tear of various physiological systems (metabolic, immune, etc.) that are related to activity of the HPA axis (McEwen, 2000). In addition, a chronic production of stress hormones can have damaging effects on mental health because glucocorticoids rapidly access the brain to influence learning, memory, and emotional processing by binding to receptors in the prefrontal cortex, amygdala, and hippocampus, three brain regions involved in learning, memory and emotional regulation. Given the slow development of the amygdala and frontal lobe during adolescence, there are indications that the adolescent brain might be especially sensitive to the effects of elevated levels of glucocorticoids (Lupien et al. 2009).

The effects of stress on the well-being and mental health of children and adolescents are substantial. Indeed, studies show that adolescents present an increased physiological response to stress compared to children and adults (Lupien et al. 2009) and stress has been shown to increase incidence of psychiatric problems at this period of development (Angold et al. 2002; Goodyer et al. 1996; Hudziak et al. 2000).

Adolescence is also a period in which the long-lasting effects of earlier stress become evident. Studies show that adolescents whose mothers were depressed in the early postnatal period present significantly higher levels of stress hormones (Halligan et al. 2007), as well as adolescents who grew up in poor economic conditions (Evans and English, 2002). Finally, other studies report that high early morning levels of stress hormones that vary markedly from day to day at the transition to adolescence predict an increased risk of depression by age 16 (Halligan et al. 2007).

Given the adverse effects of stress on well-being and its potential implication in vulnerability to adolescent depression, the need to provide children and adolescents with the skills to develop ways to manage and cope with stress is paramount.

Helping teenagers develop resilience in the face of stress

When dealing with adolescents, the school system has been identified as being an ideal setting for the implementation of prevention programmes because the school setting offers the unequaled opportunity[1] to reach adolescents, and thus avoid the selection bias of clinically-referred samples based on the presence of mental health problems (Masia-Warner et al. 2005).

Although various programmes for stress management have been developed in the past 20 years, the majority of them has been based on the cognitive appraisal model of Lazarus and Folkman (1984). This model posits that it is an individual's appraisal of a situation as being threatening or not, and her/his capacity (or not) to deal with this threat that creates stress for the individual. Consequently, teaching children and/or teenagers to better cope with (appraise) the various situations they encounter can lead to beneficial effects on psychological stress in these populations.

Although many of the programmes based on cognitive appraisal theory have revealed beneficial effects for adolescents, it is interesting to note that none of them were developed in line with discoveries made in the last 25 years in the field of psychoneuroendocrinology, a field of research that measures the causes and consequences of chronic production of glucocorticoids on the brain. Yet it has been shown repeatedly that it is the physiological response to stress that can get under the skin and the skull in order to exert a long-lasting influence on stress perception

1 However, it is important to note that this may not be the case in some low- and middle-income countries, particularly in relation to adolescent girls who often have to drop out of school when they start menstruating, because of school-based violence, early marriage, household responsibilities and other factors. Consequently, the advantage of the school system as providing an 'unequaled opportunity' is more applicable to adolescents in high-income countries.

and coping and, in turn, underline vulnerability to various mental health problems in adolescents (for a review see Lupien et al. 2009).

Research performed over the last three decades in the field of psychoneuro-endocrinology has identified four situational determinants that activate the HPA axis in humans, namely novelty (N), unpredictability (U), threat to personality (T) and a sense of low control (S) - hence the acronym 'NUTS' in the *DeStress for Success Program* (Dickerson and Kemeny, 2004; Mason, 1968). In a previous study performed with 406 children and adolescents, we reported that the transition from Grade 6 (elementary school) to Grade 7 (high school) in Quebec within Canada's school system, is associated with a significant increase in glucocorticoid levels in adolescents from both low and high socio-economic strata (Lupien et al. 2001). This finding suggested that school transition may represent a significant stressor in the life of adolescents. Transition to high school has been reported to be associated with negative outcomes including poorer attendance, declines in grades, newly emerging disciplinary problems, and new feelings of alienation or social rejection (Moyer, 1982) as well as a decline in a sense of school belonging and an increase in depressive symptoms (Newman, Lohman and Newman, 2007).

Based on these findings, we developed the *DeStress for Success Program* (Lupien et al. 2013) to expand both youth awareness and scientific knowledge on stress. The uniqueness of the *DeStress for Success Program* lies primarily in its theoretical framework rooted in psychoneuroendocrinology. Specifically, stress is recognized and deconstructed based on the four important 'NUTS' characteristics reported to lead to significant activation of the HPA axis (Dickerson and Kemeny, 2004). Secondly, the programme explains the stress response and ways to use the body to stop it. Finally, it is a relatively short programme, easy to implement in school settings.

Our team tested the efficacy of the *DeStress for Success Program* in 504 adolescents making the transition from elementary to high school in Montreal, and found that teens who started the school year with high levels of anger benefited significantly from exposure to the *DeStress for Success Program* with a significant decrease of glucocorticoids and depressive symptoms over a 5-month period (Lupien et al. 2013). These results showed for the first time that transferring scientific knowledge from the laboratory to adolescents *can* lead to significant changes in physiology and mental health.

The *DeStress for Success Program* has relevance for UNICEF and other international development stakeholders who wish to maximize the potential of adolescents through various programmes because it shows that educating adolescents on the scientific basis of stress can lead to a physiological decrease in stress hormones that can, in the short-and long-term, have significant beneficial effects on physical and mental health.

However, there are challenges to the implementation of the programme in other settings. One challenge relates to the feasibility of expanding the programme around the world for adolescents. Indeed, the *DeStress for Success Program* has been developed to be provided in class, by trained associates or professors. In the last four years, we have trained more than 380 Montreal school teachers and counselors on the *DeStress for Success Program*, and through these knowledge users, we have reached over 34,805 children/teenagers. However, it is not clear whether there would be enough resources in the various countries where UNICEF works to allow for sufficient training of facilitators to deliver the programme to populations of adolescents in low- and middle-income countries.

To overcome this problem, another approach would be to adapt the *DeStress for Success Program* for the web so that adolescents and/or key personnel working with adolescents anywhere in the world could undertake training using the internet. This would be feasible since our team has already developed an e-learning web-based programme for adults called *Stress Inc*©, as well as a mobile phone application called *iSMART*© to detect chronic stress in workers. This shows that adapting the *DeStress for Success Program* for the web and/or mobile phones is feasible and could provide a viable method for implementing the programme in locations where UNICEF works.

In conclusion, the findings from our studies have important implications for adolescents and those who work with them as they show that adolescents are receptive to scientific knowledge regarding stress and how it affects them, and that this type of educational programme can lead to significant decrease in stress hormone levels and depressive symptomatology. Given the negative effects of chronic production of stress hormones on the developing brain (Lupien et al. 2009), we believe that the development of prevention programmes for stress in adolescents will give us a unique window of opportunity to modify developmental trajectories and help teenagers around the world develop resilience in the face of stress.

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UNDERSTANDING ADOLESCENT NEUROPLASTICITY: A GUIDE TO DEVELOPING RESILIENCY PROGRAMMES FOR ADOLESCENTS

Metaphorming Humanature. Humankind's Integration with Nature (1989)

UNDERSTANDING ADOLESCENT NEUROPLASTICITY: A GUIDE TO DEVELOPING RESILIENCY PROGRAMMES FOR ADOLESCENTS

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Overview

- Resiliency programmes serve to guide adolescents through the process of learning positive, and un-learning negative behaviours.
- Resiliency programmes help adolescents minimize risk-taking and build life skills.
- Widespread implementation of these resiliency programmes will be cost effective for both adolescents and society.

Key questions

- What behaviours can be learned and un-learned during adolescence?
- What are the key components of effective resiliency programmes?
- What development strategies will support widespread implementation of these resiliency programmes and benefit the wider society?

Miss Little sighed. How was she going to respond to calls for her to expand her resiliency programme to Railway Lane? Once word had got around that her programme had resulted in an 80 per cent decrease in participants' involvement in gun crimes, and that they were all employed, the calls were endless. She muttered, "These adolescents need help".

The range of adverse outcomes among the adolescent population is well documented (see Bustreo and Chestnov, 2013). Violence, road traffic accidents, alcohol intoxication, drugs, mental health problems, teenage pregnancy, obesity, undernutrition and many other stressors, mar adolescent lives.

From the Ninis[1] in South America, Defence Crews in the Caribbean, gangs in North America, to ISIS in Syria, our current news reports focus on the impact of violence on

1 Nini stands for "ni estudian ni trabajan", the Spanish phrase for "those who neither study nor work."

adolescents as both perpetrators and victims. Although their high-risk behaviours are major contributors to the high levels of adolescent morbidity and mortality (Viner et al. 2011), John McCrone in his article 'Rebel with a Cause' (2000), and Larry Steinberg in the 'Age of Opportunity' (2014) both highlight adolescence as a development process that needs to be nurtured, and where we can minimize the risks while we build the resiliency factors. Resiliency programmes allow us an opportunity to optimize development while reducing the risks and creating resiliency in adolescents.

The neuroplasticity of the adolescent brain allows for learning and unlearning behaviours

New cells are constantly being produced in the adolescent brain, and their interconnectivity is sculpted during the process of synaptic pruning. This process is driven by brain-derived neurotropic factors resulting in the formation of new cellular circuits as the prefrontal cortex (PFC) matures. With the development of these tracts connecting the PFC to subcortical systems in adolescence comes the deepening ability to reason, plan, problem solve and to determine right from wrong. Gradually the earlier-maturing subcortical activity affecting the nucleus accumbens involved in impulsive actions, and the amygdala where emotions are processed, become more under the control of the PFC. The immediate rapid response from the nucleus accumbens and amygdala gradually becomes modulated by more textured and multi-dimensional, albeit slower, inputs, produced via the longer route involving the PFC.

During this period of subcortical ascendancy, as the PFC slowly develops adolescents are very responsive to rewards and to reward-seeking behaviour and show reduced responsiveness to adverse stimuli such as punishment (Spear, 2013). By understanding the timing and the roles of the drivers of the development of these neurobiological circuits we can guide the development of our adolescents through our resiliency programming. These drivers can be grouped into biological and environmental stressors.

Biological stressors

Metabolic switches can affect the development of the neurobiological circuits. The timing and impact of changes in the levels of growth hormones and the sex hormones testosterone and estrogen, for example, have to be considered in programming, and are undoubtedly a critical part of the developmental process. Low functioning of the prefrontal cortex allows for high levels of subcortical activity involving dopamine levels and its impact on the nucleus accumbens and amygdala, as it affects impulsivity and emotions and supports poorly modulated, risky behavioural responses. Interventions that delay the uncensored, subcortically-driven actions and allow for increased use of the PFC may help to reduce risk-taking in adolescent behaviour on a large scale.

Environmental stressors

Increased task demands, heightened emotions, and peer pressure do little to accentuate the use of tracks involving the PFC and instead promote high levels of activation of the amygdala in the subcortical region. This has been described as ‘Hot Contagion’ (Spear 2013). The recent technological explosion has accelerated information flow, contributing to sensory overload that increases the burdens of stress, grief and fear, driving unmodulated, ill-considered responses.

Resiliency programmes

If we are able to keep adolescents safe by reducing exposure to violence and other stressors on the street, in homes and online, we can facilitate the development of the prefrontal lobe and its connections; this, in turn, can provide the ‘brakes’ for risk-taking behaviours and promote the maturation of the decision-making process.

The timing, nature and intensity of impact of these stressors in sub populations within varying social and cultural settings have to be considered (Morrel-Samuels et al. 2016). As Lisbeth Schorr (2014) outlines, effective ‘complex place-based interventions’ within programmes are required. These transformative resiliency programmes can assist adolescents to un-learn and re-learn behaviours that minimize risk-taking activities.

Understanding the neurobiology and the impact of hormonal and environmental stressors has guided the development of our resiliency programmes. Eight key components have been identified in our effective programmes that **‘BALANCE’** our adolescents by providing:

- **Blue Green Therapy –** Offers opportunities for relaxation and relearning social norms, builds interpersonal skills and provides exercise that promotes neurogenesis, and releases endorphins that alleviate depression and elevate mood. Blue green therapy refers to taking persons into environments with blue skies, blue seas and green grass. The hopelessness often pervasive in grey urban concrete jungles is left behind.

- **Attachment –** Comes from parental nurturing, influence, and enhanced family connectedness/functioning. Physical interactions release serotonin that is associated with decreased levels of aggression. This underlines the importance of family, school, after-school programmes, remedial and reintegration programmes.

- **Life skills building –** Enables adolescents to set goals, handle differences, manage conflict and build self-esteem.

- **Academic enhancement –** Academic achievement builds self-esteem, and increased evidence is emerging to support the association between learning to read and reduction in aggressive behaviours.

- **Nutrition is optimized –** Good nutrition is needed for myelination and synaptic pruning in the brain, to support the growth spurt and increase in physical activity. The brain is the main consumer of the body's glucose (Mergenthaler et al. 2013).

- **Counselling for grief –** Prevention or treatment of post-traumatic stress, management of fear, anxieties, insecurity. This counselling is provided after a sudden traumatic event and needs to be repeated after a two-month period (when the adrenaline levels drop). Many persons involved in violence or high-risk behaviour have been exposed to complex trauma.

- **Enhance mindfulness –** Centring activities that retard impulsivity. These can include music, drumming, meditation, martial arts.

- **Sexuality and spirituality –** Healthy sexual maturation and formation of a spiritual identity result in the formation of sexual identity and establishment of positive relationships during the adolescent period.

The nature of programme delivery is important. Small group size, youth-friendly leaders, attachment building activities, family involvement, economic stabilization of families, provision of structured activity that provides rewards and builds resiliency, are all critical to increasing the impact of the programmes.

Timing of these programmatic components may also prove to be important. The inputs must meet the known critical developmental, metabolic and social occurrences in adolescents' lives and the nature of these inputs is influenced by community and societal norms.

While 'earlier is still better', even with the beneficial impact of early childhood interventions and effective parenting strategies, encouraging evidence of the added benefits of the BALANCES resilience programming for adolescents is emerging.

These programmes need to have components to support critical areas of adolescent development in order to exploit the plasticity of the adolescent brain and reduce the adverse impact of risk-taking behaviours.

Re-learning behaviours – that are built as new pathways as the adolescent neural circuits mature – allows for the development of the frontal lobes that serve as the brakes in the adolescent control room, the PFC. We now know how to use resiliency interventions to lay down the rails that guide the traffic flow in adolescent brains. We have shown how this can redirect those traffic flows. Resiliency programming BALANCES and builds the rails and the crash bars to minimize adverse outcomes. It provides the programmatic switches at the crossroads ahead and keeps adolescent development on the tracks.

The new development agenda can meet the needs of adolescents

When we protect adolescents from their risk-taking behaviour the benefits of harnessing and redirecting their energy and talent are apparent. To ensure that this happens, a development agenda driven by adolescents is needed. Resources must be provided for wide-scale use of the best available evidence-informed resiliency programmes that are culturally and socially relevant.

Looking forward, the strategy is to have both ongoing operational research and rigorous monitoring and evaluation frameworks to guide the implementation of these resiliency programmes. These will use and seek input from adolescents' creative energies to drive programme delivery. We must better exploit the plasticity of the adolescent brain and deliver resiliency programmes that assist in relearning behaviours that can be built into adolescent neural circuits. A development agenda embedded in a resiliency approach to adolescence is likely to reap financial benefits allowing adolescents to make significant contributions to society. As we move forward, a development agenda prioritizing and driven by adolescents is needed.

I would like to acknowledge the input of Professor Ronald Young, University of the West Indies Mona Campus, and the many professionals in the field who run the programmes for our adolescents.

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MINDFULNESS MEDITATION IMPACT ON THE ADOLESCENT BRAIN

Envisioning a Cornucopia of All-Purpose Nanomaterials (2014)

MINDFULNESS MEDITATION IMPACT ON THE ADOLESCENT BRAIN

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The adolescent period is a critical stage for strengthening neuroplasticity and building cognitive, affective and social capacities that can support positive changes in school, work and relationships over the lifespan. Recent research has shown that mindfulness meditation has an impact on adolescent brain plasticity including functional and structural changes related to attention control, emotion regulation and self-awareness improvement (Hölzel et al. 2011; Tang et al. 2015).

In general, mindfulness meditation often refers to non-judgmental attention to experiences in the present moment such as thoughts, emotions and sensations. Since mindfulness involves training attention and self-control, it is reasonable to speculate about the mechanisms associated with attention and self-control, where these capacities are crucial for adolescents in school, in future work and in relationships. It has been suggested that mindfulness meditation includes at least three components that interact closely to constitute a process of enhanced self-regulation: enhanced attention control, improved emotion regulation and altered self-awareness (Tang et al. 2015). Here we take few examples and briefly summarize the latest neuroscientific findings on mindfulness meditation associated with brain plasticity and positive behaviours.

Mindfulness improves attention, emotion, immune function, and reduces stress

We first examine one form of mindfulness training called integrative body–mind training (IBMT), for which extensive randomized trials have been conducted using relaxation training as a rigorous control (Tang et al. 2007, 2009, 2010, 2014). After five sessions of IBMT (20 to 30 minutes per session), we found greater improvement in executive attention compared to the relaxation training. IBMT also produced improvements in mood state and a reduction in the stress hormone cortisol. It also improved immunoreactivity – secretory immunoglobulin A (sIgA). The reduction in cortisol and improvement in sIgA suggest that even a few hours of IBMT could produce positive changes in diverse behaviours (Tang et al. 2007).

Mindfulness changes brain function and structure associated with self-control

We then applied brain imaging methods to explore the underlying mechanisms. After five sessions of training, activation of the anterior cingulate cortex (ACC), the self-control network in the brain, was greater following IBMT than following relaxation training (Tang et al. 2009). Moreover, parasympathetic function, measured by heart rate variability, had changed more in the IBMT group than in the relaxation training. These studies suggest that IBMT involves both central and autonomic nervous system changes (Tang et al. 2009, 2014; Tang and Posner, 2014).

These results point to short term changes after a few hours of IBMT practice, but could longer IBMT practice lead to brain structural changes? Further studies using diffusion tensor imaging revealed that several white matter tracts connecting the ACC to other areas had improved their efficiency following 10 to 20 sessions of IBMT (Tang et al. 2010, 2012). Figure 1 shows the significant changes in greater white matter related to self-control areas in the brain measured by diffusion tensor imaging following IBMT compared to the same period of relaxation training. In the demonstration map, the green area is the left anterior corona radiata, the purple area is the left superior corona radiata, the blue area is the genu of corpus callosum, and the red area is the body of corpus callosum. These findings show that connectivity related to self-control can be altered by brief IBMT (Tang et al. 2015). Since many problems and mental disorders such as learning difficulty, attention deficit hyperactivity disorder (ADHD), mood disorders, anti-social behaviour, addiction and post-traumatic stress disorder (PTSD) are associated with the deficits of self-control in the brain, our results have potential implications for all aspects of self-control related problems or disorders, including educational and clinical applications over the lifespan. These findings suggest that problems or disorders in adolescents and adults could be reduced and ameliorated through engagement in a short-term mindfulness practice (Tang et al. 2012).

Conclusion

In sum, a series of studies suggest that mindfulness meditation such as IBMT is a low-cost and effective intervention which could induce neuroplasticity that supports building self-control of cognitive, affective and social capacities in adolescents (Tang and Leve, 2016). For example, IBMT practice does not need any special infrastructure, therefore IBMT has been applied in K-12, college and adult learning environments in China and other countries (Tang, 2016). We have also tested IBMT with adolescents in low- and middle-income countries with different SES; the preliminary results suggest positive effects in attention, learning performance, emotion and behaviour.

Since IBMT only needs a few hours of practice to benefit students, including adolescents, it is relatively easy to implement within a school system and to fit into a daily curriculum. Mindfulness has impacts on the development of prefrontal brain structure and function and enhances attention control, emotion regulation and self-awareness skills in adolescents. These skills can support positive changes in school, work and relationships over the lifespan. Consistent with UNICEF's mission – to fulfill the potential of adolescents including those who have had adverse early experiences – mindfulness may provide an opportunity for adolescents to influence their brain development, improve self-control and build on capacities for positive change. Mindfulness research is directly relevant to UNICEF and other international development stakeholders who wish to maximize the potential of adolescents through programming, policy and advocacy.

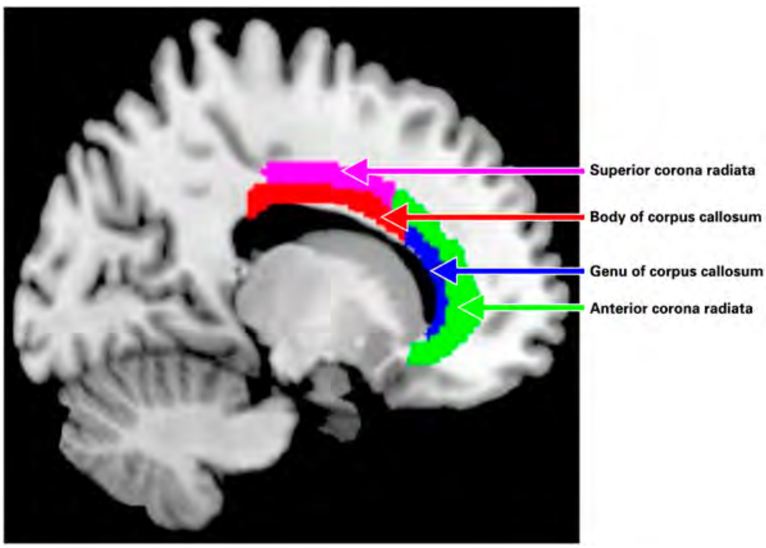

Figure 1. Demonstration of brain regions with significant changes in greater white matter after about 10 hours of IBMT compared to relaxation training (see Tang et al. 2010).

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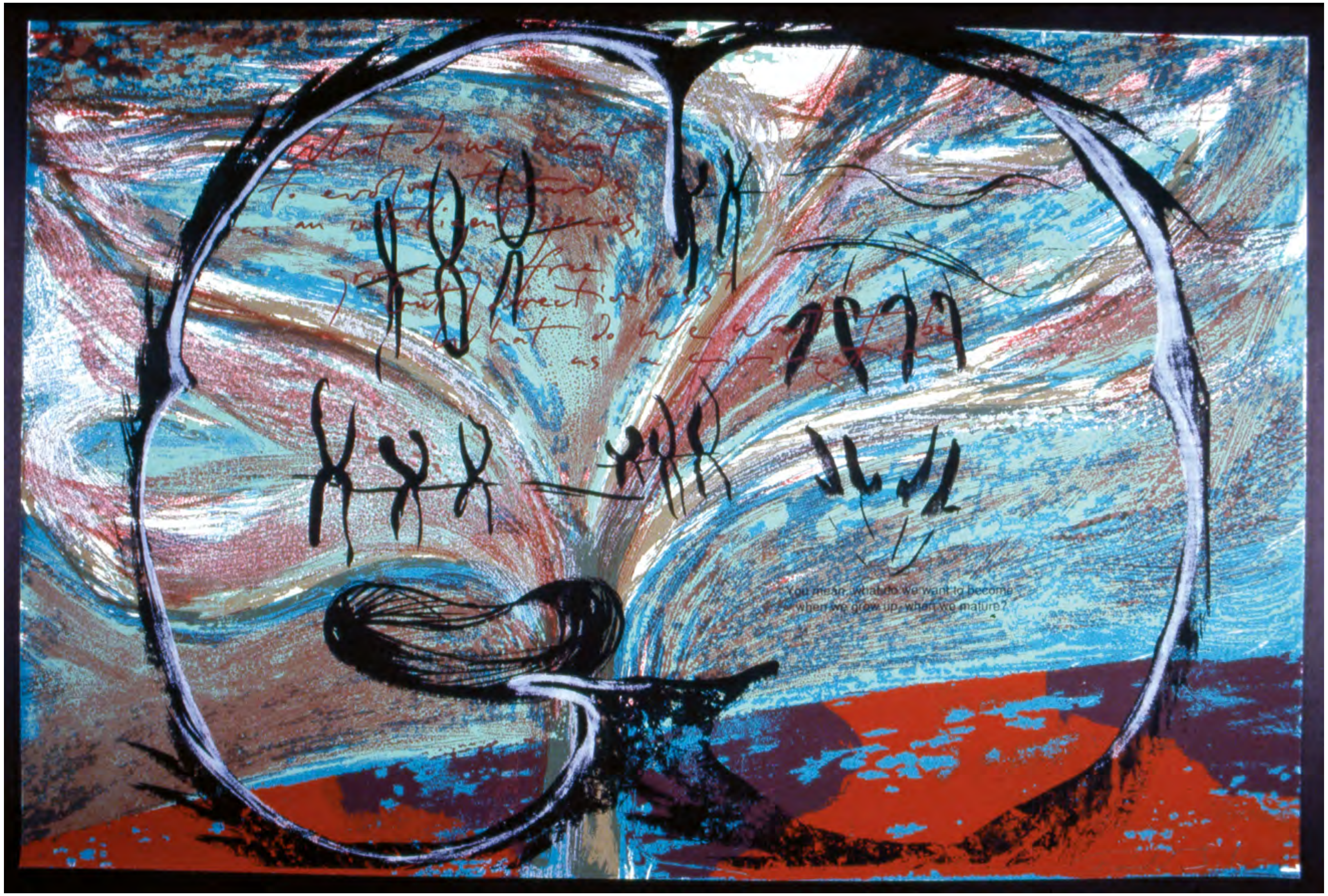
THE PERILS AND PROMISE OF TECHNOLOGY FOR THE ADOLESCENT BRAIN



Mind Icon No.8 (Questioning Our Evolution)
(1991)

THE PERILS AND PROMISE OF TECHNOLOGY FOR THE ADOLESCENT BRAIN

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The ubiquity of technology and media use in both developed and developing nations has raised much concern among policymakers, educators, and parents about the impact that technology and media may have on the brain and behaviour, and in particular on brains that are in periods of high neuroplasticity, like the adolescent brain. The fervour of these concerns, however, seems met with an equally urgent interest in the potential promise of using technology and media for pro-social outcomes, such as advancing academic achievement through edtech platforms or by connecting with otherwise unreachable users in developing countries who own smartphones but have no other means of connectivity. These dual axes of vilification and idealization of technology call for a reasoned, evidence-based approach to understanding the true perils and promises of technology on the developing mind.

To this end, there are now initial global efforts to convene scientists researching the relationships between technology use and academic, psychosocial, cognitive, and neural outcomes, in order to generate national research agendas and recommendations regarding what constitutes a healthy technology diet (e.g. the 2015 National Academy of Sciences Sackler conference on Digital Media and Developing Minds, and the 2016 Society for Research in Children's Development conference on Technology and Media in Children's Development). In this commentary, I present some key highlights of what is currently known about the potential benefits, as well as the potential costs of technology on the mind and brain.

Benefits associated with technology use

Reaching adolescents globally. Perhaps the most promising factor that technology brings to policies on education, global health, economics, and politics, is *reach*. Technology, in its optimal form, can allow for tech-enabled programmes to be (1) distributed at scale to a broad, global audience, often at a much lower cost, (2) may also provide higher quality instruction at a lower cost, and (3) may provide relevant data on how people are learning, for feedback into the programmes to optimize delivery.

In the education domain, for instance, in regions that have fewer than needed well-trained teachers but high penetration of smartphones, this fundamental challenge may be at least partially addressed by smartphone-enabled education delivery. The reach of technology can allow for best practices in teaching and learning to be scaled across markets, providing evidence-based teacher preparation and training, as well as providing opportunities for knowledge- and skill-building for students. Technology can also provide a way to gather precision data about what students are learning and how they are learning it, in real time and across many different educational contexts. Such data can serve critical functions in the *research* and *practice* domains: (1) *Research*: these data can fundamentally inform education research by allowing scientists to refine their research questions using real-world data; and (2) *Practice*: these data may also provide key insights into the practical challenge of how to deliver education at scale.

Action video games and learning-to-learn. Beyond providing creative solutions to some of our global education challenges, interacting with some forms of entertainment technology itself can provide benefits. One of the most unexpected benefits comes in the form of video game play. A growing body of evidence from neuroscience and behavioural science is revealing the positive benefits of playing ‘action video games’ (typically, face-paced games such as first and third person shooting games like *Call of Duty* or *Gears of War*, action games like the *Burnout* series, and action-adventure games like *Grand Theft Auto*). Since the first report of the positive impact of action video gameplay more than a decade ago [1], researchers have continued to uncover the breadth of benefits of action video gameplay, including improvements in perceptual decision making [2], speed of processing [3,4], ability to overcome attention capture [5,6], and the ability to remember visually presented information [7,8], as well as to perform multiple tasks concurrently (multi-task) [9-10] and rapidly switch between two tasks [11-16], among other abilities (although see [17-20] for failures to find such effects).

Importantly, these benefits are documented for skills performed well beyond the confines of the video games, so participants are not simply getting better only at the game itself. Instead, it seems that action video gameplay trains people in a wide variety of skills, and skills that are important to real-world learning. In fact, in a recent study, action-gamers were shown to be ‘better learners’, and to have become better by playing action games. In this study, the pioneers of this research field, Daphne Bavelier and Shawn Green [1, 2, 14, 23], demonstrated that they could turn non-gamers into gamers with 50 hours of action gameplay over nine weeks, and these newly minted action-gamers were then tested on their ability to learn several new tasks [21]. The action gamers learned the new tasks at a much more accelerated pace than the control group, who trained for the same number of hours on non-action video games such as *The Sims*. Surprisingly, the performance boost was long-lasting, with improvements evident several months to a year later.

Researchers have looked to the brains of action-gamers to uncover the neural basis of the foregoing behavioural benefits, and have found interesting differences between the brains of action-gamers and non-gamers. In one study, scientists showed that action-gamers' brains could suppress distracting information better, which allows for increased focus on the goal at hand [22]. In another, action-gamers' brains were more efficient at directing attention during a demanding task, requiring attention networks to work less hard to perform at the same level of ability [23].

Altogether, the research shows that action-gamers perform better on a wide variety of tasks, and do so with more efficient brain networks. It seems the action-gamers have honed a meta-cognitive skill of 'learning-to-learn', which can allow for more effective and flexible learning in real-world contexts. Developing such a skill could have far-reaching implications on adolescents around the globe. And while these factors may impart benefits to developing adolescents, we would be remiss not to caution that they should not be used as an excuse to binge on video game play, particularly at the expense of other positive behaviours such as exercise, social engagement, and interaction with the natural world.

Costs associated with technology use

Action video games and aggression. Any policies that consider the benefits of action video game play should be tempered with the findings that the violence inherent in such games has been linked to aggression in game players. In a 2008 study of 2,500 young people, for instance, Douglas and Ronald Gentile found that teens and children who played more violent video games reported more aggressive thoughts and behaviour, and more arguments with teachers [24]. This and many other such findings have led researchers who study the positive impacts of action video games to redouble their efforts to understand how to build games in the educational and therapeutic domains. There are several efforts by scientists to create games that leverage the observed benefits while removing the adverse effects of the violence.

Multi-tasking with media. Beyond video games, a growing body of evidence is revealing that our increased interaction with media and technology, particularly concurrent use of multiple media streams ('media multi-tasking'), is associated with negative outcomes. American adolescents spend more time with media than in any other activity: an average of 7.5 hours per day, every day. If the time spent juggling multiple media streams simultaneously is considered, American adolescents averaged almost 11 hours of media exposure every day [25, 26]. This phenomenon is not limited to adolescents from the United States, but is paralleled in other countries such as Kuwait, Russia, Singapore, and the Netherlands. Given that a large number of media multi-taskers are younger children, adolescents, and young adults whose brains are still developing, there is great urgency to understand the neurocognitive profile of media multi-taskers.

While the field of research on media multi-tasking is still nascent, the weight of current evidence demonstrates that heavy media multi-taskers show differences in cognition (e.g. poorer memory), psychosocial behaviour (e.g. increased impulsivity), and neural structure (e.g. reduced volume in the anterior cingulate cortex) [27]. Furthermore, research indicates that multi-tasking with media during learning (in class or at home) can negatively affect academic outcomes. Until the direction of causality is understood – whether media multi-tasking causes the observed behavioural, psycho-social, and neural differences, or whether individuals with such differences tend to multi-task with media more often – the data suggest policies that would encourage tempered engagement with concurrent media streams. Findings from current research promise to inform policy and practice on an increasingly urgent social issue, while significantly advancing our understanding of intersections between cognitive, psychosocial, neural, and real-world factors. It is important to note, however, that research on the impact of technology on the developing adolescent brain is still at a very early stage, and much more research funding will be needed to understand how, when, and where, and in what combinations, technology consumption is supportive of adolescent development. In other words, there is an urgent need to fund rigorous, unbiased research on what constitutes a health technology 'diet' for brains that are particularly vulnerable to external influences, such as the developing adolescent brain.

Conclusions

Technology has become an important and ubiquitous aspect of our society, and its responsible use will be a key tenet of policies, programmes, and advocacy for international development stakeholders, particularly for initiatives surrounding adolescents, whose brains are still developing. There is much research still to be conducted, but the current state of the evidence suggests there are both perils and promises in the use of technology for social good. On the positive side, technology can be used to deliver effective education programmes at scale, provide precision data about what and how students are learning, and allow researchers to gather real-world data to refine research questions and interventions. Furthermore, interacting with specific types of technology can confer benefits, as in the case of action video games building the meta-cognitive skill of learning-to-learn. On the negative side, the increasing consumption of multiple media streams concurrently is associated with poorer cognitive, psychosocial, neural, and academic outcomes, as is the violence in commercial action video games. In sum, the research suggests that policies and programmes designed to improve the lives of adolescents around the globe should consider technology use in a balanced way: a sensible *technology diet* will maximize the benefits and minimize the risks of technology use.

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