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The triadic model perspective for the study of adolescent motivated behavior

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ABSTRACT

The triadic neural systems model is a heuristic tool, which was developed with the goal of providing a framework for neuroscience research into motivated behaviors. Unlike dual models that highlight dynamics between approach systems centered on striatal function and control systems centered on prefrontal cortex, the triadic model also includes an avoidance system, centered on amygdala-related circuits. A first application of this model has been to account for adolescent behavior.

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1. Adolescent motivated behavior, and brain development

1.1. Adolescent behavior

Adolescence is a distinct transition period from childhood to adulthood, with unique characteristics and behaviors. This period represents both a time of opportunity for building the roots of a successful and fulfilling adult life, and a time of vulnerability owing to the adverse consequences of the typical impulsive/risky adolescent behaviors (Arnett, 1999; Dahl, 2004; Ernst & Hardin, 2009; Ernst, Pine, & Hardin, 2006) and a unique vulnerability to mental problems (Costello et al., 2002; Kessler, Berglund, Demler, Jin, & Walters, 2005).

The most commonly recognized characteristics of concern include cognitive impulsivity and emotional intensity and lability (Arnett, 1999; Dahl, 2004; Ernst & Hardin, 2009; Ernst et al., 2006). These cognitive and affective features are thought to place adolescents at an increased risk for engaging in behaviors with deleterious and dangerous consequences, such as tobacco and drug use, risky sexual activity, or reckless driving (Dahl, 2004; Eaton et al., 2006; Hingson, Heeren, Winter, & Wechsler, 2005; Spear, 2000; Steinberg, 2004, 2005). Inter-individual variability within this stereotypical description of the adolescent is large, and can be traced to hormonal changes (e.g., (Bramen et al., 2011; Forbes et al., 2010; Kuhn et al., 2010; Mazzone et al., 2011; Mueller, Ng, et al., 2010; Neufang et al., 2009; Oldehinkel, Verhulst, & Ormel, 2011), early life experience (Andersen & Teicher, 2009; Mueller, Maheu, et al., 2010; Pechtel & Pizzagalli, 2011; Suomi, 2006), genetic make-up (Cohen, 2010; Enoch, 2011; Schwandt et al., 2010), among many other factors. A better understanding of the underlying factors contributing to interindividual variability can be tremendously helpful for identifying targets for future primary and secondary treatment of untoward outcomes related to adolescent behavior. We now turn to the description of changes in brain maturation across this time window.

1.2. Coordinated brain development

Substantial neural development accompanies the rise in impulsivity, emotionality, and risk seeking over the course of adolescence. The normative trajectory of adolescent neural development is becoming well-characterized with the advent of MRI technology. These neural changes are charted at the structural, functional and connectivity level using neuroimaging tools. Most importantly and best illustrated at the structural level, different brain regions and neural circuits seem to mature along distinct trajectories, which may be orchestrated along unique predetermined timelines. The adherence to these predetermined timelines may be critical to the harmonious development of brain function as a whole (see Fig. 1) (Brain Development Cooperative Group, 2012; Casey, Getz, & Galvan, 2008; Giedd et al., 1999; Gogtay et al., 2004; Sowell et al., 2004). Similar coordinated temporal changes may also operate across complementary and interactive units of function, such as across neurotransmitter systems (e.g., dopaminergic vs. serotonergic vs. adrenergic vs. cholinergic systems) (Chambers,

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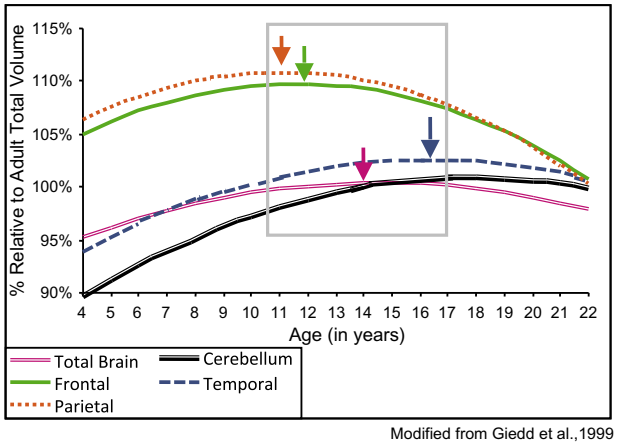

Fig. 1. Developmental trajectory of individual brain regions. Distinct brain regions reach adult maturity along variable, chronologically determined, time courses. Deviance in the chronology of the brain systems development may affect adolescents' abilities to successfully recruit and control such systems.

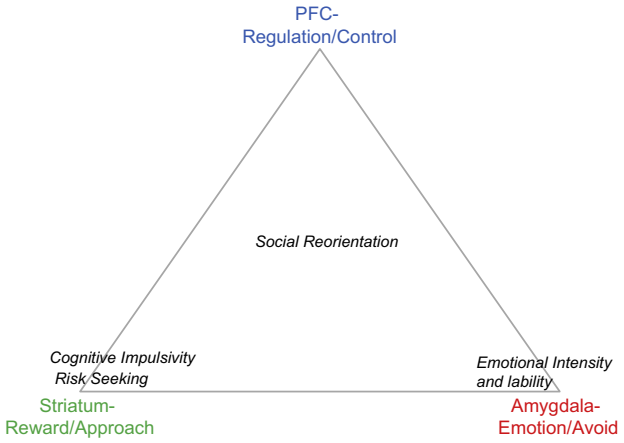

Fig. 3. The triadic model. The prefrontal cortex (PFC) has a reciprocal relationship with the striatum and amygdala, and the amygdala projects directly to the striatum. Within the triadic model the striatum represents the motivation system, and is associated with approach; the amygdala represents the emotion system, particularly responses to aversive (e.g., fearful) stimuli, and plays a significant role in avoidance; and the prefrontal cortex is the regulatory center, which serves to control approach and avoidance behaviors. Of the four behaviors typically observed in adolescence, the striatum is chiefly responsible for risk seeking and cognitive impulsivity; the amygdala for emotional intensity and lability. Social reorientation involves interactions among all three systems.

Taylor, & Potenza, 2003; Ernst & Fudge, 2009; Spear, 2000; Wahlstrom, Collins, White, & Luciana, 2010; Wahlstrom, White, & Luciana, 2010) or within a given neurotransmitter system (e.g., D2 dopamine receptor vs. D1 dopamine receptor; GABA receptors) (Andersen, 2003; Huppe-Gourgues & O'Donnell, 2012; Lewis, Melchitzky, & Burgos, 2002).

At the histological level, substantial cell, dendrite, and synapse proliferation and then elimination proceed with time (Rubia et al., 2006; Toga, Thompson, & Sowell, 2006) (see Fig. 2). These cellular changes lead to more selective and refined information processing. Together with axonal caliber enlargement, myelination contributes to the age-related decrease in gray matter and increase in white matter (Giedd, 2004; Gogtay et al., 2004; Paus, Keshavan, & Giedd, 2008; Paus et al., 1999). Diffusion tensor imaging (DTI) provides a measure, i.e., fractional anisotropy (FA), thought to reflect the diameter, density and myelination of white matter fibers that connect brain regions (Giorgio et al., 2008; Snook, Paulson, Roy, Phillips, & Beaulieu, 2005). Across adolescence, the increases in FA in major white matter pathways support the active myelination process during this period combined with the increase in axonal diameter (Paus, 2010), and have been associated with improved cognitive function (Fitzgerald et al., 2010; Muetzel et al., 2008; Nagy, Westerberg, & Klingberg, 2004; Olson et al., 2009). Accordingly, myelination speeds up the transmission of information over long distances (e.g., cross-hemispheric projections), and ultimately provides more efficient transmission of information.

The notion of a predetermined timetable of the progression of various neural changes (e.g., loss of gray matter is last in the superior temporal cortex) (Gogtay et al., 2004) has critical implications. Indeed, important behavioral consequences can result from a disruption within this predetermined order. Behavioral perturbations could emerge from the sub-optimal *coordination* among nodes or modules organizing behavioral output, and not necessarily from selective *local* regional abnormalities. This scenario emphasizes interregional influences (i.e., functional connectivity) and the role of potential imbalances in neural maturation across various brain regions, each of which is implicated in specific behavioral patterns. This formulation of functional brain development serves as the foundation of the triadic neural systems model.

2. The triadic model

2.1. Introduction to the triadic neural systems model

The triadic model (see Fig. 3) attributes the determinants of motivated behavior to three functional neural systems, which are distributed networks centered on the prefrontal cortex, striatum and amygdala. These systems are expected to mature along a predetermined order. This coordinated predetermined order is thought to affect the typical age-related changes in behavior. These three neural systems are supported by independent, but overlapping networks, and subsume basic complementary functions (Table 1).

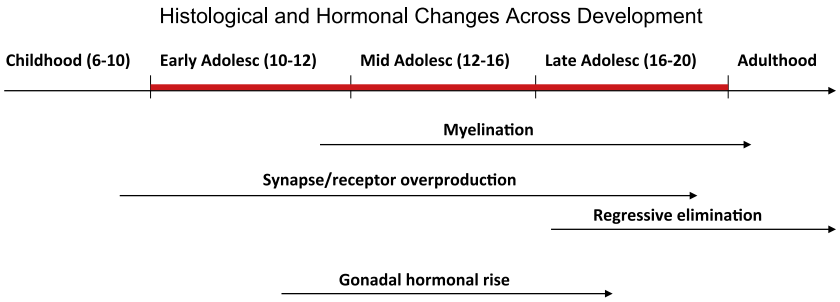

Fig. 2. Brain development with age. Several changes occur at the histological and hormonal levels and continue across development. Synapse overproduction begins in mid-to-late childhood and is followed later by regressive elimination in late adolescence. Myelination, associated with the increase of white matter and related decrease in gray matter begins in early adolescence and continues through young adulthood. Gonadal hormonal rise, part of puberty, characterizes this period.

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