Published in final edited form as:

J Res Adolesc. 2018 March ; 28(1): 4–9. doi:10.1111/jora.12379.

Adolescent Brain Development: Implications for Understanding Risk and Resilience Processes through Neuroimaging Research

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Abstract

This special section focuses on research that utilizes neuroimaging methods to examine the impact of social relationships and socioemotional development on adolescent brain function. Studies include novel neuroimaging methods that further our understanding of adolescent brain development. This special section has a particular focus on how study findings add to our understanding of risk and resilience. In this introduction to the special section, we discuss the role of neuroimaging in developmental science and provide a brief review of neuroimaging methods. We present key themes that are covered in the special section papers including: 1) emerging methods in developmental neuroscience; 2) emotion-cognition interaction; and 3) the role of social relationships in brain function. We conclude our introduction with future directions for integrating developmental neuroscience into the study of adolescence, and highlight key points from the special section's commentaries which include information on the landmark Adolescent Brain Cognitive Development (ABCD) study.

Our understanding of adolescent brain development has dramatically increased in recent years due to advances in neuroimaging techniques. Studies examining social and emotional risk and protective factors, in conjunction with markers of neural integrity, have great potential to improve our knowledge of the developmental trajectories of mental health outcomes and psychopathology (Steinberg, 2008). Nevertheless, developmental science has yet to fully integrate neuroscience findings into developmental research and theory on adolescence. In response, this special section focuses on research that utilizes neuroimaging methods to examine the impact of social relationships (parents and peers) and socioemotional development on adolescent brain function. In addition, studies include novel neuroimaging methods and genetic analyses that further our understanding of adolescent brain development. This special section has a particular focus on how study findings add to our understanding of risk and resilience trajectories of psychopathology and positive youth

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development. The special section ends with commentary discussing critical next steps for integrating developmental neuroscience into the study of adolescence, and information on the landmark Adolescent Brain Cognitive Development (ABCD) study and the potential for this open science investigation to impact the field of adolescent development.

The Role of Neuroimaging in Developmental Science

The brain is rapidly changing during adolescence, spanning microstructural to macrostructural changes. This is a dynamic, complex, and adaptive process. Neuroimaging advances have allowed developmental scientists to make great advances, as in vivo imaging has provided us with a tool to visualize and make inferences about organizational changes in the brain that likely underlie socioemotional and neurocognitive development (Bandettinni, 2012). Structural and functional neuroimaging in particular have provided a better understanding of developmental and age-related changes (Giedd, 2008). Estimates of anatomical associations with genetic and environmental influences can also be explored and discussed in the context of typical and atypical behavioral outcomes that evolve during adolescence. Using neuroimaging in developmental research can help elucidate the complex relationships between underlying neural substrates, the environment, and functional outcomes. Neuroimaging can include topics covered in this special section such as decision-making, risky behaviors, resilience, and emotional control. Despite exciting advances in technology that have changed the way we study adolescent brain development, there are methodological considerations in different neuroimaging modalities that are important to recognize in order to make informed interpretations.

Neuroimaging and Methodological Considerations

The first use of neuroimaging in humans was in 1991, which was followed by an explosion of imaging research in the early 2000s. There are several different noninvasive approaches for measuring structural brain changes and brain activity in children and adolescents. The appropriate imaging modality depends on the scientific question and falls into the two broad categories of functional and structural imaging. Functional magnetic resonance imaging (fMRI) is one of the most central and well-known imaging modalities because it is relatively safe (e.g., no radiation) and can be done repeatedly, does not require intravenous injection like its predecessor positron emission tomography (PET) imaging, can spatially localize brain activity (compared to electroencephalography or EEG), and detects subtle differences in brain activity. fMRI includes task-based paradigms, where participants are actively engaged in a cognitive task while in the scanner, as well as resting-state paradigms that seek to understand how the brain functions “at rest” (i.e., when not performing a task). fMRI signals are interpreted from a regionally correlated blood-oxygen level dependent (BOLD) signal. BOLD signal has been found to correspond with other measures of neural activity, however an ongoing critique of BOLD is its susceptibility to physiological factors that could influence relationships between blood flow and neural activity (Bandettinni, 2012; Glover et al., 2011). Further, there are logistical and computational challenges such as head motion, task compliance and performance accuracy, image registration and multiple comparisons corrections, and a lack of normative data, which could introduce bias into statistical estimates and therefore result in spurious conclusions. Advanced methodological and

computational approaches have improved the reliability of task-based fMRI developmental studies (Herting et al., 2017), and have improved data quality (Grayson & Fair, 2017).

Structural imaging provides high-resolution information about the details of macrostructural and microstructural anatomical changes that occur throughout development. While structural imaging does not provide information on functional brain activity, this mode of imaging helps make inferences about overall volume changes in gray matter (neuronal cell bodies, dendrites, and synapses) and white matter (axons connecting gray matter, white because of the fatty myelin sheath surrounding the axon), as well as more subtle changes that occur in neural tissue. For example, subtle changes in brain structure during adolescence include cortical thinning and increased myelination. Structural neuroimaging faces many of the same logistical and computational challenges as functional imaging.

MRI modalities are appealing to use for child and adolescent research as they are noninvasive and safe to use as long as the child does not have metal in or on their body. The noninvasive quality of MRI, compared to other imaging modalities that involve radiation (e.g. computed tomography), allows for repeated scans, a critical component to modeling growth trajectories over time in relation to behavioral outcomes.

Key Themes Explored in this Special Section

Three primary themes are included in this special section: 1) emerging methods, 2) emotion-cognition interaction, and 3) social relationships and brain function. As mentioned previously, a risk and resilience focus is evident within each theme and across all papers, with an emphasis on psychopathology and positive adjustment. Current models of resilience across childhood focus on multidisciplinary approaches to examine protective mechanisms within multiple levels of ecosystems, from the molecular level to broader social systems and families (Masten, 2007; Henry, Morris, Harrist, 2015), as illustrated by the studies in this special section.

Emerging methods.

Several papers in the special section focused on emerging methods, examining individual differences by analyzing person-specific networks and genetic and neural markers. Specifically, Beltz (2018) utilizes a new approach to fMRI analysis: extended unified structural equation models (euSEMs) implemented in group iterative multiple model estimation (GIMME). This person-specific, data-driven approach allows us to better understand individual differences in brain development in researching heterogeneous samples. Such an approach is useful in understanding differences in brain connectivity and has potential for answering questions about adolescent risk and resilience. Trucco et al. (2018) examined important neurobiological and genetic mechanisms that affect problematic behaviors in adolescents. Youth with a genetic risk marker in GABRA2 had different neurological responses to emotional words, and these variations predicted negative emotionality and externalizing problems. Studies such as these highlight our advancing knowledge of the nuanced relationship between neural endophenotypes and behavioral outcomes, which may aid in development of targeted prevention and intervention programs. Imaging genomics will continue to enrich our understanding of the complex issue of

adolescent brain development, including the identification of important risk and resilience factors.

Emotion-cognition interaction.

Neuroimaging research conducted with adolescents in the past decade has demonstrated that the neural substrates of emotional reactivity and cognitive control contribute to adaptive functioning and risk for psychopathology during this transition period. However, there is a need to better understand how systems that contribute to emotional reactions and cognitive control of emotions interact with each other when adolescents are faced with emotional decisions and experiences. Brieant et al. (2018) and Hansen et al. (2018) address this need by examining the influence of emotion-cognition interactions on adolescent adaptive functioning. In a longitudinal study, Brieant et al. show that high levels of positive emotion can attenuate risk for externalizing behavior problems among adolescents with lower prefrontal cognitive control on a laboratory cognitive interference task. Hansen et al. examine risky sexual decision-making, a behavior that lies at the interface of emotion and cognition. They find that although behavioral performance on a response inhibition task did not predict sexual risk, adolescents who needed to recruit more middle frontal gyrus activation on the task made riskier sexual decisions, such as reduced use of condoms. Another study in this special section, Rodrigo et al., focuses on emotional responding during risky decision-making. This study demonstrates the importance of taking a more nuanced view of emotion by focusing on neural circuits involved in the experience of counterfactual emotions, such as regret and disappointment, during a social decision-making task. These studies exemplify the ways in which neuroimaging investigations of more complex emotions and emotion-cognition interactions may help to move the field toward a better understanding of adolescents' adaptive and maladaptive functioning during real-world emotional situations.

Social relationships and brain function.

During adolescence, the brain is primed to experience social relationships and social influences (Cron & Dahl, 2012). Two of the manuscripts in the special section focus on peers and social status. Lee and colleagues (2018) examined neural responses to social status words (e.g., loser, popular) and depressive symptoms. They found that reduced activation in the dorsolateral prefrontal cortex (DLPFC, a brain region involved in emotion regulation) in response to negative social status words explained the association between self-reported social risk (peer victimization and fear of negative evaluation) and depressive symptoms, suggesting altered DLPFC activity in response to social information may be a neural correlate of depression during adolescence. Schriber et al. (2018) examined social influences of both parents and peers in their longitudinal study. They examined neural responses to social exclusion in hostile school environments and whether family connectedness buffered the effects of social exclusion on later deviance. The link between hostile school environments and social deviance was mediated by greater reactivity to social deviance in the subgenual anterior cingulate cortex, a region implicated in social pain and social susceptibility. Importantly, among youth who had a strong connection to family, this connection was not found, suggesting that family connectedness is a protective factor against this neural susceptibility. Lee, Qu, and Telzer also found protective effects of family connectedness. In their study, mother-teen dyads who reported high family connectedness

showed similar neural profiles during stressful tasks. Notably, neural synchrony among mothers and adolescents was associated with less stress in youth. Saxbe et al. (2018) examined family aggression and adversity. Using longitudinal data, they found that family aggression and externalizing behavior were predicted by differences in amygdala volumes and amygdala connectedness. Taken together, findings across these studies provide support for the premise that adolescents are “wired to connect” and when that connection is positive, it results in better outcomes for youth both concurrently and over time. In contrast, when there is family dysfunction or peer victimization, adolescents are more likely to develop neurological circuitry that puts them at risk for psychopathology.

Future Directions: Opportunities and Challenges

Incorporating neuroscience into the study of adolescence is both a challenge and an opportunity (Dahl, 2004). Nevertheless, doing so will help move the field forward by expanding our understanding of the complexity of development and the role of context and social experiences in brain function. Indeed, integration and organization of the brain connectome (i.e., circuitry) change as the adolescent brain matures (Stevens, 2016), and there is a shift from local to distributed profiles and changes in strength of neural connections as the brain increases in efficiency. Moreover, different neural networks have been found to have different developmental trajectories (Stevens et al., 2016), making adolescence an opportune developmental period to examine neurological correlates of risk and resilience.

Interdisciplinary teams are key to integrating our understanding of the complex interplay between brain, socioemotional, physical, and cognitive development, and developmental neuroscience provides an excellent opportunity to bring together scientists from multiple disciplines. BRAIN 2025, the report of the NIH Brain Initiative, recommends interdisciplinary collaborations among scientists from diverse backgrounds (e.g., physicists, engineers, statisticians, neuroscientists, psychologists and mathematicians) to establish norms for properly collecting, analyzing, and interpreting neuroimaging data (<https://www.braininitiative.nih.gov/2025/>). Initiatives to standardize methods will be integral in moving the science forward, addressing ongoing challenges, and providing opportunities to answer critical research questions to better understand adolescent neurodevelopment.

Current research in neuroscience is often narrowly focused, and would benefit from broadening its developmental focus. Indeed, many neuroimaging studies focus on the effects of abuse, trauma, or the role of brain function in psychopathology. Although such studies are ideal for many experimental paradigms (comparing healthy controls to individuals with a diagnosis or a specific history), findings are often difficult to integrate with our understanding of normative development. As is discussed in the Fuligni, Dapretto, and Galvan (2018) commentary, understanding normative development allows researchers to identify deviations in neurodevelopmental trajectories. Most adult psychiatric disorders begin during adolescence, so it is important to identify and understand the mechanisms of vulnerability, as well as resilience, across childhood and adolescence. When neural regions are considered *abnormal*, treatments or interventions can be developed that work specifically on those targeted brain areas.

The Adolescent Brain Cognitive Development (ABCD) study, discussed in the special section's commentary, provides an excellent opportunity for researchers to examine both typical and atypical development over time (Jernigan, Brown & Dowling, 2018). Indeed, ABCD will be a tremendous resource for the scientific community. ABCD will also be enhanced by other studies that utilize a similar developmental framework while focusing on one domain (e.g., peer relations) in more depth, and combine neuroimaging methods with other developmental techniques such as observations of social interactions.

One area of research discussed in the Giedd (2018) commentary that is not well represented in the special section is the impact of technology on brain and socioemotional development. With increasing use of technology, adolescent development is influenced by social media and screen time in ways that the research community is just beginning to understand. Adolescent researchers know about *the imaginary audience*, a teen's false belief that everyone is watching him or her, a phenomenon that is believed to emerge during early adolescence due to increased self-consciousness and ego-centrism (Elkind, 1967). With "likes" and "followers" and Instagram Stories, *the imaginary audience is real* for many adolescents. Developmental neuroscience is primed to examine the impact of technology on psychopathology and adjustment because it allows researchers to study the effects of technology on the brain, and to understand neurological circuitry involved in social development across real and technological contexts. Other areas in need of further study are sex differences in neurological development (see Giedd, 2018) and the role of population diversity (ethnicity and socioeconomic resources) in neural development and functioning (see Fuligni et al., 2018).

In summary, the manuscripts included in this special section cover a wide variety of developmental neuroscience topics, all with a focus on adolescents and risk and resilience processes. Developmental neuroscience is a burgeoning field and will benefit greatly from the integration of developmental concepts and theories such as family resilience (Henry et al., 2015), research on parent-adolescent relationships and attachment, studies of peer and romantic relationships, and research on emotion regulation and socialization (Morris et al., in press). Moreover, research on adolescence will benefit from findings in neuroscience that compliment and extend our understanding of social and emotional development, as is illustrated by the studies and commentaries in the special section. As Giedd (2018) points out in his commentary, it is essential for our field to not only examine neurological development in adolescence, but to clearly communicate scientific findings and apply them to policies, programming, and treatments aimed at optimal development for all adolescents.

Acknowledgments

Work on this manuscript was supported by grants from the National Institutes of Health, to Amanda Morris from award numbers P20GM109097 and U01-DA041089-03; to Lindsay Squeglia from award numbers K23 AA025399, U01 DA041093, and U24 DA041147; to Joanna Jacobus from award numbers U01 DA041089 and KL2 TR001444; and to Jennifer Silk from award number R01 MH10324. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

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