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Analysing the effects of emotional vacuum between teenagers and parents

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Abstract
Adolescents are commonly portrayed as highly emotional, with their behaviors often hijacked by their emotions. Research on the neural substrates of adolescent affective behavior is beginning to paint a more nuanced picture of how neurodevelopmental changes in brain function influence affective behavior, and how these influences are modulated by external factors in the environment. Recent neurodevelopmental models suggest that the brain is designed to promote emotion regulation, learning, and affiliation across development, and that affective behavior reciprocally interacts with age-specific social demands and different social contexts. In this review, we discuss current findings on neurobiological mechanisms of adolescents' affective behavior and highlight individual differences in and social-contextual influences on adolescents' emotionality. Neurobiological mechanisms of affective processes related to anxiety and depression are also discussed as examples. As the field progresses, it will be critical to test new hypotheses generated from the foundational empirical and conceptual work and to focus on identifying more precisely how and when neural networks change in ways that promote or thwart adaptive affective behavior during adolescence.

Keywords: affect, brain, fMRI, Puberty, physiology, individual differences, social context

Introductions
The emotional life of an adolescent is complex both inside and out. From the "inside", adolescents experience vast hormonal changes and fine tuning of the neural networks that both produce and manage emotions. From the "outside", they experience dramatic and dynamic shifts in the structure and significance of key social relationships, such as those with parents, peers, and romantic partners as well as a variety of novel experiences and increasing societal demands. The convergence of these internal and external changes can result in affective experiences and behaviors that are sometimes overwhelming, confusing, and difficult to manage.

Although adolescence has long been hailed as a period of emotional challenge (for both adolescents and their parents), it is only in the past 15 years that we have really begun to understand the "inside" of the adolescent from the perspective of the brain. Tapping into the emotional lives of adolescents is not a straightforward endeavor because adolescents can be reluctant to share their emotions, and, particularly during adolescence, emotional reactions vary tremendously by context. Fortunately, recent methodological advances in neuroscience with particular applications for developmental and clinical populations has led to considerable improvement in our understanding of neurobiological mechanisms of adolescents' emotional lives. Moreover, recent conceptual models of neurodevelopment in adolescence suggest that we can use what has been learned about brain growth and plasticity in adolescence to leverage adolescents' heightened emotionality in productive ways (e.g., civic engagement) and to discover new strategies to ameliorate forms of emotional dysregulation (e.g., anxiety and depression) that often emerge during adolescence.

In this review, we discuss evidence of three primary connections between neurobiological and affective development in adolescence. First, adolescence is marked by a high level of emotionality and a substantial increase in psychopathological levels of dysfunctional affect. Although individual differences exist in levels of adolescent emotionality, they also correspond broadly with the ordering of changes instantiated by pubertal and brain development. Second, learning to manage one's emotional reactions is a principal task of adolescence that relates to social-cognitive development. These social-cognitive processes are supported by changes in the connections among brain structures implicated in functions such as such as mentalizing, self-appraisal, social learning, and emotion regulation.

Third, in addition to the influence of brain maturation, adolescents' affective behavior is intertwined with a number of other psychological factors that modify emotional experience. The valence and novelty of certain contexts (particularly in the social domain) and the latent effects of past social experiences interact with neural bases of cognition and emotion to further modify the salience of current experiences. We conclude our review by describing implications of the findings reviewed and recommending future directions for research on the brain's role in affective behavior during adolescence.

Of note, we orient this review on research that emphasizes social context and social affect; uses neuroimaging; and focuses on a set of specific brain regions for three main reasons. First, we have argued that social interactions and relationships are among the most critical contexts to interact with neurobiological development in adolescence. Given the importance of social relationships to well-being and optimal functioning, the human brain must be designed to promote social learning and affiliation with others across development. However, adolescence is a particularly dynamic, context-dependent phase of development for social-affiliative behavior. While most individuals experience an increase in the intensity and frequency of emotions during adolescence, heightened emotionality is mostly and most strongly experienced in social settings. Affective behavior and social demands interact and, with experience and time, typically facilitate adaptive behavior. Nonetheless, although we focus on social affect and social context, we do recognize that several constructs including emotional intensity, emotion regulation, and context dependence may have broader application than just the social domain.

Second, we concentrate on functional magnetic resonance imaging (fMRI) because it is a widely used, powerful tool with which to link specific neural substrates with cognitive and behavioral responses to representations of emotional information. FMRI can reveal brain-based responses underlying emotion processing that may lack a behavioral corollary or may be undetectable through other methods of analysis (e.g., observation) or informants (e.g., parents). Furthermore, fMRI can help index inter-individual variance in the neural inputs that are recruited to achieve common behavioral outputs and delineate neural circuits that contribute to different affective phenotypes (e.g., irritability, euphoria). Although fMRI has low temporal resolution relative to electroencephalography, another commonly used assessment of the neural bases of emotion, it offers high spatial resolution for measuring neural processing within both the subcortical structures believed to be at the core of emotional responses, as well as the cortical structures implicated in behavioral integration. Finally, fMRI research has expanded recently to include tasks with high ecological validity designed to show cues or situations that represent more realistic aspects of adolescents' experiences. This shift has been significant because it has revealed nuances about the neurobiology of affective behavior that relate to social context.

Lastly, both conceptual frameworks of adolescent neurodevelopment and empirical work conducted in adult, clinical, and animal samples have guided a large number of neuroimaging studies of adolescent affective behavior to focus on the role of a relatively small number of brain regions in mediating social-affective behavior. Specifically, much attention has been given to the amygdala, striatum, insula, and anterior cingulate cortex (ACC), and a number of regions within the prefrontal cortex (PFC). These regions work together to assign salience, promote learning, monitor conflict, compute relative valence of social stimuli, and integrate this information to generate and guide affective behaviors toward wider goals and within the contexts in which they occur. Although early fMRI studies emphasized localized patterns of regional activation, a recent trend is to delineate patterns of functional interconnection both among these regions, and between these regions and brain areas that sub-serve different functional processes.

Heightened emotionality in adolescence: form and function

Behaviorally, adolescents show high levels of emotionality, with emotions that are more frequent, intense, and volatile, particularly compared with adults and in ways that differ from emotionality in early childhood (Arnett, 1999) [3]. For example, systematic sampling of adolescents' and adults' moods over the course of a week has shown that adolescents are more euphoric and more depressed in response to events (e.g., talking to friends, being in class), their positive feelings do not last as long as adults', and they are generally more emotionally responsive to events than are adults. Adolescence is also a time of thrill-seeking where emotional experiences even if they are potentially threatening - are actively sought out. This push-pull of affective stimuli bears out in reactivity of both threat-avoidance and reward-pursuit brain regions in relation to pubertal maturation.

From a functional perspective, human emotions have been preserved throughout our evolutionary history to promote adaptive responses to salient events. Across the myriad classes of information that we encounter at any given moment, stimuli with emotional salience have a high probability of attracting our attention, despite, at times, even our best intentions to block them out. The affective characteristics of stimuli then serve to direct our attention to critical information, generate a behavioral response, facilitate learning, and help generate adaptive response patterns. Adolescent hyper-emotionality is well-documented particularly in association with behaviors that involve social interaction such as with peers and parents. Other behaviors in which hyper-emotionality is clearly displayed during adolescence include risk taking and reward seeking, although these behaviors are strongly moderated by the social context in which they occur.

Another important and often overlooked aspect of adolescence is that many of the affective experiences occur in a completely novel context–particularly those related to social interaction. For example, emotional experiences related to intimacy, romantic love, jealousy, targeted rejection and acceptance by both partners and peers are often experienced for the first time during adolescence, and the novelty of these experiences may well enhance the impact of the associated emotions. The important moderating role of the social group in adolescents' emotional experience is likely to result in behaviors more conducive to norms of a novel peer group than of the natal family unit from which they are preparing to exit. Heightened impulsivity, sensation-seeking, and reward sensitivity may help to push adolescents toward seeking novel experiences and social interactions at a time when

they are leaving the natal group, establishing their identity, and developing routines in a new setting.

Control and regulation of affective behavior: Form and function

One of the primary tasks of adolescence is to refine one's cognitive control over behavior and emotional reactions. Virtually all contemporary models of emotional changes during adolescence contain some aspect of a gradually emerging modulatory control neural system. A peak of emotionality in early adolescence is followed by a slowly emerging ability to exert greater self- directed control over behaviors and emotions. This is most evident in the dual systems and imbalance conceptual models of adolescent neurodevelopment, which both characterize neocortical systems as developing increasing inhibitory control over striatal and limbic regions as adolescence progresses. Even within models that argue for a more complex relationship between top-down and bottom-up neural input across development, the influence of high emotionality on guiding behavior is thought to diminish in part due to maturation of neocortical modulatory inputs. There are many examples where cortically-mediated cognitive processes modulate emotionality in the social domain. Below, we discuss behavioral and neural evidence related to mentalizing, self-appraisal, social learning, and emotion regulation as processes that underscore the interface of cognitive and affective maturation in adolescence.

The emotional adolescent brain in context

Affective behavior during adolescence does not occur in a vacuum. In fact, evidence suggests that the neural circuits that support affective responding are highly sensitive to contextual influences, especially during adolescence. Crone and Dahl (2012), for example, argue that the adolescent brain is highly attuned to social inputs, which facilitates flexible responding among a highly salient and changing social context. This is consistent with Nelson *et al.*,'s (2005) conceptualization of adolescence as a period of neurodevelopment that corresponds with social reorientation, in which peer social interactions take on increasing salience, and Nelson and Guyer's (2011) hypothesis that protracted ventral PFC development is in place to accommodate the need for children and adolescents to develop social flexibility. In this section, we describe work showing various short- and long-term social-contextual influences on brain function, affective processing, and behavior in adolescence.

Future directions and conclusions

In our review of the literature, we have highlighted recent work illustrative of the substantial progress that has been made in our understanding of the neurobiology of adolescent affective behavior, particularly with regard to the role of social context and social experiences. As the field moves forward, we suggest extending the existing knowledge-base on the emotional adolescent brain by applying new methodological advances, integrating multiple units of analysis sampled in multiple contexts, and testing hypotheses from theoretical conceptualizations of neurobiological development.

With regard to methodology, researchers will need to continue pairing neuroimaging methods with new task paradigms that have a high level of ecological validity and capability of capturing real- time cognitions and behaviors. This approach will allow us to probe adolescent emotional behavior more deeply and in novel ways by simulating social experiences encountered in daily life. One of the limitations of using neuroimaging is that the scanning environment is constrained in its ability to capture how the brain represents information in a contextually-sensitive way, demonstrating the need to add real-world experience as much as possible. For example, new fMRI paradigms could be designed to assess adolescent affective behavior in response to peer interactions delivered in a simulated social media context or, as done in recent work, a virtual classroom environment. For the study of adolescent emotional and brain development, this is particularly important given that daily fluctuations in affective behavior relate to the types of activities in which adolescents are engaged.

Because the relation between neural function and sources of daily changes in adolescents' mood are not well understood, it will also be important to increasingly link fMRI and EMA measures to real-world affective behavior. For example, Price *et al.*, (2016) recently showed that PFC-amygdalar connectivity during threat processing was associated with the use of emotion regulation strategies in the real-world as assessed via EMA in anxious adolescents. The use of wearable, mobile technologies to assess ambulatory psychophysiology may be another way to capture nuances in adolescents' daily emotional experiences that can be integrated with measures of brain function to provide a more complete picture of adolescent affective behavior. In addition to EMA, methods such as eye-tracking and fNIRS are promising new techniques that may integrate well with neuroimaging data, but also offer more flexible usage. A challenge here is to account for differing time scales across these measurements. Modeling of their unique time courses will need to be addressed through analytical advancements and careful experimental design with respect to onset and duration of task stimuli or emotional challenges used to elicit responses across systems. Nonetheless, affective behavior is generated from multiple systems at different levels, and capturing these facets should elucidate target points for intervention.

Recent advances in the ability to conduct real-time fMRI may also help to reveal the neural substrates of dynamic changes in affect as they unfold. For example, fMRI-based neurofeedback has been used to teach adolescents to up-regulate activity in the insula, a key region in emotion regulation neural circuitry. Based on a Granger causality analysis, Cohen Kadosh *et al.*, (2016) found that the flow of information increased from the amygdala to the insula and from the insula to the mid-cingulate cortex, supplementary motor area and inferior parietal lobe specifically when youth engaged in up-regulation. This work highlights the potential for future interventions with adolescents that target the use of emotional regulation to change brain response and vice versa.

The application of advanced statistical modeling and patterning techniques will be important for characterizing adolescent development from an individual differences perspective. Incorporating methods such as pattern-classification algorithms to multi-voxel pattern analysis of fMRI data will help elucidate how social-emotional information is represented in the adolescent brain for different cognitive states and at different stages of

processing. For example, time course changes in how peer feedback or emotionally-laden stimuli are represented and processed in the brain during adolescence may increase the precision of our interpretations of brain activity. Graph theory is a another statistical method for classifying patterns of interconnectivity between brain regions that has generated important insights into neurodevelopmental processes and could increase our understanding of the interface between cognitive-control and affective neural circuits during social-emotional information processing.

Deeper characterization of the neural coding and processing of social-emotional information will also inform both typical neurobiological profiles of adolescent emotional development and dimensions of dysregulation that characterize adolescents with affect system difficulties such as depression and anxiety. For example, a recent study reported the development of a brain maturation index using structural MRI images. This index was derived from a regression-based algorithm 'trained' to integrate changes in brain anatomy across age to enhance prediction accuracy and differentiation of individual brain maturity. Results of this study provided a validated, accurate metric of brain maturation, which is significant in its potential application to reliably identify those who may deviate from a normative trajectory of brain development. Functional changes (e.g., peak or extent of activation) in regions with documented reactivity to social-affective cues could be similarly integrated across chronological age or pubertal stage to predict an adolescent's affective brain maturation index, which could be useful in a diagnostic or clinical intervention setting.

From a conceptualization standpoint, neuroimaging research has been limited in its integration of developmental theory into either design or interpretation of experimental results. A number of biologically-based developmental theories such as developmental systems theory, differential susceptibility (Belsky *et al.*, 2007a) [6], interactive specialization (Johnson, 2011), and critical periods of development (Takesian and Hensch, 2013) have been articulated in the developmental literature, but not necessarily used to guide neuroimaging research as suggested in a recent paper using differential susceptibility as an example. Relevant hypotheses from these theories could be tested in a neuroimaging environment and, in turn, these theories could be further refined. We believe the field of adolescent developmental neuroscience would benefit from a greater integration of the theoretical and methodological approaches discussed in this section.

Finally, conceptual understanding of affective neurobiology would be deepened by capturing other aspects of adolescents' emotional lives. This might include further consideration of more complex emotions like contempt, pride, and disgust, as done in the study by Goddings *et al.*, (2012). Similarly, more focus on the neural underpinnings of experiences related to intimacy and sexual relationships is needed. Indeed, recent work has examined the neural correlates of sexual decision-making in adolescent girls and found greater ACC activity during high-risk sexual decisions, along with sexual decision ratings that aligned with sexual emotions and behaviors.

A common theme of the work reviewed in this paper is the importance of both representing what happens externally in adolescents' emotional lives and upholding methodological control to test how those experiences are represented internally by the brain. By using techniques such as fMRI, we are beginning to identify more precisely in the brain how adolescents' affective behavior differs from adults or with age, varies with individual differences such as pubertal maturation and affective forms of psychopathology, and differs in response to specific social experiences. We expect future neuroscientific investigations that integrate multiple methods will advance knowledge of the brain-based opportunities and vulnerabilities of adolescent affective behavior.

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