Neuroscience and Biobehavioral Reviews 94 (2018) 179–195

Contents lists available at ScienceDirect

Neuroscience and Biobehavioral Reviews

journal homepage: www.elsevier.com/locate/neubiorev

Review article

Adolescence as a neurobiological critical period for the development of higher-order cognition

Bart Larsen[a,b,*], Beatriz Luna[b,c]

[a] Department of Psychology, University of Pittsburgh, Pittsburgh, PA, 15213, United States
[b] Center for the Neural Basis of Cognition, Pittsburgh, PA, 15213, United States
[c] Department of Psychiatry, University of Pittsburgh, Pittsburgh, PA, 15213, United States

ARTICLE INFO

Keywords:
Adolescence
Development
Critical period
Cognition
Prefrontal cortex
Dopamine
Parvalbumin
GABA

ABSTRACT

The transition from adolescence to adulthood is characterized by improvements in higher-order cognitive abilities and corresponding refinements of the structure and function of the brain regions that support them. Whereas the neurobiological mechanisms that govern early development of sensory systems are well-understood, the mechanisms that drive developmental plasticity of association cortices, such as prefrontal cortex (PFC), during adolescence remain to be explained. In this review, we synthesize neurodevelopmental findings at the cellular, circuit, and systems levels in PFC and evaluate them through the lens of established critical period (CP) mechanisms that guide early sensory development. We find remarkable correspondence between these neurodevelopmental processes and the mechanisms driving CP plasticity, supporting the hypothesis that adolescent development is driven by CP mechanisms that guide the rapid development of neurobiology and cognitive ability during adolescence and their subsequent stability in adulthood. Critically, understanding adolescence as a CP not only provides a mechanism for normative adolescent development, it provides a framework for understanding the role of experience and neurobiology in the emergence of psychopathology that occurs during this developmental period.

Neurodevelopment is the process of growth and specialization that shapes the brain to fit its environment under the influence of experience, neurobiology, and genetic mechanisms. Stages of development mark specific periods of significant brain and behavioral change. Adolescence is widely recognized as the stage of development that occurs between childhood and adulthood and is characterized by the onset of puberty as well as unique neurobiological, social, and cognitive development. This period of transition is of particular interest because of transient increases in mortality rates due to risk-taking behavior and because it is a time when major psychopathology (e.g. schizophrenia, substance use disorders, mood disorders) begins to emerge. Normative adolescent behavior is characterized by a peak in sensation seeking (Spear, 2000) that is believed to adaptively motivate experience that supports individuation during the transition to adult roles and responsibilities but can also create vulnerability to risk-taking (Dahl, 2004; Spear, 2000). This occurs in the context of continued refinement of higher-order cognitive abilities, such as working memory, response inhibition, and performance monitoring, and their reliably successful instantiation in service of goals, i.e. cognitive control (Luna et al., 2015). Refinement of higher-order cognition is evidenced by a reduction in the variability in performance on cognitive tasks, including reduced error rates and the stabilization of response latency (McIntosh et al., 2008; Montez et al., 2017; Ordaz et al., 2013; Tamnes et al., 2012). In parallel to improvements in performance in cognitive tasks are important brain maturational processes. Human neuroimaging studies have demonstrated that association cortices—i.e. multimodal integration areas like prefrontal cortex (PFC), posterior parietal cortex, and superior temporal cortex that are thought to support higher order cognition—undergo continued structural and functional maturation during adolescence, including gross morphology, connectivity, and task-induced activation (Giedd, 2004; Gogtay et al., 2004; Luna et al., 2010, 2015; Marek et al., 2015; Simmonds et al., 2014; Sowell et al., 2004).

Though prior work has been instrumental in characterizing both cognitive development and large-scale patterns of brain development during adolescence, the neural mechanisms that drive these changes are not well understood. The specificity of the timing (adolescence) and location (association cortices) of these changes and their temporal co-occurrence with gains in cognitive abilities are suggestive of a critical period (CP) of development, akin to early developmental CPs for vision

* Corresponding author at: 121 Meyran Ave., Room 109, Pittsburgh, PA, 15231, United States.
E-mail address: bsl18@pitt.edu (B. Larsen).

https://doi.org/10.1016/j.neubiorev.2018.09.005
Received 5 March 2018; Received in revised form 29 June 2018; Accepted 6 September 2018
Available online 07 September 2018
0149-7634/

(Wiesel and Hubel, 1963) and language (Penfield and Roberts, 1959). Indeed, others have described adolescence as a sensitive period or CP from a psychological and sociocultural perspective (Blakemore and Mills, 2014; Steinberg, 2008). However, CPs are governed by a specific set of consistent neurobiological mechanisms that have been well-established in models of sensory system development (for review, see (Hensch, 2005; Levelt and Hübener, 2012)), and the extent to which these neurobiological mechanisms are present during adolescent neurodevelopment has not been fully assessed. In this review, we address this hypothesis by synthesizing the way in which advancements in the understanding of neural development in adolescent association cortex fit within the mechanistic framework of CP plasticity. We suggest that studies of development at the cellular, circuit, and systems levels reveal an important co-occurrence of neurobiological factors that reflect CP mechanisms of development, and as such, we propose that cortical plasticity during adolescence is driven by a neurobiological CP for the development and specialization of brain areas such as PFC that support higher-order cognition. We further suggest the CP may open at the onset of puberty and is, at least in part, triggered by the development of mesocortical dopamine (DA) system, which continues to develop throughout adolescence. This CP process drives the rapid development of brain structure and function and cognitive ability during adolescence and their subsequent stability in adulthood. Understanding mechanisms driving this period of developmental plasticity can inform how perturbations to normative CP developmental processes during adolescence can contribute to the emergence of major psychopathology that is associated with impaired cognition during this time.

In what follows, we first briefly synthesize the neurobiological factors that promote the opening and closing of CP plasticity and then review findings in cellular, circuit, systems, and network level development in the context of CP mechanisms. We then discuss how abnormal development during adolescence, including the emergence of psychopathology, can be understood in a CP framework. Due to the predominance of neurodevelopmental literature on PFC across species and levels of analysis (cellular, circuit, systems, cognition), we focus this review on the development of PFC as an exemplar of an areas of association cortex undergoing CP development. However, considering the similarly protracted developmental trajectories of other areas of association cortex, such as posterior parietal and superior temporal cortices (Gogtay et al., 2004; Krongold et al., 2017; Raznahan et al., 2011), we hypothesize that they follow similar neurodevelopmental processes.

1. Principles of early critical period development

Experience and neurobiology are interrelated throughout the lifespan; an individual's neurobiology can bias them toward certain types of experience, and an individual's experience can shape their own neurobiology over time. However, there are particular windows of development where this relationship is pronounced for specific brain areas, known as CPs (Erzurumlu and Gaspar, 2012; Levelt and Hübener, 2012; Nabel and Morishita, 2013; Takesian and Hensch, 2013). CPs are strict time windows during which experience and neurobiological factors interact to shape normative brain development and permanently alter behavior. The term sensitive period is sometimes also used (including in regards to adolescence (Blakemore and Mills, 2014; Steinberg, 2008)), particularly when the developmental time window is less well established or the effects on behavior are thought to be less permanent, i.e. a limited time during which the effect of experience on brain structure is particularly strong; however, though these terms distinguish a degree of permanence in behavioral outcomes or specificity of developmental timing, they are not distinct from a neurobiological perspective as critical and sensitive periods operate under the same set of neural mechanisms (Hensch, 2005, 2004). CPs have been predominantly associated with early developmental sensory system plasticity and the cellular mechanisms that drive this plasticity have been studied for over 50 years (see (Espinosa and Stryker, 2012; Hensch, 2005; Levelt and Hübener, 2012; Takesian and Hensch, 2013) for comprehensive review). The core set of neurobiological mechanisms that underlie CP development is conserved across the development of functionally different systems throughout the brain. In summary, these periods of elevated plasticity are typically preceded by a proliferation of synapses and axons that are then shaped into reliable, efficient circuits in an experience-dependent manner (Knudsen, 2004). The opening of the CP is triggered by the adjustment of the excitation-inhibition (E/I) balance, which is largely driven by the maturation of inhibitory function (Dorrn et al., 2010; Espinosa and Stryker, 2012; Hensch and Fagiolini, 2005; Long et al., 2005; Toyoizumi et al., 2013; Zhang et al., 2011). Maturing inhibitory circuitry increasingly suppresses spontaneous, stimulus-irrelevant activity in favor of stimulus-driven inputs, increasing the signal-to-noise ratio (SNR) of stimulus-evoked circuit activity (Hensch, 2005; Toyoizumi et al., 2013). This evoked activity then interacts with neurobiological factors that promote plasticity to shape cortical circuits, i.e. *facilitating factors*. Subsequently, *braking factors* stabilize the developed circuits to restrict additional plasticity and close the CP window. CP plasticity results in reliable, efficient, and effective neural circuit computation and communication, allowing for consistent, optimized neural (and thus behavioral) responses to particular stimuli or task demands (Knudsen, 2004). In effect, CP development functions to adaptively suit an organism to its surroundings by using experience to tune the brain to the demands of its environment.

1.1. Facilitating factors

Facilitating factors are molecular mechanisms that promote plasticity throughout the CP and are involved in the opening of the CP window (Takesian and Hensch, 2013). These include both inhibitory and excitatory processes.

1.1.1. Inhibition

The development of GABAergic inhibitory circuitry plays an essential role in CP plasticity, dampening spontaneous activity in favor of evoked activity and thus improving the signal-to-noise ratio (SNR) of stimulus-evoked computation. Though there are many classes of GABAergic inhibitory interneurons with different functional roles, the class of GABAergic interneurons that are centrally involved in driving CP neurocognitive maturation are parvalbumin positive (PV) interneurons (Hensch, 2005). PV interneurons are particularly well-suited to assist in CP plasticity for several reasons. First, PV interneurons are highly interconnected, fast-spiking inhibitory interneurons that are widespread throughout the cortex and account for as much as 40% of GABAergic neurons. Second, PV interneurons fire in response to diverse stimuli including sensory cues, motor action, and trial outcomes (Pinto and Dan, 2015; Rudy et al., 2011). Third, PV interneurons adaptively adjust the firing rates and excitatory output of a circuit, functioning as local gain control (Scholl et al., 2015). These properties allow networks of PV interneurons to synchronize output and facilitate gamma oscillations, which support higher-order cognitive functions like working memory (Honkanen et al., 2015; Yamamoto et al., 2014) that continue to significantly improve into adulthood (Conklin et al., 2007; Luna et al., 2004; Montez et al., 2017; Østby et al., 2011; Simmonds et al., 2017).

The maturation of PV circuitry plays a role in triggering CP onset by decreasing the E/I balance and suppressing spontaneous activity in favor of stimulus-evoked activity (Fagiolini and Hensch, 2000; Toyoizumi et al., 2013). This allows evoked activity to more powerfully drive circuit plasticity. Developmental studies manipulating the timing of GABA/PV development have shown that the development of this inhibitory circuitry is sufficient to manipulate the timing of CP onset. Local administration of GABA agonists like benzodiazapines into visual cortex during the visual cortex CP accelerates the maturation of inhibition and accelerates the onset of CP plasticity whereas GAD67

knockout mice, which lack the GAD67 gene necessary for normal GABA cell function, never initiate CP plasticity (Fagiolini et al., 2004; Hensch, 2005; Hensch et al., 1998). In addition to decreasing the spontaneous-to-evoked activity ratio of cortical circuits, inhibitory circuitry facilitates plasticity in a number of ways during the CP window. Multisynaptic inhibition by developed PV interneurons restricts the summation window for spike time dependent plasticity, favoring the most temporally synchronous inputs, and facilitates LTP plasticity of synapses (Pouille and Scanziani, 2001). In addition, $GABA_A\alpha1$ receptor subunits (GABAAα1R), which are preferentially synapsed by PV interneurons, proliferate during CPs and are specifically implicated in driving experience-dependent cortical CP plasticity (Fagiolini et al., 2004; Katagiri et al., 2007).

1.1.2. Excitation

In general, monosynaptic activity-dependent plasticity follows Hebbian mechanisms of long-term potentiation (LTP) and long-term depression (LTD), which respectively strengthen and weaken synapses. N-methyl-D-aspartate (NMDA) transmission is central to this process and is thought to be a mechanistic substrate for learning-related plasticity (Malenka and Bear, 2004). Certain NMDA receptor subtypes are particularly important in facilitating LTP. In particular, the NR1 and NR2B receptors are more favorable to synaptic remodeling than NR3A and NR2 A (Gambrill and Barria, 2011; Sur et al., 2013). The proportion of NR1 and NR2B is typically greater during CPs, facilitating plasticity (Chen et al., 2000; Erisir and Harris, 2003).

1.1.3. Brain derived neurotrophic factor

Brain derived neurotrophic factor (BDNF) expression is activity-dependent and facilitates plastic changes to neuronal form, including dendritic growth and synaptogenesis (Greenberg et al., 2009). BDNF expression has been demonstrated to be a necessary facilitator of CP plasticity; BDNF over-expression induces precocious maturation of inhibition and accelerates CP timing, and BDNF blockade inhibits CP plasticity in both primary visual cortex (Huang et al., 1999; Hanover et al., 1999) and primary auditory cortex (Anomal et al., 2013). Importantly, BDNF expression promotes GABAergic neuron development (Mizuno et al., 1994), and both BDNF expression and GABA transmission are reduced in sensory deprivation experiments that delay CP onset (Hensch, 2005; Morales et al., 2002). Thus, BDNF may be a mechanistic link between stimulus-evoked activity and the maturation of GABAergic inhibitory circuitry during CP development (Deidda et al., 2015; Huang et al., 1999).

1.1.4. Experience and the opening of a critical period

CP plasticity is experience-dependent, and its initiation thus relies on non-random input, i.e. evoked activity that engages the circuit that will be specialized. In the case of the visual system, CPs begin with the onset of stimulus-evoked visual experience that occurs with the opening of the eyes, triggering synchronized, stimulus-evoked activity of thalamocortical visual circuitry. When visual activity is experimentally manipulated in one eye, e.g. by the inactivation of the eye, ocular dominance columns for the impaired eye fail to develop and are outcompeted for by the active eye, leading to amblyopia (Gordon and Stryker, 1996; Prusky and Douglas, 2003; Wiesel and Hubel, 1963, p. 196). When sensory experience is entirely deprived during early development, e.g. dark rearing in cats (Mower, 1991), acoustic isolation in finches (Balmer et al., 2009), or whisker trimming in mice (Erzurumlu and Gaspar, 2012; McRae et al., 2007), CPs for vision, audition, and somatosensation, respectively, are prevented or delayed. In a similar manner to ocular dominance competition during the visual CP, projections from hippocampus and amygdala have been found to compete for target innervation of prefrontal cortex (PFC) during adolescence; when rat ventral hippocampus is lesioned during childhood (perinatal day (PD) 7), basolateral amygdala innervation of layer V mPFC is increased after adolescence (~PD70) relative to control animals with intact ventral hippocampi (Guirado et al., 2016). Thus, the impact of lesions of hippocampal-prefrontal pathways during adolescence seems to mimic the effect of monocular deprivation in early visual cortex development.

1.2. Braking factors and the closing of a critical period

Once a circuit becomes efficient and reliable, it is advantageous to stabilize circuit configuration to prevent plasticity mechanisms from excessively pruning and rewiring. This stabilization is accomplished by the implementation of sets of physical barriers to pruning and outgrowth, including the formation of perineuronal nets (PNN) on cell bodies and myelin on axons (Takesian and Hensch, 2013).

1.2.1. Perineuronal nets

PNNs are a component of the extracellular matrix that ensheath cell bodies and proximal dendrites to stabilize synaptic architecture (Celio and Blümcke, 1994). PNNs primarily surround mature PV interneurons, forming physical barriers to plasticity of inhibitory circuits, and PNNs have been observed to proliferate near the closing of CPs across brain areas to limit future experience-dependent plasticity (Balmer et al., 2009; McRae et al., 2007). Their development has been found to be triggered by the activity dependent accumulation of the Otx2 (orthodenticle homeobox protein 2) homeoprotein in maturing PV interneurons and their formation restricts further plasticity of these cells (Sugiyama et al., 2008). Animals with diminished PNNs have persistent plasticity (Carulli et al., 2010)—which can result in excessive, unnecessary, and inefficient restructuring of circuit architecture—and the degradation of PNNs can reinstate CP plasticity (Pizzorusso et al., 2002) suggesting that PNNs play an important role in braking CP development.

1.2.2. Myelination

Myelination of axons is a mechanism of plasticity that is directed in an activity-dependent manner and results in increased speed and fidelity of neural signaling (Fields, 2015). Myelin formation increases near the end of CPs and myelin-related inhibitory proteins, MAG (myelin associated glycoprotein) and NogoA (neurite outgrowth inhibitor), bind to the myelin related Nogo receptor preventing future branching of neural circuits (Bavelier et al., 2010; McGee et al., 2005). The critical role of Nogo proteins as a braking factor for myelination is evidenced in Nogo receptor knockout mice which show persistent plasticity that extends beyond the CP window (McGee et al., 2005; Yang et al., 2012). As such, myelination serves as an important CP braking factor.

1.3. Functional outcomes of CP plasticity

The cellular/neuroanatomical changes that occur during the CP window have a range of functional outcomes in cortical circuits. These outcomes contribute to the reliability of a circuit response to a given input and are highly driven by the development of inhibitory circuits and subsequent stabilization by braking factors. First, the E/I balance decreases as PV interneurons mature, and the population activity of a developing circuit goes from largely spontaneous to largely evoked (i.e. decreasing the spontaneous-to-evoked ratio), in essence increasing the signal-to-noise ratio (SNR) of the circuit in response to a stimulus (Dorrn et al., 2010; Hensch, 2005; Hensch and Fagiolini, 2005; Toyoizumi et al., 2013). The start of this process may be important for the opening of the CP itself because, as mentioned above, evoked activity is critical in driving experience-dependent activity during the CP window (Toyoizumi et al., 2013). Next, maturing PV interneurons allow for increases in the synchrony of population responses, allowing for the emergence of high gamma oscillatory capability (Cardin et al., 2009; Doischer et al., 2008). In sum, CP mechanisms result in a neural circuit that responds with high SNR to a given input and responds with a synchronous and consistent output, delivering information with high

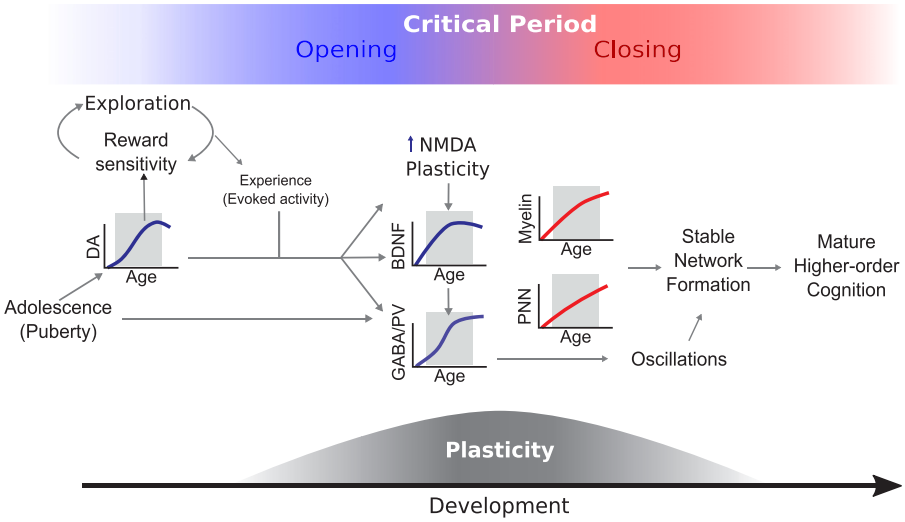


Fig. 1. A critical period model of adolescent development. Adolescence begins with the onset of puberty and a concomitant increase in dopamine (DA) availability. Increases in DA motivate exploratory behavior and heightened reward reactivity which, in turn, promote the experience accumulation necessary to shape experience-dependent plasticity. DA, puberty, novel experience may jointly function to trigger critical period activity through their interaction with neurobiological factors that facilitate critical period (CP) plasticity. These facilitating factors include changes in NMDA signaling and receptor concentrations that promote experience-dependent plasticity, increased levels of brain-derived neurtrophic factor (BDNF), and maturation of GABAergic inhibitory circuitry (particularly parvalbumin positive (PV) interneurons). The maturation of inhibitory circuitry has important functional consequences including a reduction in the excitation-to-inhibition balance (E/I balance) and facilitation of high-frequency oscillatory capability of local circuits. As the critical period progresses, age-related increases in critical period braking factors, including myelination and PNN formation, begin to restrict further plasticity to close the CP window and stabilize circuits into adulthood. This stabilization leads to consistent and reliable circuit function and communication which underlies the stabilization of trial-to-trial cognitive ability that is characteristic of mature higher-order cognitive function. Note: Developmental curves are schematics meant to summarize prior work. Blue and red curves represent the development of facilitating and braking factors, respectively. Shaded grey area reflects the adolescent period (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

SNR to downstream circuits. Importantly, this refined circuit is sculpted by the experience of the organism in order to be ideally suited to respond to the demands of its environment (Takesian and Hensch, 2013).

1.4. Critical period hierarchy

CPs appear to progress in a hierarchical fashion, starting from primary sensory areas and progressing to areas of cortex involved in higher-order processing necessary for more complex cognition and experience (Takesian and Hensch, 2013; Toyoizumi et al., 2013). The cascade of CP maturation is thought to follow the maturation of inhibition as the adjustment of the E/I balance triggers the opening of the CP (Toyoizumi et al., 2013). This notion is exemplified on a smaller scale within sensory systems. For example, cascades of PV circuit maturation and corresponding reductions in the spontaneous/evoked activity ratio progress from basic to more complex areas of the visual (Bourne and Rosa, 2006; Condé et al., 1996) and auditory pathways (Barkat et al., 2011; Insanally et al., 2009). As consistent, synchronous, evoked activity is necessary to drive CP maturation, it follows that brain areas that perform basic stimulus-dependent computations must mature earlier in order to provide consistent output signals with high SNR that is necessary to generate evoked activity in areas that integrate this information for more advanced computation. As such, areas that integrate multisensory information to perform higher-order cognitive functions will then require stable (i.e. developed) inputs from multimodal processing streams in order to effectively undergo their own experience-dependent plasticity or CP.

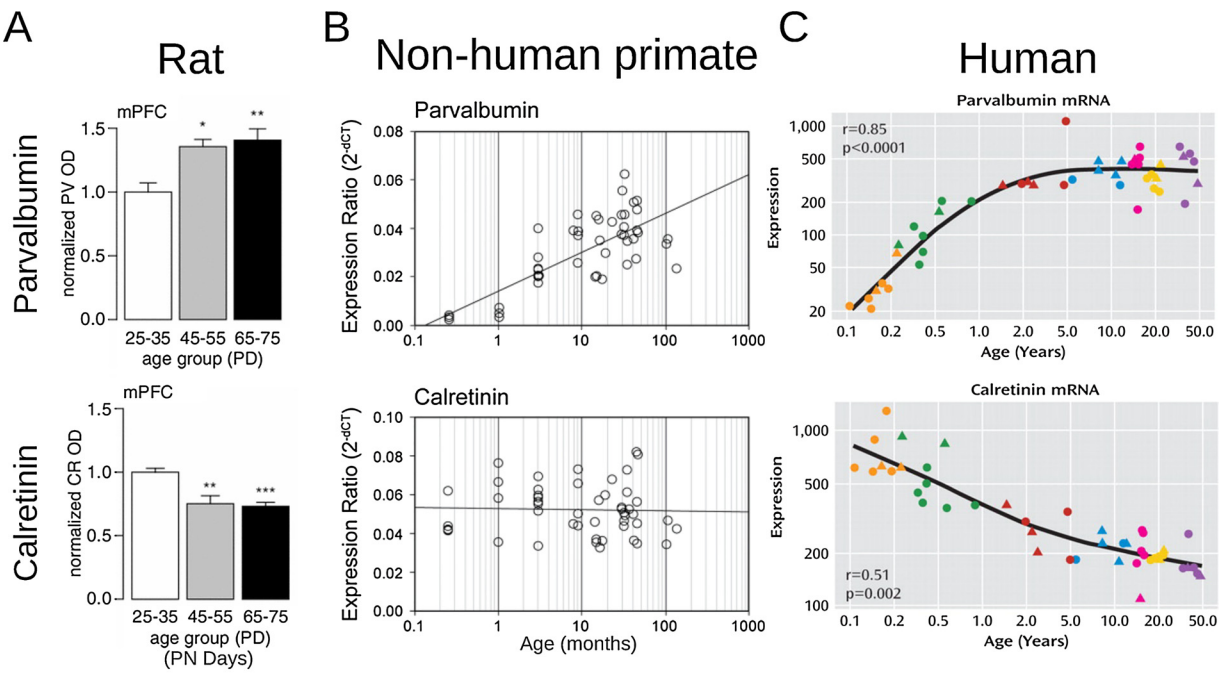
1.4.1. Adolescence as the ultimate step in the critical period hierarchy

We hypothesize that CP plasticity in PFC and other association cortices, including posterior parietal cortex, and superior temporal lobe, which receive afferents from all sensory cortices (e.g. see (Barbas, 2000; Barbas et al., 2011; Barbas and Zikopoulos, 2007)) would necessarily follow that of sensory areas in a hierarchical progression of CP maturation. In animal models, sensory system inhibitory plasticity (e.g. visual (Chattopadhyaya et al., 2004) and somatosensory systems (Micheva and Beaulieu, 1997)) is completed prior to adolescence (Huang et al., 2007). This earlier sensory maturation would effectively change the nature of signaling to downstream association cortices from inconsistent to reliable (decreasing the spontaneous-to-evoked activity ratio) and allow for successful integration of the complex inputs from multiple sensory systems that is necessary to process higher level experiences (e.g. social peer interactions, reasoning). These complex experiences can then function to shape CP plasticity of association cortices. Understanding adolescence as a CP of development would support observed patterns of higher-order cognitive development. Though core cognitive functions like working memory and inhibitory control are available even in early development (Gilmore and Johnson, 1995; Johnson, 1995) and rapidly improve throughout childhood, adolescents do not perform at adult-like levels (Conklin et al., 2007; Luna et al., 2004). Most saliently, adolescents are more variable in their performance (both between individuals and within an individual), having greater error rates (Montez et al., 2017; Ordaz et al., 2013) and slower and more variable response latencies (Montez et al., 2017; Tamnes et al., 2012). That is, on the single trial level, children and adolescents can perform equivalent to adults, but their performance is more variable across trials as the processes that support reliable and cognitive performance are still developing throughout adolescence. Thus, the transition from adolescent to adult cognition is a process of increasing the reliability of successful instantiation of cognitive processes and reducing behavioral variability, leading to consistently optimal responses. Underlying this developmental stabilization is likely an increase in the reliability and effectiveness of neuronal signaling and communication at the circuit and network level, which are functional outcomes of CP development. Indeed, mature prefrontal inhibitory circuitry—and thus an optimal, developmental reduction in the E/I balance—is critical for higher-order cognitive functions as an abnormally disinhibited PFC has been linked to impaired cognitive flexibility, a hallmark of adult-like cognitive control (Gruber et al., 2010).

To support this hypothesis, we next synthesize recent work in cellular and circuit level development of adolescent association cortex, focusing on PFC as an exemplar, in the context of the CP principles and mechanisms outlined above.

2. Critical period development during adolescence

Studies of the development of the human brain, including patterns of gray matter thinning (Gogtay et al., 2004), white matter pathway integrity (Simmonds et al., 2014), and synapse proliferation (Bourgeois et al., 1994; Huttenlocher, 1990; Petanjek et al., 2011), indicate a period of significant plasticity and neurodevelopment that extends into adulthood. Below, we provide evidence that this plasticity is driven and



D

Species	Adolescent period
Human	8-20 years
Non-human primate	30-60 months
Rat	35-60 days

Fig. 2. The development of GABAergic interneuron subtypes in prefrontal cortex through adolescence. The development of parvalbumin (PV) interneurons is an essential factor for critical period development. Here we show findings from studies of PV development in the prefrontal cortex (PFC) in three different species (A–C top panels). Developmental trajectories for calretinin (CR) interneurons are also provided (A–C lower panel) to highlight the specificity of PV increases during adolescence. A) PV protein expression significantly increases from childhood (white) to adolescence (grey) and adulthood (black) in the medial PFC of healthy rats (top panel). In contrast, CR protein expression decreases over the same period (bottom panel). Data is adapted from (Caballero et al., 2014). B) Parvalbumin mRNA levels increase with age throughout adolescence in the healthy macaque monkey PFC (top panel), while CR mRNA levels either remain stable or decrease (bottom panel). Data is adapted from (Hoftman et al., 2015). C) PV mRNA expression, assessed postmortem, increases from childhood to adulthood in the human dorsolateral PFC (top panel) while CR mRNA expression decreases (bottom panel). Triangles = females; circles = males. Representative mRNA expression profiles for PV, CR and calbindin (CB) interneuron subtypes (bottom panel) indicate a possible peak in PV during adolescence while CR and CB decrease. Data adapted from (Fung et al., 2010). Panels A–C indicate increasing ratios of PV to CR expression in PFC across rat, non-human primate, and human species. D) Approximate windows for adolescence in the species represented in this figure (Kilb, 2012; Piekarski et al., 2017a, 2017b; Spear, 2000; Zehr et al., 2005).

then stabilized by the same neurobiological factors that govern early CP development of core sensory systems, and this process contributes to reliable and effective neuronal signaling that, in turn, supports reliable and stable higher-order cognitive functions in adolescence. These critical period processes at play during adolescence are summarized in Fig. 1.

2.1. Facilitating factors

2.1.1. Inhibition

As described above, the development of inhibitory circuitry is perhaps the most essential facilitator of CP development (Hensch, 2005; Toyoizumi et al., 2013). During adolescence, prefrontal GABAergic inhibitory circuitry undergoes significant modifications that are evident in both animal models and human developmental studies (Fig. 2). PV interneurons, a critical component of early sensory system CP development, are at higher levels in the adolescent (PD 45–55) rat medial PFC than in that of juvenile (PD 25–35) animals (Caballero et al., 2014). Importantly, these changes are specific to PV GABA interneurons, as calretinin positive (CR) interneurons do not show the same pattern of development (Fig. 2A), indicating an increased ratio of PV to CR interneurons (Caballero et al., 2014). The same pattern is reflected in the DLPFC of the non-human primate where PV expression and PV axon terminals in DLPFC increase during the pubertal period while CR remains stable or decreases (Fig. 2B) (Erickson and Lewis, 2002; Hoftman et al., 2015; Hoftman and Lewis, 2011; Lewis et al., 2005). At the same time, inhibitory neurotransmision increases in both mice and non-human primates. In mice, the frequency and amplitude of mini inhibitory post-synaptic currents (IPSCs) onto layer II/III pyramidal cells of cingulate cortex increase from pre- to post-adolescence (Piekarski et al., 2017a). In non-human primates, the frequency and amplitude of spontaneous IPSCs onto layer III pyramidal cells in DLPFC increases from childhood to adulthood, and the rise-time and decay time constant decreases (Gonzalez-Burgos et al., 2014). Computational simulations indicate that these developmental changes should lead to mature gamma oscillatory capability in PFC (Gonzalez-Burgos et al., 2014). These findings are supported by human studies which indicate a similar pattern of inhibitory neurodevelopment. MR spectroscopy studies suggest that global GABA concentration in the dorsal anterior cingulate cortex increases from adolescence to adulthood (Silveri et al., 2013) with no concomitant change in glutamate concentration, indicating both a developmental increase in GABA and a resulting decrease in the

E/I balance (Ghisleni et al., 2015). Human postmortem evidence also suggests a peak or plateau in the development of PV expression in human DLPFC while CR and calbindin (CB) concentrations decrease (Fig. 2C) (Fung et al., 2010), again indicating an increased ratio of PV to CR interneurons during adolescence. At the same time, there is an increase in PFC gamma band power (Uhlhaas et al., 2009). Increased gamma band power is known to relate to many higher-order cognitive processes, such as working memory (Howard et al., 2003; Roux et al., 2012), which continue to mature throughout adolescence and into adulthood (Luna, 2004; Montez et al., 2017; Simmonds et al., 2017). Taken together, these results indicate a maturation of inhibitory circuitry—particularly for PV interneurons—in PFC that mirrors cortical development during early sensory system CPs (Fig. 2) and leads to a permissive environment for CP plasticity in these brain areas during adolescence.

Emerging evidence is suggesting that puberty may operate as a trigger of inhibitory neurodevelopment in PFC (Piekarski et al., 2017b). In a study of female mice, Piekarski et al. (Piekarski et al., 2017a) demonstrated that mice that undergo ovariectomy prior to puberty (PD 24–25) do not show developmental increases in the frequency or amount of inhibitory neurotransmission in layer II/III cingulate cortex, however this inhibitory neurodevelopment can be rescued if pubertal hormones (estradiol and progesterone) are administered later in life (PD 40–42). Further, precocious puberty (induced by hormone administration at PD 24–26, prior to typical pubertal onset) is sufficient to accelerate inhibitory neurodevelopment. These findings indicate that manipulating the timing of pubertal hormones is sufficient to manipulate the timing of the development of inhibitory neurotransmission in mouse frontal cortex. Interestingly, the amplitude of inhibitory signaling, which increases throughout adolescence in the frontal cortex of both mice and non-human primates (Gonzalez-Burgos et al., 2014; Piekarski et al., 2017a), is not sensitive to manipulations of pubertal hormone administration (Piekarski et al., 2017a), indicating that some aspects of inhibitory circuit development—perhaps relating to $GABA_A\alpha1R$ expression (which plays a key role in CP development; see Section 1.1.1)—may rely on other developmental processes or triggers, such as DA (described below). As this study focused on females, it is not known if similar mechanisms unfold in males (though considering the relationship between testosterone and estradiol, it is possible one exists). However prior work has implicated testosterone as a contributor to the development of cortical gray matter morphology during adolescence (e.g. Koolschijn et al., 2014; Nguyen et al., 2013), suggesting puberty may act as a trigger in males as well. Future work is needed to elucidate the role of testosterone as well as other sex hormones including estradiol, in the development of the male PFC at the cellular level.

2.1.2. Excitation

During adolescence, excitatory circuitry undergoes significant changes in NMDA receptor subunit composition, which influence the function of NMDA receptors. In humans, the density of the NR1 subtype of NMDA receptors either peaks or plateaus in the DLPFC while, in contrast, the NR3A subunit, which can down-regulate NMDA plasticity and prevent synapse maturation (Das et al., 1998; Roberts et al., 2009), peaks early in development and decreases throughout adolescence in adulthood (Henson et al., 2008). Thus, in humans, the ratio of NR1/NR3A NMDA receptor subtypes during adolescence strongly favors activity dependent plasticity and maturation. Interestingly, the NR1 has been shown to be critical to training-related plasticity of corticostriatal circuits that subserves reductions in neural and behavioral variability (Santos et al., 2015). As adolescence is marked by reductions in variability of cognitive performance that is reliant on DLPFC, a rise in NR1 could similarly allow for experience-dependent plasticity of DLPFC circuits that in turn increases the reliability of higher-order cognitive functions. In addition, there is some evidence of a developmental increase in the plasticity favoring NR2B subunit during adolescence (Morales and Spear, 2014). Rodent studies indicate this increase is centered on mPFC layer V apical dendrites and that increased NR2B is associated with longer lasting EPSCs of layer V pyramidal cells in response to hippocampal input and the facilitation of LTP plasticity (Flores-Barrera et al., 2014). The late emergence of this mechanism would promote context dependent plasticity based on input from hippocampus to PFC (Murty et al., 2016).

2.1.3. Brain derived neurotrophic factor

BDNF is a necessary trigger for CP plasticity in primary sensory cortices that promotes the maturation of inhibitory circuitry (see Section 1.2.3). A similar developmental pattern occurs during adolescence in areas of the PFC that support higher-order cognition. The expression of BDNF mRNA in the human DLPFC increases from adolescence into young adulthood, when it stabilizes (Webster et al., 2002) or decreases (Hayashi et al., 1997). This developmental change is not a brain-wide phenomenon, as the same developmental pattern is not seen in occipital cortex (Webster et al., 2002). Thus the developmental trajectories of BDNF expression and inhibitory circuitry are aligned during the human adolescent CP in the DLPFC as they are in early development CPs of sensory systems. These findings are supported by studies in mice that demonstrate increases in frontal BDNF expression that begins during the onset of adolescence (~PD 28 for females, ~PD 35 for males) (Hill et al., 2012). Interestingly, there is evidence that adolescent increases in BDNF may be regulated by testosterone (Hill et al., 2012; Purves-Tyson et al., 2015) and estrogen (Sohrabji and Lewis, 2006).

Together, these facilitating factors present in adolescent association cortex, would allow for stimulus-evoked activity to induce neuroanatomical cortical plasticity in an experience-dependent manner by strengthening effective connections and pruning those that are ineffective or suboptimal (see (Selemon, 2013) for review) thus increasing the SNR and reliability of local circuits.

2.2. The opening of the adolescent critical period

CPs are thought to be triggered by a combination of experience and the reduction of the E/I balance that follows the maturation of neural inhibition (Toyoizumi et al., 2013). For example, visual system plasticity begins with the influx of stimulus-evoked visual information that follows eye opening and the maturation of PV interneurons. Possible triggers for CP development in adolescence may be multifactorial. First, the influx of mature and reliable sensory information that supports complex information integration could trigger the need for specialization in relevant association cortices. Second, the emergence of the facilitating factors outlined above (which may be regulated, in part, by the onset of puberty (Piekarski et al., 2017a, 2017b) allow for experience-dependent (i.e. stimulus evoked) activity to shape plasticity of cortical circuits. Finally and importantly, the development of the mesocorticolimbic DA system, which is unique during adolescence, could act as a neurochemical and behavioral trigger to initiate CP plasticity. It is important to note that these triggers are complex, and probably rely on a combination of biological, genetic, and experiential factors, and as such, the specific timing of critical period onset will likely vary between individuals. Next, we discuss the role of experience and the development of mesocorticolimbic DA circuitry in triggering the CP in association cortex.

2.2.1. Adolescent experience

All CPs are driven by experience, but the nature of the experience necessary to optimally drive developmental plasticity varies according to the specific functional sensitivity and computational processing of differing brain areas (e.g. visual input for primary visual cortex, auditory input for auditory cortex, etc.). Thus, to drive plasticity of areas of association cortex like PFC that support complex cognitive processes, complex experience that taxes these higher-order cognitive processes

would be optimal. We propose that during adolescence there are unique developmental characteristics that lead to a qualitative shift in the nature of experience gathering that should optimally engage the specialization of PFC and other areas of association cortex. First, by adolescence the majority of body growth has been completed affording increased agency for exploration. Though the process of body growth is continuous from childhood, adolescence is unique in that the ability to autonomously explore the environment can be exercised with an unprecedented level of independence from the parental or adult direction that is predominant in childhood. Second, across cultures (Schlegel and Barry, 1991) and species (Spear, 2000), adolescence is a time of increased social autonomy and peak sensation seeking behavior that affords the freedom and drive to accumulate experience under novel contexts in a manner that is unique from earlier stages of development. Third, sexual maturation is occurring, encouraging the exploration of mating behavior. Fourth, as detailed below, DA availability is at its peak, promoting behaviors aimed at receiving rewards and motivating exploration of one's environment. Together, these influences combine during adolescence to promote the accumulation of novel and increasingly complex experience, such as intricate social interactions, mating, entering the workforce, etc., that are psychologically, socially, and cognitively demanding. As this experience increases in complexity (and as adolescents are increasingly responsible for navigating them without parental instruction), brain areas like PFC that support increasingly complex behaviors, such as socioemotional processing, planning, reasoning, and abstract thought, must be engaged and specialized to meet the demands of the environment. As such, increasingly complex adolescent experience operates as the optimal input to drive adolescent CP experience-dependent plasticity (see Section 3.1 for further discussion of abnormal experience-dependent critical period plasticity during adolescence). As an example, play behavior—which involves complex peer-peer social interaction and cognitive flexibility (Spinka et al., 2001) —peaks during the adolescent period in the rat (Panksepp, 1981), is mediated by mPFC activity (van Kerkhof et al., 2013) and induces plastic changes in the mPFC that persist into adulthood (Bell et al., 2010; Himmler et al., 2013). Similarly, sexual experience leads to greater spine density of rat mPFC pyramidal neurons and enhances cognitive flexibility (Glasper et al., 2015). In parallel, human studies suggest inter-regional white matter pathways that support complex behaviors, such as the uncinate fasciculus and the superior longitudinal fasciculus, are last to mature, continuing throughout adolescence before stabilizing in adulthood (Lebel et al., 2012; Simmonds et al., 2014).

Importantly, at the same time that adolescents are encountering new experiences, sensory systems are providing high SNR output to downstream brain areas that supported higher order cognition. As outlined above, CPs for sensory systems close prior to adolescence allowing for consistent, high SNR output to efferent targets that integrate sensory information, such as PFC. As a result, these brain areas are receiving high-fidelity multisensory input, driving stimulus-evoked activity and creating an optimal milieu to shape experience-dependent plasticity in these brain areas.

2.2.2. The development of the dopamine system and the opening of the adolescent critical period

It is important to note that many theoretical models of adolescent neurocognitive development posit an interaction between the development of neural systems supporting cognitive control and reward-processing in shaping behavior. Theories such as the dual systems and triadic models of adolescent development suggest that a hyperactive DA system and a less-influential cognitive system may facilitate heightened reward driven behavior based on an inability of cognitive systems to exert top-down control over reward systems (Shulman et al., 2016). In this way, it is thought that developmental interactions between cognitive systems and DA circuitry shape reward-driven behavior. We propose that, in addition, the development of the DA system serves a broader developmental purpose. It is part of an adaptive process whereby the development of the DA system actively shapes cortical development from the cellular to circuit to network level (Luna et al., 2015). Specifically, we put forward the hypothesis that the development of the mesocortical DA system works in synergy with cellular-level changes in PFC to drive a period of enhanced cortical plasticity that mirrors early CP mechanisms and functions to refine circuit integration supporting mature/adult-like cognitive ability.

DA is a neurotransmitter that is strongly implicated in reward-driven behavior and learning via neuromodulation of the mesolimbic and mesocortical circuits. Specifically, DA activity supports reward processing and reinforcement by signaling the reward expectancy and value of action outcomes (Clarke et al., 2014; Dreher et al., 2009; Frank, 2005; Hariri, 2009; Luciana et al., 2012; Schultz et al., 1997). Adolescence is characterized, across cultures and species, as a period of heightened reward-driven behavior that is marked by increases in sensation seeking and novelty seeking (Spear, 2000). This behavior is thought to be linked to the development of the DA system (for Reviews see: (Luciana et al., 2012; Padmanabhan and Luna, 2014; Sturman and Moghaddam, 2011; Telzer, 2016; Wahlstrom et al., 2010)). In general, findings from animal models of PFC development indicate that though the overall laminar organization of DA mesocortical DA projections are established in childhood, the density of DA innervation, including axonal length and total number of axonal varicosities, that increases from childhood into adolescence and either decreases or stabilizes in adulthood, particularly in layer III (Rosenberg and Lewis, 1994, 1995). At the same time, DA levels and synthetic capacity follow a protracted development, increasing into puberty when they reach adult levels (Goldman-Rakic and Brown, 1982; Leslie et al., 1991) and synapse appositions with individual layer III pyramidal cells (Lambe et al., 2000) and layer V/VI GABA cells (Benes et al., 1996) follow a linear increase into adulthood. Notably, serotonin innervation is stable over the same developmental period, indicating development of DA is distinct from other monoamines (Lambe et al., 2000). DA transporter (DAT) concentration also increases from adolescence to adulthood in rodent PFC and cingulate cortex (Coulter et al., 1996). Findings from animal studies of the development of DA receptor density vary somewhat between rodent and non-human primate models of adolescence. Rodent studies of PFC DA receptor density have shown monotonic increases in cortical D1 and D2 receptor concentrations from childhood to adulthood (Tarazi et al., 1998; Tarazi and Baldessarini, 2000), though one study found a periadolescent peak in D1 receptor density (Leslie et al., 1991). Non-human primate studies find D1 and D2 receptor density tends to peak in late childhood or early adolescence and decrease into adulthood (Lidow et al., 1991; Lidow and Rakic, 1992), with D1 receptors remaining in higher concentration throughout development. One postmortem human study found that this peak occurs later, in young adulthood (Weickert et al., 2007). These findings from animal models of cortical DA development are summarized in Fig. 3. Human MRI studies provide similar evidence of prolonged maturation of the structure (Larsen and Luna, 2015; Raznahan et al., 2014; Sowell et al., 1999; Walhovd et al., 2014) and function (Ernst et al., 2005; Galvan et al., 2007; Geier et al., 2010) of DAergic reward systems during adolescence (for reviews see (Galvan, 2010; Padmanabhan and Luna, 2014; Shulman et al., 2016; Wahlstrom et al., 2010)).

The parallel development of DA innervation and cortical development has historically led researches to posit that DA plays a role in cortical development (Kalsbeek et al., 1988, 1989; Porter et al., 1999; Wang et al., 1996). Recent work has specifically implicated the development of the mesocortical DA system in the structural and functional development of PFC excitatory and inhibitory circuitry. For example, DA and the ingrowth of DA axons have been demonstrated to accelerate the development of frontal PV neurons both in vivo and in vitro through interactions with D2 and NMDA receptors (Porter et al., 1999). During adolescence, the functional influence of mesocortical DA release on PV GABAergic interneurons also develops. In prepubertal rodents, patch

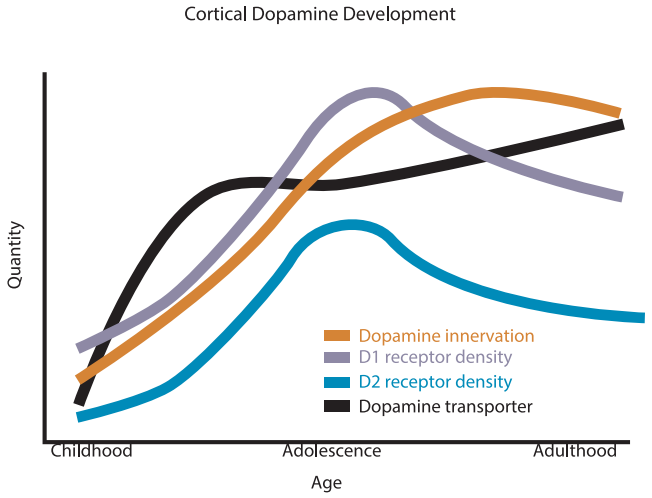


Fig. 3. Development of cortical dopamine during adolescence. This schematic summarizes rodent and non-human primate evidence for the dynamic and multifaceted development of the mesocortical dopamine system during adolescence. Dopamine innervation of PFC, including fiber volume, fiber length, density of varicosities and appositions, and dopamine concentration increase throughout adolescence and either decrease (Rosenberg and Lewis, 1995) or stabilize (Benes et al., 1996; Lambe et al., 2000; Leslie et al., 1991; Willing et al., 2017) during the transition to adulthood. D1 and D2 receptor densities peak during adolescence or early adulthood in non-human primates and D1 expression is stably greater than D2 expression across adolescence (Lidow et al., 1991; Lidow and Rakic, 1992). The peak may be less pronounced in rodent studies (e.g. Andersen et al., 2000; Tarazi and Baldessarini, 2000). Dopamine transporter increases from late childhood to adulthood in rodent PFC and cingulate cortex (Coulter et al., 1996).

clamp recordings of PFC slices demonstrate that DA can excite PV interneurons via D1R, but during adolescence the ability for DA to further excite these cells via D2R emerges (Tseng and O'Donnell, 2007), causing greater inhibitory activity in response to DA release throughout adolescence and adulthood. A similar increase occurs in the nucleus accumbens, which also receives dense dopaminergic inputs, during this developmental stage (Benoit-Marand and O'Donnell, 2008). This functional property allows for DA to facilitate inhibitory circuit function, including context-irrelevant noise suppression, in effect decreasing the spontaneous/evoked ratio of circuit activity by decreasing the E/I balance (O'Donnell, 2010). The decreasing of the E/I balance is centrally involved in triggering of a CP onset (Takesian and Hensch, 2013; Toyoizumi et al., 2013). This is one way peak DA availability in adolescence may serve as a neurobiological initiator of CP plasticity in PFC.

2.2.3. *Dopamine and experience-dependent plasticity*

In addition to triggering neurobiological processes, the development of the DA system also plays role in both motivating the experience that is necessary to shape circuits during the CP window and enhancing the plasticity that results from that experience. Mesolimbic DA activity biases behavior toward exploration and novelty-seeking in both humans (Zald et al., 2008) and animal models (Koob et al., 1978; Le Moal and Simon, 1991) as well as computational simulations (Humphries et al., 2012). As such, elevated DA availability drives adolescents to explore novel environments and situations, amounting to a drive to seek new and more complex experience. Accordingly, large-scale self-report studies have found that sensation seeking and openness to new experience peak during late adolescence and decrease into adulthood (Collado et al., 2014; Harden and Tucker-Drob, 2011; McCrae et al., 2002; Steinberg, 2008). These findings are supported by rodent studies that find that rodents show greater preference for novelty and greater exploratory behavior in novel environments during puberty as compared to adult rats (Adriani et al., 1998; Stansfield and Kirstein, 2006). In many cultures and species, this increased drive coincides with increased *freedom* to explore as adolescents are given greater autonomy, responsibility, and social freedoms (Schlegel and Barry, 1991; Spear, 2000). For example, adolescence is the period when rodents begin to leave the nest, forage for food, and interact socially with rodents outside the family (Spear, 2000).Together, these factors contribute to a vast accumulation of experience under novel and increasingly complex contexts. This new experience then serves as the input to the experience-dependent plasticity mechanisms that drive CP plasticity in higher order association cortices.

DA also plays a critical role in promoting experience-dependent plasticity of prefrontal circuits in response to adolescent experience. Midbrain DA neurons fire phasically in response to reward receipt or in response to stimuli that predict reward outcomes (Mirenowicz and Schultz, 1996). Whereas phasic DA *release* facilitates LTP of corticostriatal circuits, transient *cessation* of firing in response to reward omission facilitates LTD of these circuits, particularly when rewards or omissions are unpredicted (Reynolds and Wickens, 2002). Thus, elevated mesofrontal DA function, as outlined above, should contribute to heightened DAergic facilitation of experience-dependent synaptic plasticity mechanisms. Critically, the ability for phasic DA release to exert an excitatory response in layer 5 prefrontal pyramidal cells via its action on D1 receptors comes online during adolescence (Tseng and O'Donnell, 2005, 2004). When DA-related excitation of prefrontal pyramidal D1R is coupled with concurrent stimulus-evoked glutamatergic signaling, NMDA receptors can be activated to induce upstates in pyramidal cells (Tseng and O'Donnell, 2005). Upstates are periods of sustained activation (sustained excitatory post-synaptic currents) that indicate active information processing and allow for synaptic plasticity to occur (O'Donnell, 2003). As DA release from the ventral tegmental area (VTA; the primary locus of mesocortical DA production) occurs in a context-dependent manner, the ability for DA to excite PFC pyramidal cells forms a mechanism by which context-relevant stimulus processing can drive PFC circuits and induce plasticity. Furthermore, phasic activity of rat mesofrontal DA neurons in response to direct VTA stimulation, or stimulating experience such as wheel-running, induces the formation of axon buttons on mesofrontal projections during adolescence but not in adulthood (Mastwal et al., 2014), and amphetamine exposure during adolescence but not adulthood leads to an increase in DA innervation in rodent PFC (Reynolds et al., 2015). Together, these findings suggest that heightened functional DA availability in adolescence both motivates adolescents to explore novel experiences and enhances responses to the outcomes of exploration, facilitating plasticity of PFC circuits in response to new experiences.

The increasing influence of DA on PV interneurons (Porter et al., 1999; Tseng and O'Donnell, 2007) implies that DA may also increase the ability of PFC circuits to generate high-frequency oscillations. As these oscillations are implicated in higher-order cognitive processes, such as working memory, context-dependent DA release may enhance context-dependent cognition (Murty et al., 2016). Given that oscillatory activity is thought to play a role in neuronal communication (Fries, 2005), developmental increases in DA may increase the efficacy of neuronal communication from PFC to other areas of the brain. This idea is further supported by the specific increase in influence of DA on the excitability of layer V pyramidal cells (Flores-Barrera et al., 2014; Tseng and O'Donnell, 2005), considering layer V pyramidal cells form the output layer of cortex and thus promote system wide neural communication.

In sum, increasing DA concentration and innervation in adolescence leads to both a drive for exploration and novel experience and a heightened reward response to novel outcomes, facilitating experience-dependent plasticity. Further, the increase in the influence of DA on prefrontal excitatory and inhibitory circuitry leads to a significant increase in SNR of stimulus representations and neuronal computations (O'Donnell, 2010) and may play an important role in triggering the CP window for PFC development during adolescence.

2.3. Braking factors and the closing of the adolescent critical period

There is evidence of at least two major braking factors operating in PFC during adolescence: PNNs and myelination. The development of PNNs, which as described above (see 1.2.1) stabilize synaptic architecture, during adolescence has received increasing attention due to the association between abnormal PNN formation and schizophrenia (Berretta et al., 2015; Enwright et al., 2016). A human postmortem study indicated that the number of PNNs in the PFC increases throughout adolescence and into early adulthood (Mauney et al., 2013), suggesting a stabilization of circuit plasticity occurring during this time. The same pattern is evident in rat prelimbic and frontal association cortices (Paylor et al., 2016), and this developmental increase in frontal cortex PNN formation is primarily driven by the formation of PNNs on PV interneurons (Baker et al., 2017). In addition, myelination, which as described above prevents future branching of neural circuits, continues throughout adolescence and follows an even more protracted development in humans relative to other non-human primates, such as chimpanzees (Miller et al., 2012). Histological (Yakovlev et al., 1967), myelin mapping (Grydeland et al., 2013; Shafee et al., 2015), and diffusion MRI studies (Lebel et al., 2012; Simmonds et al., 2014) jointly provide evidence that myelination of association cortices and, in particular, integrative white matter pathways linking association cortices, like the uncinate fasciculus, superior longitudinal fasciculus and cingulum, have protracted developmental trajectories that extend into the 30 s (Lebel et al., 2012; Simmonds et al., 2014). The occurrence of these braking factors during adolescence provides further evidence for the mechanisms of CP plasticity shaping development during this time.

2.3.1. Critical period closure

The formation of braking factors functions to restrict plasticity and close CP windows. However, in brain areas responsible for complex, abstract, and flexible cognition, it may be beneficial to permit higher levels of life-long plasticity than in brain areas involved in more basic, concrete function like primary sensory areas. Accordingly, it is possible that the CP for association cortices does not close to the same extent as early sensory CPs, affording for more life-long adaptation of complex cognitive function. For this reason, similar to the timing of critical period onset, there may be substantial interindividual differences in the precise timing of critical period closure. Indeed, as the developmental stage for adolescence appears to be extending in duration in western societies (Arnett, 2000; Committee on Improving the Health, Safety, and Well-Being of Young Adults et al., 2015), the CP window may extend accordingly. Future research may address this point more directly. Nevertheless, CP braking factors place restraints on adulthood plasticity that severely limit the potential rate and magnitude of plasticity relative to adolescence, and further plasticity occurring outside the CP window will be constrained within the foundational aspects of brain architecture established through the CP.

2.4. Functional outcomes of critical period development of association cortices during adolescence

Functional development of prefrontal and parietal association cortices continues into adulthood (Uhlhaas et al., 2010) and the nature of this functional development reflects the functional outcomes of CP neuroanatomical development. Electrophysiological studies in non-human primates demonstrate reductions in asynchronous firing (Jiang et al., 2015), increases in IPSC amplitude, and shortened IPSC decay time in DLPFC neurons in response to inhibitory interneuron signaling during adolescence (Gonzalez-Burgos et al., 2014; Hashimoto et al., 2009). The decay rate of these inhibitory responses can influence the frequency of oscillatory activity (Buzsáki and Wang, 2012), facilitating high frequency oscillatory capability through development. Computational simulations have demonstrated that this pattern of functional development enables mature levels of gamma band power at late stages of adolescent development (Gonzalez-Burgos et al., 2014). Accordingly, EEG studies in humans suggest a late period of neurophysiological development occurring during adolescence in frontal cortex (Hudspeth and Pribram, 1992) that is marked by increases in task-evoked gamma (and theta) band power (Uhlhaas et al., 2009; Uhlhaas and Singer, 2011). During the same period, there is a strengthening of task-evoked fronto-parietal theta band synchrony and a reorganization of brain-wide beta band phase-synchrony relationships (Uhlhaas and Singer, 2011). As high-frequency oscillations are thought to contribute to fMRI BOLD signal amplitude (Niessing et al., 2005; Ojemann et al., 2013), similar effects should be detectable using fMRI. Indeed, age-related improvements in working-memory execution are paralleled by age-related increases in fronto-parietal BOLD activation during working-memory tasks though adolescence (Geier et al., 2009; Klingberg et al., 2002; O'Hare et al., 2008; Satterthwaite et al., 2013; Thomason et al., 2009). Considering the role of mature inhibitory circuitry in generating high-frequency oscillatory activity and the contribution of high-frequency oscillatory activity to BOLD signal amplitude described above, it is possible that these developmental increases in BOLD activation are, to some extent, reflecting local inhibitory neural development. However, the relationship is likely to be more complicated. For example, other studies of the development of BOLD activation in PFC during response inhibition and working memory find greater BOLD response in childhood during correct trials that decreases into adulthood (though overall performance is lower in childhood) (Ordaz et al., 2013; Simmonds et al., 2017). One possible explanation that has been put forth is that greater activation in PFC during cognitive control reflects greater effort (Luna et al., 2010) akin to evidence of greater BOLD activation in PFC in adults with increasing cognitive load (Braver et al., 1997). Considering these findings, it may be possible that the CP maturation of PFC circuitry results in more effective and energy efficient computation and thus developmental reductions in BOLD in some contexts. It is likely that the differing findings from developmental fMRI studies are a result of interactions between developmental effects occurring between individuals (e.g. the maturation of inhibitory circuitry) and cognitive load effects occurring within individuals (e.g. changing task difficulty and required effort). Future work is needed to determine the precise relationship between the maturation of inhibitory circuitry at the micro scale and the development of PFC BOLD activation at the macro scale under different levels of cognitive demand (and to determine if this relationship is constant across development).

2.4.1. Network development

Many of the functional outcomes of adolescent CP development relate to enhanced neuronal communication and thus have important implications for network development—a topic that has received a lot of attention recently. The development of inhibitory circuits in association cortices leads to improvements in neuronal synchrony and oscillatory activity, which are thought to improve the SNR of long-range communication. Neuronal communication is further supported by the development of the DA system (Steullet et al., 2014) and its influence on PFC inhibitory interneurons and pyramidal cells (O'Donnell, 2010). Additionally, evidence from rodent models indicates that during adolescence there is an up-regulation of stimulus evoked NMDA transmission onto PFC layer 5 pyramidal cells and an increase in DA-induced excitatory response on these cells (Flores-Barrera et al., 2014), which may have particular significance for neuronal communication considering that layer 5 is the primary output layer of PFC with layer 5 pyramidal cells sending axonal projections to distant brain areas. At the same time, the developmental formation of myelin should increase the speed and fidelity of long-distance neuronal signaling (Yakovlev et al., 1967). Together, as these changes develop throughout adolescence, the efficacy and SNR of large-scale network connectivity and computation should also increase. Supporting this notion, fMRI and MEG studies show a strengthening of PFC connectivity to other cognitive control-related brain regions that, in turn, supports mature cognitive control

(Hwang et al., 2016, 2010), and recent resting-state fMRI studies indicate that cingulo-opercular/salience networks, which support sustained cognitive control, show developmental increases in their integration with other brain networks, supporting improvements in executive function (Marek et al., 2015).

3. Role of critical period mechanisms in developmental psychopathology

Adolescence is the developmental period of onset for numerous psychiatric disorders that are characterized by deficits in higher-order cognition, including substance abuse, schizophrenia, depression, and anxiety disorders (Paus et al., 2008). Though treatments are available and recovery is possible, these disorders typically persist throughout the lifespan (Davydov et al., 2010; Demyttenaere et al., 2004; Jääskeläinen et al., 2013). This suggests that while cognitive functions are normatively refined during adolescence, the enhanced plasticity of cortical circuits at this time may also present a vulnerability to abnormal neurodevelopment with long-lasting and potentially serious consequences. Considering the exceptionally strong interaction between experience and neurobiology that shapes circuit plasticity and influences behavior during CP development, perturbations to *either* normal experience or neurobiology may manifest long-term abnormal outcomes. In the first circumstance, the neurobiological CP mechanisms unfolding are normal, but plasticity unfolds in response to an abnormal environment (e.g. stressful, impoverished), resulting abnormal function in adulthood. This process may still be adaptive when considered in context; i.e. prefrontal circuitry and behavior may be abnormal in relation to normative developmental trajectories but nevertheless optimized for the abnormal environment of an individual. In the second circumstance, experience may be normal but interactions with abnormal neurobiology—perhaps caused by genetic factors, disease, injury, or earlier developmental abnormalities—lead to abnormal CP plasticity and thus abnormal circuit function and behavior. In either case, perturbations should lead to long-lasting, largely irreversible outcomes that would not occur if the same perturbations were experienced later in life.

In the following sections, we discuss prominent examples of the way in which abnormal experience, focusing on stress and social isolation, and abnormal neurobiology, focusing on schizophrenia, impact the neurodevelopment of PFC during adolescence and have long-term neurocognitive consequences that persist in adulthood.

3.1. Abnormal experience leads to abnormal outcomes during adolescence

Abnormal amounts of stress during the transition to adolescence can affect CP development of the PFC, resulting in abnormal outcomes. Chronic or abnormally high levels of stress hormones have particularly strong effects on the plasticity of prefrontal cortical circuitry and PFC dependent functions like working memory and flexibility (Cerqueira et al., 2007a, 2007b). Given the developmental mechanisms at play in adolescent PFC, and evidence of increased hormonal stress response in adolescence (Klein and Romeo, 2013), stressful experience has a particularly strong influence at this time (McEwen and Morrison, 2013). For example, rodent models show that chronic stress in the form of 6 h periods of restraint daily from PD 20–41 (approximately late childhood and early adolescence) resulted in pyramidal cell atrophy in prelimbic PFC and was associated with the emergence of depressive-like symptoms (Eiland et al., 2012). Similarly, five days of intruder-induced stress in rodents was found to produce specific deficits in a mPFC-dependent strategy shifting task when experienced in late adolescence (PD 42–46), but not early adolescence (PD 25–32) or adulthood (PD 70–74) (Snyder et al., 2014). In humans, early adolescent reports of psychological distress are associated with future impairments in self-control, a behavior associated with PFC function (Duckworth et al., 2012) and have been suggested to influence vulnerability to schizophrenia (Gomes and Grace, 2017) through effects on DA processing (Belujon and Grace, 2015). Further, when abuse occurs during adolescence (ages 14–16) it impacts the development of frontal cortex gray matter volume, whereas abuse suffered in childhood impacts the development of hippocampal, but not frontal, gray matter volume (Andersen et al., 2008). Of particular relevance to our CP hypothesis, stress-related effects on brain development and cognition may be, at least in part, mediated by two central CP facilitators: PV maturation and BDNF. Rodent studies that are able to manipulate early life stress, including during prenatal and/or adolescent periods, provide evidence that early life stress impacts the development of PV interneurons in PFC, leading to reduced PV expression in adolescence and increased expression in adulthood (Brenhouse and Andersen, 2011; Ganguly et al., 2015; Wieck et al., 2013). Sex may moderate the influence of stress on PV maturation such that females have an earlier and more pronounced effect that relates to disruptions in social and emotional behavior (Holland et al., 2014; Shepard et al., 2016).Similarly, BDNF and other genes involved in BDNF LTP (Coppens et al., 2011) are impacted by early life stress in frontal cortex, generally in the form of precocious increases during adolescence followed by prolonged decreases in adulthood relative to control animals (Bath et al., 2013; Callaghan et al., 2013; Luoni et al., 2014; Roceri et al., 2004; Xu et al., 2016). This effect may be more pronounced in males than females (Hill et al., 2014) and has been associated with impairments in cognitive flexibility (Xu et al., 2016).

Increased social autonomy allows adolescents to encounter novel experiences that shape the development of PFC. Conversely, social isolation has been shown to disproportionately affect PFC development when experienced during pre- and peri-adolescent development. In rats, post-weaning social isolation has been found to lead to reductions in dendritic complexity (Wang et al., 2012), D2R labeling (Fitzgerald et al., 2013), and myelin thickness and MAG (see section 1.2.2 for discussion of the role of myelin and MAG as CP braking factors) (Makinodan et al., 2012) in the mPFC that persist throughout adulthood (Wang et al., 2012). Isolation also leads to increases in BDNF expression in mPFC (Han et al., 2011; Kumari et al., 2016; Meng et al., 2011; Shao et al., 2013) that occur in parallel to cognitive impairment (Han et al., 2011; Shao et al., 2013). When isolation is delayed to the onset of adolescence, dendritic density is reduced in adult mPFC but not hippocampus (Leussis et al., 2008). Social isolation is also associated with abnormal rat mPFC function. Post-weaning isolation leads to abnormal responses of adult mPFC pyramidal cells to VTA stimulation (Peters and O'Donnell, 2005) and DA agonists (Baarendse et al., 2013) as well as decreased behavioral sensitivity to enhanced DA transmission (Baarendse et al., 2013), indicating an abnormal impact of mesocortical DA circuitry on PFC function. These functional and neuroanatomical abnormalities were also associated with impairments of PFC-dependent behaviors like impulse control and decision making that persisted after re-socialization in adulthood (Baarendse et al., 2013). Together, these findings highlight how experience, such as lack of social interaction, during adolescence can influence the structure and function of PFC circuitry, leading to disruptions in higher-order cognitive abilities—suggestive of CP development.

3.2. Abnormal neurobiology leads to abnormal outcomes during adolescence

A prominent example of abnormal neurobiology contributing to abnormal CP development is schizophrenia. Schizophrenia is a developmental disorder that emerges during adolescence and young adulthood and is strongly associated with life-long impairments in cognitive ability (e.g. (Rapoport et al., 2012)). Though schizophrenia has a lower incidence rate than other types of psychopathology that emerge during adolescence (e.g. mood disorders and anxiety) and is likely not the only psychiatric disorder that can be linked to critical or sensitive period development (e.g. see (Andersen and Teicher, 2008; Tucker et al., 2015) for a discussion of sensitive periods for stress and the

development of depression), it serves as a particularly useful example because the underlying neurobiology has been extensively researched in both humans and animal models, and it has been associated with abnormalities in multiple facilitating factors (e.g. GABA and PV interneurons, NMDA function) and braking factors (e.g. PNN) that drive CP maturation (see (Catts et al., 2013) for review of neurodevelopmental abnormalities in schizophrenia). We detail these factors and their neurodevelopmental consequences below.

First, dysfunction of cortical GABAergic inhibitory circuits leads to an increased E/I balance relative to healthy individuals and may be central to impaired cognition in schizophrenia (O'Donnell, 2012). Individuals with schizophrenia have reduced GAD67, indicating reduced GABA synthesis, and reduced expression of PV mRNA in the human DLPFC relative to healthy controls (see (Lewis et al., 2005) for review). Second, correspondingly, schizophrenia is also associated with abnormalities in GABA receptor concentration. Patients show relative reductions in the $GABA_A\alpha1R$ subtype, which have faster and greater GABA sensitivity that is important for PV signaling (and CP development (Fagiolini et al., 2004)), and increases in the slower $GABA_A\alpha2R$ (e.g. (Beneyto et al., 2010)). The combined reductions in synthesis, PV interneurons, and $GABA_A\alpha1R$ have important functional consequences for cortical inhibitory circuits. Inhibitory dysfunction in schizophrenia has been extensively reviewed elsewhere (e.g. (Gonzalez-Burgos et al., 2010); to summarize, abnormal PV neurons and $GABA_AR$ lead to altered neural synchrony, reduced gamma band oscillatory activity in PFC, and impairments in working memory. Third, hypofunction of NMDA transmission has been implicated in schizophrenia, including decreased numbers of NR1 and increased NR3A receptors in the DLPFC relative to healthy controls (Weickert et al., 2013). Fourth, individuals with schizophrenia show decreased prefrontal DRD1 and elevated DRD2 binding (Hess et al., 1987). Interestingly the reduced ratio of D1/D2 receptors, reduced ratio of NR1/NR3A, reduced PV expression, reduced GABAAα1R/GABAA2R ratio reflect preadolescent levels, leading to the hypothesis that schizophrenia may represent a persistently immature cortical state (Catts et al., 2013). This view is supported by recent work that shows an important CP braking factor, PNN formation, is reduced in schizophrenia (Berretta et al., 2015; Enwright et al., 2016; Mauney et al., 2013),suggesting a lack of normative circuit stabilization. The possible developmentally immature state of PFC circuitry in schizophrenia, particularly the relative reduction in PNN, would predispose these circuits to perpetually elevated plasticity (Carulli et al., 2010). Accordingly, schizophrenia has been associated with excessive gray matter thinning (Cannon et al., 2015) and pruning of synapses (Glantz and Lewis, 2000) in the PFC (Faludi and Mirnics, 2011). These cellular-level abnormalities then lead to abnormal and diminished intra- and inter-regional connectivity (for review see (Karlsgodt et al., 2008)). In sum, schizophrenia is characterized by abnormalities in multiple facilitating factors (maturation of GABA and NMDA systems) and braking factors (PNN formation) central to adolescent CP developmental processes, resulting in long-lasting deficits in brain function and cognitive ability.

3.3. Interrelations

Though we have highlighted how abnormal experience or neurobiology can individually influence adolescent CP development, it is important to underscore that experience and neurobiology are interrelated across all stages of development. The hierarchical nature of CPs throughout the brain predicts that abnormal experience at early stages of development, leading to abnormal development of earlier-developing brain regions, could have a cascading influence on the development of higher-order brain areas as a result of abnormal inputs shaping CP plasticity and specialization. That is, perturbations to sensory systems undermining sensory perception in early development could affect the quality of the information driving CP of downstream cortical areas that integrate sensory inputs, like PFC, and impact later cognitive development (LeBlanc and Fagiolini, 2011). Additionally, pre-adolescent differences in brain function may also predispose individuals to seek out different environments during adolescence. This process would be akin to an active gene-environment correlation (Dick, 2011). Such early developing abnormalities may impair adolescent CP development as a result of abnormal sensory systems providing abnormal inputs to PFC, but it may also lead individuals to seek out abnormal or impoverished social experiences during adolescence, further exacerbating abnormal development and impaired adulthood outcomes. Importantly, the adolescent CP could also afford an important window of opportunity to restructure and establish compensatory mechanisms to overcome predispositions to abnormal development. The notion of resilience has garnered much attention as some individuals are able to suppress neurobiological and environmental adversity (Rutter, 2013, p. 201). For example, not all psychotic episodes, which predominantly emerge during adolescence, result in schizophrenia. Similarly, many individuals with childhood ADHD do not continue to express symptoms in adulthood, suggesting a process of recovery or compensation occurring during adolescence.

4. Conclusion

Understanding the mechanisms that drive neurobiological plasticity during adolescence is critical for advancing the understanding of typical and atypical adolescent development and psychopathology. Here, we have presented compelling evidence that the characteristics of cellular and circuit-level cortical development jointly reflect CP mechanisms of neurobiological development in PFC and other association cortices during the adolescent period. These CP mechanisms inform the nature of refinements in higher-order cognitive ability during adolescence and provide important context for the interpretation of human structural and functional neuroimaging findings. Importantly, adolescent CP development is strongly affected by experience, which can inform the way in which environment can not only lead to vulnerability to disorders but also provide an opportunity to alter developmental trajectories. Though neurobiological and genetic vulnerabilities or adverse experiences, such as in trauma, can set forth an abnormal developmental trajectory, the adaptive nature of CP plasticity also makes adolescence a time when informed interventions could positively affect or correct outcomes in adulthood. As such, understanding adolescence as a CP for the development of association cortices supporting higher-order cognitive abilities can not only provide a mechanistic framework for understanding why adolescence is the developmental period of emergence of many psychiatric disorders but also potentially provide an important window for intervention. Interestingly, from a societal perspective, it has been noted that in western societies markers of independence (e.g., starting a career, financial independence, starting a family) have been delayed into the twenties (Committee on Improving the Health, Safety, and Well-Being of Young Adults et al., 2015), suggesting a prolonged period of adolescence (sometimes referred to as emerging adulthood (Arnett, 2000)). While its impact is debated, this may be a societally adaptive process that functions to prolong and facilitate CP development, creating a larger window for refinement and specialization as well as a larger window for intervention to impact adult trajectories.

While the available evidence presented here is compelling there is a need for further research to continue to test these hypotheses. Many of the studies reviewed here rely on animal models of development. Though it is often difficult to collect specific and targeted evidence of molecular and circuit-level neurobiology in-vivo in humans, it is important for future work to continue to investigate these mechanisms and their correlates in humans. Techniques such as PET imaging and MR spectroscopy that provide gross information about specific neurotransmitter concentrations and receptor densities or techniques like pharmacological interventions or transcranial magnetic stimulation (TMS) that impact excitatory or inhibitory brain function either locally

or globally may be particularly useful in this regard. Multimodal approaches that combine these techniques with others like EEG, MEG, and fMRI that can measure functional dynamics across different timescales can provide insights that span across levels of analysis. Further work should also seek to further elucidate the triggers that open the CP window during adolescence such as contributions from pubertal processes that define the adolescent period (Piekarski et al., 2017b). Investigating possible interactions between gonadal hormones, mesocortical DA, and other neurotransmitter systems such as GABA may be particularly informative (Piekarski et al., 2017a).

Acknowledgements

This work was supportedby the National Institute of Mental Health [grant numbers R01MH067924, R01MH080243] and the Staunton Farm Foundation.

References

Adriani, W., Chiarotti, F., Laviola, G., 1998. Elevated novelty seeking and peculiar d-amphetamine sensitization in periadolescent mice compared with adult mice. Behav.Neurosci. 112, 1152–1166.

Andersen, S.L., Teicher, M.H., 2008. Stress, sensitive periods and maturational events in adolescent depression. Trends Neurosci. 31, 183–191. https://doi.org/10.1016/j.tins.2008.01.004.

Andersen, S.L., Thompson, A.T., Rutstein, M., Hostetter, J.C., Teicher, M.H., 2000. Dopamine receptor pruning in prefrontal cortex during the periadolescent period in rats. Synap. N. Y. N 37, 167–169. https://doi.org/10.1002/1098-2396(200008)37:2<167::AID-SYN11>3.0.CO;2-B.

Andersen, S.L., Tomada, A., Vincow, E.S., Valente, E., Polcari, A., Teicher, M.H., 2008. Preliminary evidence for sensitive periods in the effect of childhood sexual abuse on regional brain development. J. Neuropsychiatry Clin. Neurosci. 20, 292–301. https://doi.org/10.1176/appi.neuropsych.20.3.292.

Anomal, R., de Villers-Sidani, E., Merzenich, M.M., Panizzutti, R., 2013. Manipulation of BDNF signaling modifies the experience-dependent plasticity induced by pure tone exposure during the critical period in the primary auditory cortex. PLoS One 8, e64208. https://doi.org/10.1371/journal.pone.0064208.

Arnett, J.J., 2000. Emerging adulthood. A theory of development from the late teens through the twenties. Am. Psychol. 55, 469–480.

Baarendse, P.J.J., Counotte, D.S., O'Donnell, P., Vanderschuren, L.J.M.J., 2013. Early social experience is critical for the development of cognitive control and dopamine modulation of prefrontal cortex function. Neuropsychopharmacology 38, 1485–1494. https://doi.org/10.1038/npp.2013.47.

Baker, K.D., Gray, A.R., Richardson, R., 2017. The development of perineuronal nets around parvalbumin gabaergic neurons in the medial prefrontal cortex and basolateral amygdala of rats. Behav. Neurosci. 131, 289–303. https://doi.org/10.1037/bne0000203.

Balmer, T.S., Carels, V.M., Frisch, J.L., Nick, T.A., 2009. Modulation of perineuronal nets and parvalbumin with developmental song learning. J. Neurosci. Off. J. Soc. Neurosci. 29, 12878–12885. https://doi.org/10.1523/JNEUROSCI.2974-09.2009.

Barbas, H., 2000. Connections underlying the synthesis of cognition, memory, and emotion in primate prefrontal cortices. Brain ResBull 52, 319–330.

Barbas, H., Zikopoulos, B., Timbie, C., 2011. Sensory pathways and emotional context for action in primate prefrontal cortex. Biol. Psychiatry Prefrontal Cortical Circuits Regul. Attent. Behav. Emot. 69, 1133–1139. https://doi.org/10.1016/j.biopsych.2010.08.008.

Barbas, H., Zikopoulos, B., 2007. The prefrontal cortex and flexible behavior. Neurosci. Rev. J. Bringing Neurobiol. Neurol. Psychiatry 13, 532–545. https://doi.org/10.1177/1073858407301369.

Barkat, T.R., Polley, D.B., Hensch, T.K., 2011. A critical period for auditory thalamocortical connectivity. Nat. Neurosci. 14, 1189–1194. https://doi.org/10.1038/nn.2882.

Bath, K.G., Schilit, A., Lee, F.S., 2013. Stress effects on BDNF expression: effects of age, sex, and form of stress. Neuroscience 239, 149–156. https://doi.org/10.1016/j.neuroscience.2013.01.074.

Bavelier, D., Levi, D.M., Li, R.W., Dan, Y., Hensch, T.K., 2010. Removing brakes on adult brain plasticity: from molecular to behavioral interventions. J. Neurosci. 30, 14964–14971. https://doi.org/10.1523/JNEUROSCI.4812-10.2010.

Bell, H.C., Pellis, S.M., Kolb, B., 2010. Juvenile peer play experience and the development of the orbitofrontal and medial prefrontal cortices. Behav. Brain Res. 207, 7–13. https://doi.org/10.1016/j.bbr.2009.09.029.

Belujon, P., Grace, A.A., 2015. Regulation of dopamine system responsivity and its adaptive and pathological response to stress. Proc. Biol. Sci. 282. https://doi.org/10.1098/rspb.2014.2516.

Benes, F.M., Vincent, S.L., Molloy, R., Khan, Y., 1996. Increased interaction of dopamine-immunoreactive varicosities with GABA neurons of rat medial prefrontal cortex occurs during the postweanling period. Synap. N. Y. N 23, 237–245. https://doi.org/10.1002/(SICI)1098-2396(199608)23:4%3C237::AID-SYN1%3E3.0.CO;2-8.

Beneyto, M., Abbott, A., Hashimoto, T., Lewis, D.A., 2010. Lamina-specific alterations in cortical GABAA receptor subunit expression in schizophrenia. Cereb. Cortex.

Benoit-Marand, M., O'Donnell, P., 2008. D2 dopamine modulation of corticoaccumbens synaptic responses changes during adolescence. Eur. J. Neurosci. 27, 1364–1372. https://doi.org/10.1111/j.1460-9568.2008.06107.x.

Berretta, S., Pantazopoulos, H., Markota, M., Brown, C., Batzianouli, E.T., 2015. Losing the sugar coating: potential impact of perineuronal net abnormalities on interneurons in schizophrenia. Schizophr. Res. GABA Syst. Schizophrenia: Cells Mol. Microcircuitry 167, 18–27. https://doi.org/10.1016/j.schres.2014.12.040.

Blakemore, S.-J., Mills, K.L., 2014. Is adolescence a sensitive period for sociocultural processing? Annu. Rev. Psychol. 65, 187–207. https://doi.org/10.1146/annurev-psych-010213-115202.

Bourgeois, J.P., Goldman-Rakic, P.S., Rakic, P., 1994. Synaptogenesis in the prefrontal cortex of rhesus monkeys. Cereb. Cortex N. Y. N 1991 (4), 78–96.

Bourne, J.A., Rosa, M.G.P., 2006. Hierarchical development of the primate visual cortex, as revealed by neurofilament immunoreactivity: early maturation of the middle temporal area (MT). Cereb. Cortex N. Y. N 1991 (16), 405–414. https://doi.org/10.1093/cercor/bhi119.

Braver, T.S., Cohen, J.D., Nystrom, L.E., Jonides, J., Smith, E.E., Noll, D.C., 1997. A parametric study of prefrontal cortex involvement in human working memory. Neuroimage 5, 49–62.

Brenhouse, H.C., Andersen, S.L., 2011. Nonsteroidal anti-inflammatory treatment prevents delayed effects of early life stress in rats. Biol. Psychiatry 70, 434–440.

Buzsáki, G., Wang, X.-J., 2012. Mechanisms of gamma oscillations. Annu. Rev. Neurosci. 35, 203–225. https://doi.org/10.1146/annurev-neuro-062111-150444.

Caballero, A., Flores-Barrera, E., Cass, D.K., Tseng, K.Y., 2014. Differential regulation of parvalbumin and calretinin interneurons in the prefrontal cortex during adolescence. Brain Struct. Funct. 219, 395–406. https://doi.org/10.1007/s00429-013-0508-8.

Callaghan, B.L., Graham, B.M., Li, S., Richardson, R., 2013. From resilience to vulnerability: mechanistic insights into the effects of stress on transitions in critical period plasticity. Front. Psychiatry 4, 90. https://doi.org/10.3389/fpsyt.2013.00090.

Cannon, T.D., Chung, Y., He, G., Sun, D., Jacobson, A., van Erp, T.G.M., McEwen, S., Addington, J., Bearden, C.E., Cadenhead, K., Cornblatt, B., Mathalon, D.H., McGlashan, T., Perkins, D., Jeffries, C., Seidman, L.J., Tsuang, M., Walker, E., Woods, S.W., Heinssen, R., North American Prodrome Longitudinal Study Consortium, 2015. Progressive reduction in cortical thickness as psychosis develops: a multisite longitudinal neuroimaging study of youth at elevated clinical risk. Biol. Psychiatry 77, 147–157. https://doi.org/10.1016/j.biopsych.2014.05.023.

Cardin, J., Carlén, M., Meletis, K., Knoblich, U., Zhang, F., Deisseroth, K., Tsai, L., Moore, C., 2009. Driving fast-spiking cells induces gamma rhythm and controls sensory responses. Nature 459, 663–667. https://doi.org/10.1038/nature08002.

Carulli, D., Pizzorusso, T., Kwok, J.C.F., Putignano, E., Poli, A., Forostyak, S., Andrews, M.R., Deepa, S.S., Glant, T.T., Fawcett, J.W., 2010. Animals lacking link protein have attenuated perineuronal nets and persistent plasticity. Brain J. Neurol. 133, 2331–2347. https://doi.org/10.1093/brain/awq145.

Catts, V.S., Fung, S.J., Long, L.E., Joshi, D., Vercammen, A., Allen, K.M., Fillman, S.G., Moore, L., Rothmond, D., Sinclair, D., Tiwari, Y., Tsai, S.-Y., Weickert, T.W., Shannon Weickert, C., 2013. Rethinking schizophrenia in the context of normal neurodevelopment. Front. Cell. Neurosci. 7, 60. https://doi.org/10.3389/fncel.2013.00060.

Celio, M.R., Blümcke, I., 1994. Perineuronal nets–a specialized form of extracellular matrix in the adult nervous system. Brain Res. Brain Res. Rev. 19, 128–145.

Cerqueira, J.J., Mailliet, F., Almeida, O.F.X., Jay, T.M., Sousa, N., 2007a. The prefrontal cortex as a key target of the maladaptive response to stress. J. Neurosci. 27, 2781–2787. https://doi.org/10.1523/JNEUROSCI.4372-06.2007.

Cerqueira, J.J., Taipa, R., Uylings, H.B.M., Almeida, O.F.X., Sousa, N., 2007b. Specific configuration of dendritic degeneration in pyramidal neurons of the medial prefrontal cortex induced by differing corticosteroid regimens. Cereb. Cortex 17, 1998–2006. https://doi.org/10.1093/cercor/bhl108.

Chattopadhyaya, B., Di Cristo, G., Higashiyama, H., Knott, G.W., Kuhlman, S.J., Welker, E., Huang, Z.J., 2004. Experience and activity-dependent maturation of perisomatic GABAergic innervation in primary visual cortex during a postnatal critical period. J. Neurosci. Off. J. Soc. Neurosci. 24, 9598–9611. https://doi.org/10.1523/JNEUROSCI.1851-04.2004.

Chen, L., Cooper, N.G., Mower, G.D., 2000. Developmental changes in the expression of NMDA receptor subunits (NR1, NR2A, NR2B) in the cat visual cortex and the effects of dark rearing. Brain Res. Mol. Brain Res. 78, 196–200.

Clarke, H.F., Cardinal, R.N., Rygula, R., Hong, Y.T., Fryer, T.D., Sawiak, S.J., Ferrari, V., Cockcroft, G., Aigbirhio, F.I., Robbins, T.W., Roberts, A.C., 2014. Orbitofrontal dopamine depletion upregulates caudate dopamine and alters behavior via changes in reinforcement sensitivity. J. Neurosci. 34, 7663–7676. https://doi.org/10.1523/JNEUROSCI.0718-14.2014.

Collado, A., Felton, J.W., MacPherson, L., Lejuez, C.W., 2014. Longitudinal trajectories of sensation seeking, risk taking propensity, and impulsivity across early to middle adolescence. Addict. Behav., "Impulsivity: Mechanisms, Moderators and Implications for Addictive Behaviors" Vol. 39. pp. 1580–1588. https://doi.org/10.1016/j.addbeh.2014.01.024.

Committee on Improving the Health, Safety, and Well-Being of Young Adults, Board on Children, Youth, and Families, Institute of Medicine, National Research Council, 2015. Investing in the Health and Well-Being of Young Adults. National Academies Press (US), Washington (DC).

Condé, F., Lund, J.S., Lewis, D.A., 1996. The hierarchical development of monkey visual cortical regions as revealed by the maturation of parvalbumin-immunoreactive neurons. Dev. Brain Res. 96, 261–276. https://doi.org/10.1016/0165-3806(96)00126-5.

Conklin, H.M., Luciana, M., Hooper, C.J., Yarger, R.S., 2007. Working memory performance in typically developing children and adolescents: behavioral evidence of protracted frontal lobe development. Dev. Neuropsychol. 31, 103–128. https://doi.org/10.1080/87565640709336889.

Coppens, C.M., Siripornmongcolchai, T., Wibrand, K., Alme, M.N., Buwalda, B., de Boer, S.F., Koolhaas, J.M., Bramham, C.R., 2011. Social defeat during adolescence and adulthood differentially induce BDNF-regulated immediate early genes. Front. Behav. Neurosci. 5, 72. https://doi.org/10.3389/fnbeh.2011.00072.
Coulter, C.L., Happe, H.K., Murrin, L.C., 1996. Postnatal development of the dopamine transporter: a quantitative autoradiographic study. Brain Res. Dev. 92, 172–181.
Dahl, R.E., 2004. Adolescent brain development: a period of vulnerabilities and opportunities. Keynote address. Ann. N. Y. Acad. Sci. 1021, 1–22. https://doi.org/10.1196/annals.1308.001.
Das, S., Sasaki, Y.F., Rothe, T., Premkumar, L.S., Takasu, M., Crandall, J.E., Dikkes, P., Conner, D.A., Rayudu, P.V., Cheung, W., Chen, H.S., Lipton, S.A., Nakanishi, N., 1998. Increased NMDA current and spine density in mice lacking the NMDA receptor subunit NR3A. Nature 393, 377–381. https://doi.org/10.1038/30748.
Davydov, D.M., Stewart, R., Ritchie, K., Chaudieu, I., 2010. Resilience and mental health. Clin. Psychol. Rev. 30, 479–495. https://doi.org/10.1016/j.cpr.2010.03.003.
Deidda, G., Allegra, M., Cerri, C., Naskar, S., Bony, G., Zunino, G., Bozzi, Y., Caleo, M., Cancedda, L., 2015. Early depolarizing GABA controls critical-period plasticity in the rat visual cortex. Nat. Neurosci. 18, 87–96. https://doi.org/10.1038/nn.3890.
Demyttenaere, K., Bruffaerts, R., Posada-Villa, J., Gasquet, I., Kovess, V., Lepine, J.P., Angermeyer, M.C., Bernert, S., de Girolamo, G., Morosini, P., Polidori, G., Kikkawa, T., Kawakami, N., Ono, Y., Takeshima, T., Uda, H., Karam, E.G., Fayyad, J.A., Karam, A.N., Mneimneh, Z.N., Medina-Mora, M.E., Borges, G., Lara, C., de Graaf, R., Ormel, J., Gureje, O., Shen, Y., Huang, Y., Zhang, M., Alonso, J., Haro, J.M., Vilagut, G., Bromet, E.J., Gluzman, S., Webb, C., Kessler, R.C., Merikangas, K.R., Anthony, J.C., Von Korff, M.R., Wang, P.S., Brugha, T.S., Aguilar-Gaxiola, S., Lee, S., Heeringa, S., Pennell, B.-E., Zaslavsky, A.M., Ustun, T.B., Chatterji, S., WHO World Mental Health Survey Consortium, 2004. Prevalence, severity, and unmet need for treatment of mental disorders in the World Health Organization World Mental Health Surveys. JAMA 291, 2581–2590. https://doi.org/10.1001/jama.291.21.2581.
Dick, D.M., 2011. Gene-environment interaction in psychological traits and disorders. Annu. Rev. Clin. Psychol. 7, 383–409. https://doi.org/10.1146/annurev-clinpsy-032210-104518.
Doischer, D., Hosp, J.A., Yanagawa, Y., Obata, K., Jonas, P., Vida, I., Bartos, M., 2008. Postnatal differentiation of basket cells from slow to fast signaling devices. J. Neurosci. Off. J. Soc. Neurosci. 28, 12956–12968. https://doi.org/10.1523/JNEUROSCI.2890-08.2008.
Dorrn, A.L., Yuan, K., Barker, A.J., Schreiner, C.E., Froemke, R.C., 2010. Developmental sensory experience balances cortical excitation and inhibition. Nature 465, 932–936. https://doi.org/10.1038/nature09119.
Dreher, J.C., Kohn, P., Kolachana, B., Weinberger, D.R., Berman, K.F., 2009. Variation in dopamine genes influences responsivity of the human reward system. Proc. Natl. Acad. Sci. U. S. A. 106, 617–622.
Duckworth, A.L., Kim, B., Tsukayama, E., 2012. Life stress impairs self-control in early adolescence. Front. Psychol. 3, 608. https://doi.org/10.3389/fpsyg.2012.00608.
Eiland, L., Ramroop, J., Hill, M.N., Manley, J., McEwen, B.S., 2012. Chronic juvenile stress produces corticolimbic dendritic architectural remodeling and modulates emotional behavior in male and female rats. Psychoneuroendocrinology 37, 39–47. https://doi.org/10.1016/j.psyneuen.2011.04.015.
Enwright, J.F., Sanapala, S., Foglio, A., Berry, R., Fish, K.N., Lewis, D.A., 2016. Reduced labeling of parvalbumin neurons and perineuronal nets in the dorsolateral prefrontal cortex of subjects with schizophrenia. Neuropsychopharmacol. Off. Publ. Am. Coll. Neuropsychopharmacol. 41, 2206–2214. https://doi.org/10.1038/npp.2016.24.
Erickson, S.L., Lewis, D.A., 2002. Postnatal development of parvalbumin- and GABA transporter-immunoreactive axon terminals in monkey prefrontal cortex. J. Comp. Neurol. 448, 186–202. https://doi.org/10.1002/cne.10249.
Erisir, A., Harris, J.L., 2003. Decline of the critical period of visual plasticity is concurrent with the reduction of NR2B subunit of the synaptic NMDA receptor in layer 4. J. Neurosci. Off. J. Soc. Neurosci. 23, 5208–5218.
Ernst, M., Nelson, E., Jazbec, S., McClure, E., Monk, C., Leibenluft, E., Blair, R.J.R., Pine, D., 2005. Amygdala and nucleus accumbens in responses to receipt and omission of gains in adults and adolescents. NeuroImage 25, 1279–1291.
Erzurumlu, R.S., Gaspar, P., 2012. Development and critical period plasticity of the barrel cortex. Eur. J. Neurosci. 35, 1540–1553. https://doi.org/10.1111/j.1460-9568.2012.08075.x.
Espinosa, J.S., Stryker, M.P., 2012. Development and plasticity of the primary visual cortex. Neuron 75, 230–249. https://doi.org/10.1016/j.neuron.2012.06.009.
Fagiolini, M., Hensch, T.K., 2000. Inhibitory threshold for critical-period activation in primary visual cortex. Nature 404, 183–186. https://doi.org/10.1038/35004582.
Fagiolini, M., Fritschy, J.-M., Löw, K., Möhler, H., Rudolph, U., Hensch, T.K., 2004. Specific GABAA circuits for visual cortical plasticity. Science 303, 1681–1683. https://doi.org/10.1126/science.1091032.
Faludi, G., Mirnics, K., 2011. Synaptic changes in the brain of subjects with schizophrenia. Int. J. Dev. Neurosci. Off. J. Int. Soc. Dev. Neurosci. 29, 305–309. https://doi.org/10.1016/j.ijdevneu.2011.02.013.
Fields, R.D., 2015. A new mechanism of nervous system plasticity: activity-dependent myelination. Nat. Rev. Neurosci. 16, 756–767. https://doi.org/10.1038/nrn4023.
Fitzgerald, M.L., Mackie, K., Pickel, V.M., 2013. The impact of adolescent social isolation on dopamine D2 and cannabinoid CB1 receptors in the adult rat prefrontal cortex. Neuroscience 235, 40–50. https://doi.org/10.1016/j.neuroscience.2013.01.021.
Flores-Barrera, E., Thomases, D.R., Heng, L.-J., Cass, D.K., Caballero, A., Tseng, K.Y., 2014. Late adolescent expression of GluN2B transmission in the prefrontal cortex is input-specific and requires postsynaptic protein kinase A and D1 dopamine receptor signaling. Biol. Psychiatry 75, 508–516. https://doi.org/10.1016/j.biopsych.2013.07.033.
Frank, M.J., 2005. Dynamic dopamine modulation in the basal ganglia: a neurocomputational account of cognitive deficits in medicated and nonmedicated Parkinsonism. JCogn Neurosci 17, 51–72.
Fries, P., 2005. A mechanism for cognitive dynamics: neuronal communication through neuronal coherence. Trends Cognit. Sci. 9, 474–480. https://doi.org/10.1016/j.tics.2005.08.011.
Fung, S.J., Webster, M.J., Sivagnanasundaram, S., Duncan, C., Elashoff, M., Weickert, C.S., 2010. Expression of interneuron markers in the dorsolateral prefrontal cortex of the developing human and in schizophrenia. Am. J. Psychiatry 167, 1479–1488. https://doi.org/10.1176/appi.ajp.2010.09060784.
Galvan, A., 2010. Adolescent development of the reward system. Front. Hum. Neurosci.
Galvan, A., Hare, T., Voss, H., Glover, G., Casey, B.J., 2007. Risk-taking and the adolescent brain: who is at risk? Dev. Sci. 10, F8–F14.
Gambrill, A.C., Barria, A., 2011. NMDA receptor subunit composition controls synaptogenesis and synapse stabilization. Proc. Natl. Acad. Sci. U. S. A. 108, 5855–5860. https://doi.org/10.1073/pnas.1012676108.
Ganguly, P., Holland, F.H., Brenhouse, H.C., 2015. Functional uncoupling NMDAR NR2A subunit from PSD-95 in the prefrontal cortex: effects on behavioral dysfunction and parvalbumin loss after early-life stress. Neuropsychopharmacology 40, 2666–2675. https://doi.org/10.1038/npp.2015.134.
Geier, C.F., Garver, K., Terwilliger, R., Luna, B., 2009. Development of working memory maintenance. J. Neurophysiol. 101, 84–99.
Geier, C.F., Terwilliger, R., Teslovich, T., Velanova, K., Luna, B., 2010. Immaturities in reward processing and its influence on inhibitory control in adolescence. Cereb. Cortex 20, 1613–1629.
Ghisleni, C., Bollmann, S., Poil, S.-S., Brandeis, D., Martin, E., Michels, L., O'Gorman, R.L., Klaver, P., 2015. Subcortical glutamate mediates the reduction of short-range functional connectivity with age in a developmental cohort. J. Neurosci. 35, 8433–8441. https://doi.org/10.1523/JNEUROSCI.4375-14.2015.
Giedd, J.N., 2004. Structural magnetic resonance imaging of the adolescent brain. Ann. Acad. Med. Sci. 1021, 77–85.
Gilmore, R.O., Johnson, M.H., 1995. Working memory in infancy: six-month-olds' performance on two versions of the oculomotor delayed response task. J. Exp. Child Psychol. 59, 397–418.
Glantz, L.A., Lewis, D.A., 2000. DEcreased dendritic spine density on prefrontal cortical pyramidal neurons in schizophrenia. Arch. Gen. Psychiatry 57, 65–73. https://doi.org/10.1001/archpsyc.57.1.65.
Glasper, E.R., LaMarca, E.A., Bocarsly, M.E., Fasolino, M., Opendak, M., Gould, E., 2015. Sexual experience enhances cognitive flexibility and dendritic spine density in the medial prefrontal cortex. Neurobiol. Learn. Mem. 125, 73–79. https://doi.org/10.1016/j.nlm.2015.07.007.
Gogtay, N., Giedd, J.N., Lusk, L., Hayashi, K.M., Greenstein, D., Vaituzis, A.C., Nugent 3rd, T.F., Herman, D.H., Clasen, L.S., Toga, A.W., Rapoport, J.L., Thompson, P.M., 2004. Dynamic mapping of human cortical development during childhood through early adulthood. Proc. Natl. Acad. Sci. U. S. A. 101, 8174–8179. https://doi.org/10.1073/pnas.0402680101.
Goldman-Rakic, P.S., Brown, R.M., 1982. Postnatal development of monoamine content and synthesis in the cerebral cortex of rhesus monkeys. Brain Res. 256, 339–349.
Gomes, F.V., Grace, A.A., 2017. Prefrontal cortex dysfunction increases susceptibility to schizophrenia-like changes induced by adolescent stress exposure. Schizophr. Bull. 43, 592–600. https://doi.org/10.1093/schbul/sbw156.
Gonzalez-Burgos, G., Hashimoto, T., Lewis, D.A., 2010. Alterations of cortical GABA neurons and network oscillations in schizophrenia. Curr. Psychiatry Rep. 12, 335–344. https://doi.org/10.1007/s11920-010-0124-8.
Gonzalez-Burgos, G., Miyamae, T., Pafundo, D.E., Yoshino, H., Rotaru, D.C., Hoftman, G., Datta, D., Zhang, Y., Hammond, M., Sampson, A.R., Fish, K.N., Ermentrout, G.B., Lewis, D.A., 2014. Functional maturation of GABA synapses during postnatal development of the monkey dorsolateral prefrontal cortex. Cereb. Cortex. https://doi.org/10.1093/cercor/bhu122. bhu122.
Gordon, J.A., Stryker, M.P., 1996. Experience-dependent plasticity of binocular responses in the primary visual cortex of the mouse. J. Neurosci. Off. J. Soc. Neurosci. 16, 3274–3286.
Greenberg, M.E., Xu, B., Lu, B., Hempstead, B.L., 2009. New insights in the biology of BDNF synthesis and release: implications in CNS function. J. Neurosci. Off. J. Soc. Neurosci. 29, 12764–12767. https://doi.org/10.1523/JNEUROSCI.3566-09.2009.
Gruber, A.J., Calhoon, G.G., Shusterman, I., Schoenbaum, G., Roesch, M.R., O'Donnell, P., 2010. More is less: a disinhibited prefrontal cortex impairs cognitive flexibility. J. Neurosci. Off. J. Soc. Neurosci. 30, 17102–17110. https://doi.org/10.1523/JNEUROSCI.4623-10.2010.
Grydeland, H., Walhovd, K.B., Tamnes, C.K., Westlye, L.T., Fjell, A.M., 2013. Intracortical myelin links with performance variability across the human lifespan: results from T1- and T2-weighted MRI myelin mapping and diffusion tensor imaging. J. Neurosci. 33, 18618–18630. https://doi.org/10.1523/JNEUROSCI.2811-13.2013.
Guirado, R., Umemori, J., Sipilä, P., Castrén, E., 2016. Evidence for competition for target innervation in the medial prefrontal cortex. Cereb. Cortex 26, 1287–1294. https://doi.org/10.1093/cercor/bhv280.
Han, X., Wang, W., Xue, X., Shao, F., Li, N., 2011. Brief social isolation in early adolescence affects reversal learning and forebrain BDNF expression in adult rats. Brain Res. Bull. 86, 173–178. https://doi.org/10.1016/j.brainresbull.2011.07.008.
Hanover, J.L., Huang, Z.J., Tonegawa, S., Stryker, M.P., 1999. Brain-derived neurotrophic factor overexpression induces precocious critical period in mouse visual cortex. J. Neurosci. Off. J. Soc. Neurosci. 19 RC40.
Harden, K.P., Tucker-Drob, E.M., 2011. Individual differences in the development of sensation seeking and impulsivity during adolescence: further evidence for a dual systems model. Dev. Psychol. 47, 739–746. https://doi.org/10.1037/a0023279.
Hariri, A.R., 2009. The neurobiology of individual differences in complex behavioral traits. Annu. Rev. Neurosci. 32, 225–247. https://doi.org/10.1146/annurev.neuro.051508.135335.

Hashimoto, T., Nguyen, Q.L., Rotaru, D., Keenan, T., Arion, D., Beneyto, M., Gonzalez-Burgos, G., Lewis, D.A., 2009. Protracted developmental trajectories of GABAA receptor alpha1 and alpha2 subunit expression in primate prefrontal cortex. Biol. Psychiatry 65, 1015–1023. https://doi.org/10.1016/j.biopsych.2009.01.004.

Hayashi, M., Yamashita, A., Shimizu, K., 1997. Somatostatin and brain-derived neurotrophic factor mRNA expression in the primate brain: decreased levels of mRNAs during aging. Brain Res. 749, 283–289. https://doi.org/10.1016/S0006-8993(96)01317-0.

Hensch, T.K., 2004. Critical period regulation. Annu. Rev. Neurosci. 27, 549–579. https://doi.org/10.1146/annurev.neuro.27.070203.144327.

Hensch, T.K., 2005. Critical period plasticity in local cortical circuits. Nat. Rev. Neurosci. 6, 877–888. https://doi.org/10.1038/nrn1787.

Hensch, T.K., Fagiolini, M., 2005. Excitatory–inhibitory balance and critical period plasticity in developing visual cortex. Prog. Brain Res. Development, Dynamics and Pathiology of Neuronal Networks: from Molecules to Functional Circuits Vol. 147. pp. 115–124. https://doi.org/10.1016/S0079-6123(04)47009-5.

Hensch, T.K., Fagiolini, M., Matage, N., Stryker, M.P., Baekkeskov, S., Kash, S.F., 1998. Local GABA circuit control of experience-dependent plasticity in developing visual cortex. Science 282, 1504–1508.

Henson, M.A., Roberts, A.C., Salimi, K., Vadlamudi, S., Hamer, R.M., Gilmore, J.H., Jarskog, L.F., Philpot, B.D., 2008. Developmental regulation of the NMDA receptor subunits, NR3A and NR1, in human prefrontal cortex. Cereb. Cortex N. Y. N 1991 (18), 2560–2573. https://doi.org/10.1093/cercor/bhn017.

Hess, E.J., Bracha, H.S., Kleinman, J.E., Creese, I., 1987. Dopamine receptor subtype imbalance in schizophrenia. Life Sci. 40, 1487–1497.

Hill, R.A., Wu, Y.W.C., Kwek, P., van den Buuse, M., 2012. Modulatory effects of sex steroid hormones on brain-derived neurotrophic factor-tyrosine kinase B expression during adolescent development in C57Bl/6 mice. J. Neuroendocrinol. 24, 774–788. https://doi.org/10.1111/j.1365-2826.2012.02277.x.

Hill, R.A., Kiss Von Soly, S., Ratnayake, U., Klug, M., Binder, M.D., Hannan, A.J., van den Buuse, M., 2014. Long-term effects of combined neonatal and adolescent stress on brain-derived neurotrophic factor and dopamine receptor expression in the rat forebrain. Biochim. Biophys. Acta 1842, 2126–2135. https://doi.org/10.1016/j.bbadis.2014.08.009.

Himmler, B.T., Pellis, S.M., Kolb, B., 2013. Juvenile play experience primes neurons in the medial prefrontal cortex to be more responsive to later experiences. Neurosci. Lett. 556, 42–45. https://doi.org/10.1016/j.neulet.2013.09.061.

Hoftman, G.D., Lewis, D.A., 2011. Postnatal developmental trajectories of neural circuits in the primate prefrontal cortex: identifying sensitive periods for vulnerability to schizophrenia. Schizophr. Bull. 37, 493–503. https://doi.org/10.1093/schbul/sbr029.

Hoftman, G.D., Volk, D.W., Bazmi, H.H., Li, S., Sampson, A.R., Lewis, D.A., 2015. Altered cortical expression of GABA-related genes in schizophrenia: illness progression vs developmental disturbance. Schizophr. Bull. 41, 180–191. https://doi.org/10.1093/schbul/sbt178.

Holland, F.H., Ganguly, P., Potter, D.N., Chartoff, E.H., Brenhouse, H.C., 2014. Early life stress disrupts social behavior and prefrontal cortex parvalbumin interneurons at an earlier time-point in females than in males. Neurosci. Lett. 566, 131–136. https://doi.org/10.1016/j.neulet.2014.02.023.

Honkanen, R., Rouhinen, S., Wang, S.H., Palva, J.M., Palva, S., 2015. Gamma oscillations underlie the maintenance of feature-specific information and the contents of visual working memory. Cereb. Cortex N. Y. N 1991 (25), 3788–3801. https://doi.org/10.1093/cercor/bhu263.

Howard, M.W., Rizzuto, D.S., Caplan, J.B., Madsen, J.R., Lisman, J., Aschenbrenner-Scheibe, R., Schulze-Bonhage, A., Kahana, M.J., 2003. Gamma oscillations correlate with working memory load in humans. Cereb. Cortex N. Y. N 1991 (13), 1369–1374.

Huang, Z.J., Kirkwood, A., Pizzorusso, T., Porciatti, V., Morales, B., Bear, M.F., Maffei, L., Tonegawa, S., 1999. BDNF regulates the maturation of inhibition and the critical period of plasticity in mouse visual cortex. Cell 98, 739–755.

Huang, Z.J., Di Cristo, G., Ango, F., 2007. Development of GABA innervation in the cerebral and cerebellar cortices. Nat. Rev. Neurosci. 8, 673–686.

Hudspeth, W.J., Pribram, K.H., 1992. Psychophysiological indices of cerebral maturation. Int. J. Psychophysiol. 12, 19–29. https://doi.org/10.1016/0167-8760(92)90039-E.

Humphries, M.D., Khamassi, M., Gurney, K., 2012. Dopaminergic control of the exploration-exploitation trade-off via the basal ganglia. Decis. Neurosci. 6, 9. https://doi.org/10.3389/fnins.2012.00009.

Huttenlocher, P.R., 1990. Morphometric study of human cerebral cortex development. Neuropsychologia 28, 517–527.

Hwang, K., Velanova, K., Luna, B., 2010. Strengthening of top-down frontal cognitive control networks underlying the development of inhibitory control: a functional magnetic resonance imaging effective connectivity study. J. Neurosci. 30, 15535–15545.

Hwang, K., Ghuman, A.S., Manoach, D.S., Jones, S.R., Luna, B., 2016. Frontal preparatory neural oscillations associated with cognitive control: a developmental study comparing young adults and adolescents. NeuroImage 136, 139–148. https://doi.org/10.1016/j.neuroimage.2016.05.017.

Insanally, M.N., Köver, H., Kim, H., Bao, S., 2009. Feature-dependent sensitive periods in the development of complex sound representation. J. Neurosci. Off. J. Soc. Neurosci. 29, 5456–5462. https://doi.org/10.1523/JNEUROSCI.5311-08.2009.

Jääskeläinen, E., Juola, P., Hirvonen, N., McGrath, J.J., Saha, S., Isohanni, M., Veijola, J., Miettunen, J., 2013. A systematic review and meta-analysis of recovery in schizophrenia. Schizophr. Bull. 39, 1296–1306. https://doi.org/10.1093/schbul/sbs130.

Jiang, M., Yang, M., Yin, L., Zhang, X., Shu, Y., 2015. Developmental reduction of asynchronous GABA release from neocortical fast-spiking neurons. Cereb. Cortex N. Y. N 1991 (25), 258–270. https://doi.org/10.1093/cercor/bht236.

Johnson, M.H., 1995. The inhibition of automatic saccades in early infancy. Dev. Psychobiol. 28, 281–291.

Kalsbeek, A., Voorn, P., Buijs, R.M., Pool, C.W., Uylings, H.B., 1988. Development of the dopaminergic innervation in the prefrontal cortex of the rat. J. Comp. Neurol. 269, 58–72. https://doi.org/10.1002/cne.902690105.

Kalsbeek, A., Matthijssen, Ma.H., Uylings, H.B.M., 1989. Morphometric analysis of prefrontal cortical development following neonatal lesioning of the dopaminergic mesocortical projection. Exp. Brain Res. 78, 279–289. https://doi.org/10.1007/BF00228899.

Karlsgodt, K.H., Sun, D., Jimenez, A.M., Lutkenhoff, E.S., Willhite, R., van Erp, T.G.M., Cannon, T.D., 2008. Developmental disruptions in neural connectivity in the pathophysiology of schizophrenia. Dev. Psychopathol. 20, 1297–1327. https://doi.org/10.1017/S095457940800062X.

Katagiri, H., Fagiolini, M., Hensch, T.K., 2007. Optimization of somatic inhibition at critical period onset in mouse visual cortex. Neuron 53, 805–812. https://doi.org/10.1016/j.neuron.2007.02.026.

Kilb, W., 2012. Development of the GABAergic System from Birth to Adolescence. Neurosci. 18, 613–630. https://doi.org/10.1177/1073858411422114.

Klein, Z.A., Romeo, R.D., 2013. Changes in hypothalamic–pituitary–adrenal stress responsiveness before and after puberty in rats. Horm. Behav. Puberty Adolesc. 64, 357–363. https://doi.org/10.1016/j.yhbeh.2013.01.012.

Klingberg, T., Forssberg, H., Westerberg, H., 2002. Increased brain activity in frontal and parietal cortex underlies the development of visuospatial working memory capacity during childhood. J. Cognit. Neurosci. 14, 1–10.

Knudsen, E.I., 2004. Sensitive periods in the development of the brain and behavior. J. Cognit. Neurosci. 16, 1412–1425. https://doi.org/10.1162/0898929042304796.

Koob, G.F., Riley, S.J., Smith, S.C., Robbins, T.W., 1978. Effects of 6-hydroxydopamine lesions of the nucleus accumbens septi and olfactory tubercle on feeding, locomotor activity, and amphetamine anorexia in the rat. J. Comp. Physiol. Psychol. 92, 917–927.

Koolschijn, P.C.M.P., Peper, J.S., Crone, E.A., 2014. The influence of sex steroids on structural brain maturation in adolescence. PLoS One 9, e83929. https://doi.org/10.1371/journal.pone.0083929.

Krongold, M., Cooper, C., Bray, S., 2017. Modular development of cortical gray matter across childhood and adolescence. Cereb. Cortex 27, 1125–1136. https://doi.org/10.1093/cercor/bhv307.

Kumari, A., Singh, P., Baghel, M.S., Thakur, M.K., 2016. Social isolation mediated anxiety like behavior is associated with enhanced expression and regulation of BDNF in the female mouse brain. Physiol. Behav. 158, 34–42. https://doi.org/10.1016/j.physbeh.2016.02.032.

Lambe, E.K., Krimer, L.S., Goldman-Rakic, P.S., 2000. Differential postnatal development of catecholamine and serotonin inputs to identified neurons in prefrontal cortex of rhesus monkey. J. Neurosci. 20, 8780–8787.

Larsen, B., Luna, B., 2015. In vivo evidence of neurophysiological maturation of the human adolescent striatum. Dev. Cognit. Neurosci. 12, 74–85. https://doi.org/10.1016/j.dcn.2014.12.003.

Le Moal, M., Simon, H., 1991. Mesocorticolimbic dopaminergic network: functional and regulatory roles. Physiol. Rev. 71, 155–234.

Lebel, C., Gee, M., Camicioli, R., Wieler, M., Martin, W., Beaulieu, C., 2012. Diffusion tensor imaging of white matter tract evolution over the lifespan. NeuroImage 60, 340–352. https://doi.org/10.1016/j.neuroimage.2011.11.094.

LeBlanc, J.J., Fagiolini, M., 2011. Autism: a “critical period” disorder? Neural Plast., 921680. https://doi.org/10.1155/2011/921680.

Leslie, C.A., Robertson, M.W., Cutler, A.J., Bennett, J.P., 1991. Postnatal development of D1 dopamine receptors in the medial prefrontal cortex, striatum and nucleus accumbens of normal and neonatal 6-hydroxydopamine treated rats: a quantitative autoradiographic analysis. Brain Res. Dev. Brain Res. 62, 109–114.

Leussis, M.P., Lawson, K., Stone, K., Andersen, S.L., 2008. The enduring effects of an adolescent social stressor on synaptic density, part II: poststress reversal of synaptic loss in the cortex by adinazolam and MK-801. Synap. N. Y. N 62, 185–192. https://doi.org/10.1002/syn.20483.

Levelt, C.N., Hübener, M., 2012. Critical-period plasticity in the visual cortex. Annu. Rev. Neurosci. 35, 309–330. https://doi.org/10.1146/annurev-neuro-061010-113813.

Lewis, D.A., Hashimoto, T., Volk, D.W., 2005. Cortical inhibitory neurons and schizophrenia. Nat. Rev. Neurosci. 6, 312–324. https://doi.org/10.1038/nrn1648.

Lidow, M.S., Rakic, P., 1992. Scheduling of monoaminergic neurotransmitter receptor expression in the primate neocortex during postnatal development. Cereb. Cortex 2 (5), 401–416.

Lidow, M.S., Goldman-Rakic, P.S., Gallager, D.W., Rakic, P., 1991. Distribution of dopaminergic receptors in the primate cerebral cortex: Quantitative autoradiographic analysis using [3H]raclopride, [3H]spiperone and [3H]sch23390. Neuroscience 40, 657–671.

Long, M.A., Cruikshank, S.J., Jutras, M.J., Connors, B.W., 2005. Abrupt maturation of a spike-synchronizing mechanism in neocortex. J. Neurosci. Off. J. Soc. Neurosci. 25, 7309–7316. https://doi.org/10.1523/JNEUROSCI.0375-05.2005.

Luciana, M., Wahlstrom, D., Porter, J.N., Collins, P.F., 2012. Dopaminergic modulation of incentive motivation in adolescence: age-related changes in signaling, individual differences, and implications for the development of self-regulation. Dev. Psychol. 48, 844–861. https://doi.org/10.1037/a0027432.

Luna, B., 2004. Algebra and the adolescent brain. Trends Cognit. Sci. 8 (10), 437–439.

Luna, B., Garver, K.E., Urban, T.A., Lazar, N.A., Sweeney, J.A., 2004. Maturation of cognitive processes from late childhood to adulthood. Child Dev. 75, 1357–1372.

Luna, B., Padmanabhan, A., O’Hearn, K., 2010. What has fMRI told us about the development of cognitive control through adolescence? Brain Cognit. 72, 101–113. https://doi.org/10.1016/j.bandc.2009.08.005.

Luna, B., Marek, S., Larsen, B., Tervo-Clemmens, B., Chahal, R., 2015. An integrative model of the maturation of cognitive control. Annu. Rev. Neurosci. 38, 151–170.

https://doi.org/10.1146/annurev-neuro-071714-034054.
Luoni, A., Berry, A., Calabrese, F., Capoccia, S., Bellisario, V., Gass, P., Cirulli, F., Riva, M.A., 2014. Delayed BDNF alterations in the prefrontal cortex of rats exposed to prenatal stress: preventive effect of lurasidone treatment during adolescence. Eur. Neuropsychopharmacol. J. Eur. Coll. Neuropsychopharmacol. 24, 986–995. https://doi.org/10.1016/j.euroneuro.2013.12.010.
Makinodan, M., Rosen, K.M., Ito, S., Corfas, G., 2012. A critical period for social experience–dependent oligodendrocyte maturation and myelination. Science 337, 1357–1360. https://doi.org/10.1126/science.1220845.
Malenka, R.C., Bear, M.F., 2004. LTP and LTD: an embarrassment of riches. Neuron 44, 5–21. https://doi.org/10.1016/j.neuron.2004.09.012.
Marek, S., Hwang, K., Foran, W., Hallquist, M.N., Luna, B., 2015. The contribution of network organization and integration to the development of cognitive control. PLoS Biol. 13, e1002328. https://doi.org/10.1371/journal.pbio.1002328.
Mastwal, S., Ye, Y., Ren, M., Jimenez, D.V., Martinowich, K., Gerfen, C.R., Wang, K.H., 2014. Phasic dopamine neuron activity elicits unique mesofrontal plasticity in adolescence. J. Neurosci. 34, 9484–9496. https://doi.org/10.1523/JNEUROSCI.1114-14.2014.
Mauney, S.A., Athanas, K.M., Pantazopoulos, H., Shaskan, N., Passeri, E., Berretta, S., Woo, T.-U.W., 2013. Developmental pattern of perineuronal nets in the human prefrontal cortex and their deficit in schizophrenia. Biol. Psychiatry 74, 427–435. https://doi.org/10.1016/j.biopsych.2013.05.007.
McCrae, R.R., Costa, P.T., Terracciano, A., Parker, W.D., Mills, C.J., De Fruyt, F., Mervielde, I., 2002. Personality trait development from age 12 to age 18: longitudinal, cross-sectional, and cross-cultural analyses. J. Pers. Soc. Psychol. 83, 1456–1468.
McEwen, B.S., Morrison, J.H., 2013. The brain on stress: vulnerability and plasticity of the prefrontal cortex over the life course. Neuron 79, 16–29. https://doi.org/10.1016/j.neuron.2013.06.028.
McGee, A.W., Yang, Y., Fischer, Q.S., Daw, N.W., Strittmatter, S.M., 2005. Experience-driven plasticity of visual cortex limited by myelin and nogo receptor. Science 309, 2222–2226. https://doi.org/10.1126/science.1114362.
McIntosh, A.R., Kovacevic, N., Itier, R.J., 2008. Increased brain signal variability accompanies lower behavioral variability in development. PLoS Comput. Biol. 4. https://doi.org/10.1371/journal.pcbi.1000106.
McRae, P.A., Rocco, M.M., Kelly, G., Brumberg, J.C., Matthews, R.T., 2007. Sensory deprivation alters aggrecan and perineuronal net expression in the mouse barrel cortex. J. Neurosci. Off. J. Soc. Neurosci. 27, 5405–5413. https://doi.org/10.1523/JNEUROSCI.5425-06.2007.
Meng, Q., Li, N., Han, X., Shao, F., Wang, W., 2011. Effects of adolescent social isolation on the expression of brain-derived neurotrophic factors in the forebrain. Eur. J. Pharmacol. 650, 229–232. https://doi.org/10.1016/j.ejphar.2010.09.061.
Micheva, K.D., Beaulieu, C., 1997. Development and plasticity of the inhibitory neocortical circuitry with an emphasis on the rodent barrel field cortex: a review. Can. J. Physiol. Pharmacol. 75, 470–478.
Miller, D.J., Duka, T., Stimpson, C.D., Schapiro, S.J., Baze, W.B., McArthur, M.J., Fobbs, A.J., Sousa, A.M.M., Sestan, N., Wildman, D.E., Lipovich, L., Kuzawa, C.W., Hof, P.R., Sherwood, C.C., 2012. Prolonged myelination in human neocortical evolution. Proc. Natl. Acad. Sci. U. S. A. 109, 16480–16485. https://doi.org/10.1073/pnas.1117943109.
Mirenowicz, J., Schultz, W., 1996. Preferential activation of midbrain dopamine neurons by appetitive rather than aversive stimuli. Nature 379, 449–451. https://doi.org/10.1038/379449a0.
Mizuno, K., Carnahan, J., Nawa, H., 1994. Brain-derived neurotrophic factor promotes differentiation of striatal GABAergic neurons. Dev. Biol. 165, 243–256. https://doi.org/10.1006/dbio.1994.1250.
Montez, D.F., Calabro, F.J., Luna, B., 2017. The expression of established cognitive brain states stabilizes with working memory development. eLife 6, e25606. https://doi.org/10.7554/eLife.25606.
Morales, M., Spear, L.P., 2014. The effects of an acute challenge with the NMDA receptor antagonists, MK-801, PEAQX, and ifenprodil, on social inhibition in adolescent and adult male rats. Psychopharmacology (Berl.) 231, 1797–1807. https://doi.org/10.1007/s00213-013-3278-3.
Morales, B., Choi, S.-Y., Kirkwood, A., 2002. Dark rearing alters the development of GABAergic transmission in visual cortex. J. Neurosci. Off. J. Soc. Neurosci. 22, 8084–8090.
Mower, G.D., 1991. The effect of dark rearing on the time course of the critical period in cat visual cortex. Brain Res. Dev. Brain Res. 58, 151–158.
Murty, V.P., Calabro, F., Luna, B., 2016. The role of experience in adolescent cognitive development: integration of executive, memory, and mesolimbic systems. Neurosci. Biobehav. Rev. 70, 46–58. https://doi.org/10.1016/j.neubiorev.2016.07.034.
Nabel, E.M., Morishita, H., 2013. Regulating critical period plasticity: insight from the visual system to fear circuitry for therapeutic interventions. Front. Psychiatry 4, 146. https://doi.org/10.3389/fpsyt.2013.00146.
Nguyen, T.-V., McCracken, J., Ducharme, S., Botteron, K.N., Mahabir, M., Johnson, W., Israel, M., Evans, A.C., Karama, S., 2013. Testosterone-related cortical maturation across childhood and adolescence. Cereb. Cortex 23, 1424–1432. https://doi.org/10.1093/cercor/bhs125.
Niessing, J., Ebisch, B., Schmidt, K.E., Niessing, M., Singer, W., Galuske, R.A., 2005. Hemodynamic signals correlate tightly with synchronized gamma oscillations. Science 309, 948–951.
O'Donnell, P., 2003. Dopamine gating of forebrain neural ensembles. Eur. J. Neurosci. 17, 429–435.
O'Donnell, P., 2010. Adolescent maturation of cortical dopamine. Neurotox. Res. 18, 306–312. https://doi.org/10.1007/s12640-010-9157-3.
O'Donnell, P., 2012. Cortical interneurons, immune factors and oxidative stress as early targets for schizophrenia. Eur. J. Neurosci. 35, 1866–1870. https://doi.org/10.1111/j.1460-9568.2012.08130.x.
O'Hare, E.D., Lu, L.H., Houston, S.M., Bookheimer, S.Y., Sowell, E.R., 2008. Neurodevelopmental changes in verbal working memory load-dependency: an fMRI investigation. NeuroImage 42, 1678–1685. https://doi.org/10.1016/j.neuroimage.2008.05.057.
Østby, Y., Tamnes, C.K., Fjell, A.M., Walhovd, K.B., 2011. Morphometry and connectivity of the fronto-parietal verbal working memory network in development. Neuropsychologia 49, 3854–3862. https://doi.org/10.1016/j.neuropsychologia.2011.10.001.
Ojemann, G.A.M., Ramsey, N.F.P., Ojemann, J.M.D., 2013. Relation between functional magnetic resonance imaging (fMRI) and single neuron, local field potential (LFP) and electrocorticography (ECoG) activity in human cortex. Front. Hum. Neurosci. 7, 34. https://doi.org/10.3389/fnhum.2013.00034.
Ordaz, S.J., Foran, W., Velanova, K., Luna, B., 2013. Longitudinal growth curves of brain function underlying inhibitory control through adolescence. J. Neurosci. Off. J. Soc. Neurosci. 33, 18109–18124. https://doi.org/10.1523/JNEUROSCI.1741-13.2013.
Padmanabhan, A., Luna, B., 2014. Developmental imaging genetics: linking dopamine function to adolescent behavior. Brain Cognit. 89, 27–38. https://doi.org/10.1016/j.bandc.2013.09.011.
Panksepp, J., 1981. The ontogeny of play in rats. Dev. Psychobiol. 14, 327–332. https://doi.org/10.1002/dev.420140405.
Paus, T., Keshavan, M., Giedd, J.N., 2008. Why do many psychiatric disorders emerge during adolescence? Nat. Rev. Neurosci. 9, 947–957. https://doi.org/10.1038/nrn2513.
Paylor, J.W., Lins, B.R., Greba, Q., Moen, N., Moraes, R.S., de, Howland, J.G., Winship, I.R., 2016. Developmental disruption of perineuronal nets in the medial prefrontal cortex after maternal immune activation. Sci. Rep. 6https://doi.org/10.1038/srep37580. srep37580.
Penfield, W., Roberts, L., 1959. Speech and Brain Mechanisms, Speech and Brain Mechanisms. Princeton University Press, Princeton, NJ, US.
Petanjek, Z., Judaš, M., Šimić, G., Rašin, M.R., Uylings, H.B.M., Rakic, P., Kostović, I., 2011. Extraordinary neoteny of synaptic spines in the human prefrontal cortex. Proc. Natl. Acad. Sci. 108, 13281–13286. https://doi.org/10.1073/pnas.1105108108.
Peters, Y.M., O'Donnell, P., 2005. Social isolation rearing affects prefrontal cortical response to ventral tegmental area stimulation. Biol. Psychiatry 57, 1205–1208. https://doi.org/10.1016/j.biopsych.2005.02.011.
Piekarski, D.J., Boivin, J.R., Wilbrecht, L., 2017a. Ovarian hormones organize the maturation of inhibitory neurotransmission in the frontal cortex at puberty onset in female mice. Curr. Biol. CB 27, 1735–1745. https://doi.org/10.1016/j.cub.2017.05.027. e3.
Piekarski, D.J., Johnson, C.M., Boivin, J.R., Thomas, A.W., Lin, W.C., Delevich, K., Galarce, M., Wilbrecht, L., 2017b. Does puberty mark a transition in sensitive periods for plasticity in the associative neocortex? Brain Res. 1654, 123–144. https://doi.org/10.1016/j.brainres.2016.08.042.
Pinto, L., Dan, Y., 2015. Cell-type-specific activity in prefrontal cortex during goal-directed behavior. Neuron 87, 437–450. https://doi.org/10.1016/j.neuron.2015.06.021.
Pizzorusso, T., Medini, P., Berardi, N., Chierzi, S., Fawcett, J.W., Maffei, L., 2002. Reactivation of ocular dominance plasticity in the adult visual cortex. Science 298, 1248–1251. https://doi.org/10.1126/science.1072699.
Porter, L.L., Rizzo, E., Hornung, J.P., 1999. Dopamine affects parvalbumin expression during cortical development in vitro. J. Neurosci. Off. J. Soc. Neurosci. 19, 8990–9003.
Pouille, F., Scanziani, M., 2001. Enforcement of temporal fidelity in pyramidal cells by somatic feed-forward inhibition. Science 293, 1159–1163. https://doi.org/10.1126/science.1060342.
Prusky, G.T., Douglas, R.M., 2003. Developmental plasticity of mouse visual acuity. Eur. J. Neurosci. 17, 167–173. https://doi.org/10.1046/j.1460-9568.2003.02420.x.
Purves-Tyson, T.D., Allen, K., Fung, S., Rothmond, D., Noble, P.L., Handelsman, D.J., Shannon Weickert, C., 2015. Adolescent testosterone influences BDNF and TrkB mRNA and neurotrophin-interneuron marker relationships in mammalian frontal cortex. Schizophr. Res. 168, 661–670. https://doi.org/10.1016/j.schres.2015.05.040.
Rapoport, J.L., Giedd, J.N., Gogtay, N., 2012. Neurodevelopmental model of schizophrenia: update 2012. Mol. Psychiatry 17, 1228–1238. https://doi.org/10.1038/mp.2012.23.
Raznahan, A., Lerch, J.P., Lee, N., Greenstein, D., Wallace, G.L., Stockman, M., Clasen, L., Shaw, P.W., Giedd, J.N., 2011. Patterns of coordinated anatomical change in human cortical development: a longitudinal neuroimaging study of maturational coupling. Neuron 72, 873–884. https://doi.org/10.1016/j.neuron.2011.09.028.
Raznahan, A., Shaw, P.W., Lerch, J.P., Clasen, L.S., Greenstein, D., Berman, R., Pipitone, J., Chakravarty, M.M., Giedd, J.N., 2014. Longitudinal four-dimensional mapping of subcortical anatomy in human development. Proc. Natl. Acad. Sci. 111, 1592–1597. https://doi.org/10.1073/pnas.1316911111.
Reynolds, J.N.J., Wickens, J.R., 2002. Dopamine-dependent plasticity of corticostriatal synapses. Neural Netw. 15, 507–521. https://doi.org/10.1016/S0893-6080(02)00045-X.
Reynolds, L.M., Makowski, C.S., Yogendran, S.V., Kiessling, S., Cermakian, N., Flores, C., 2015. Amphetamine in adolescence disrupts the development of medial prefrontal cortex dopamine connectivity in a DCC-dependent manner. Neuropsychopharmacol. Off. Publ. Am. Coll. Neuropsychopharmacol. 40, 1101–1112. https://doi.org/10.1038/npp.2014.287.
Roberts, A.C., Díez-García, J., Rodriguiz, R.M., López, I.P., Luján, R., Martínez-Turrillas, R., Picó, E., Henson, M.A., Bernardo, D.R., Jarrett, T.M., Clendeninn, D.J., López-Mascaraque, L., Feng, G., Lo, D.C., Wesseling, J.F., Wetsel, W.C., Philpot, B.D., Pérez-

Otaño, I., 2009. Downregulation of NR3A-containing NMDARs is required for synapse maturation and memory consolidation. Neuron 63, 342–356. https://doi.org/10.1016/j.neuron.2009.06.016.
Roceri, M., Cirulli, F., Pessina, C., Peretto, P., Racagni, G., Riva, M.A., 2004. Postnatal repeated maternal deprivation produces age-dependent changes of brain-derived neurotrophic factor expression in selected rat brain regions. Biol. Psychiatry 55, 708–714. https://doi.org/10.1016/j.biopsych.2003.12.011.
Rosenberg, D.R., Lewis, D.A., 1994. Changes in the dopaminergic innervation of monkey prefrontal cortex during late postnatal development: a tyrosine hydroxylase immunohistochemical study. Biol. Psychiatry 36, 272–277.
Rosenberg, D.R., Lewis, D.A., 1995. Postnatal maturation of the dopaminergic innervation of monkey prefrontal and motor cortices: a tyrosine hydroxylase immunohistochemical analysis. J. Comp. Neurol. 358, 383–400. https://doi.org/10.1002/cne.903580306.
Roux, F., Wibral, M., Mohr, H.M., Singer, W., Uhlhaas, P.J., 2012. Gamma-band activity in human prefrontal cortex codes for the number of relevant items maintained in working memory. J. Neurosci. Off. J. Soc. Neurosci. 32, 12411–12420. https://doi.org/10.1523/JNEUROSCI.0421-12.2012.
Rudy, B., Fishell, G., Lee, S., Hjerling-Leffler, J., 2011. Three groups of interneurons account for nearly 100% of neocortical GABAergic neurons. Dev. Neurobiol. 71, 45–61. https://doi.org/10.1002/dneu.20853.
Rutter, M., 2013. Annual research review: resilience–clinical implications. J. Child Psychol. Psychiatry 54, 474–487. https://doi.org/10.1111/j.1469-7610.2012.02615.x.
Santos, F.J., Oliveira, R.F., Jin, X., Costa, R.M., 2015. Corticostriatal dynamics encode the refinement of specific behavioral variability during skill learning. eLife 4, e09423. https://doi.org/10.7554/eLife.09423.
Satterthwaite, T.D., Wolf, D.H., Erus, G., Ruparel, K., Elliott, M.A., Gennatas, E.D., Hopson, R., Jackson, C., Prabhakaran, K., Bilker, W.B., Calkins, M.E., Loughead, J., Smith, A., Roalf, D.R., Hakonarson, H., Verma, R., Davatzikos, C., Gur, R.C., Gur, R.E., 2013. Functional maturation of the executive system during adolescence. J. Neurosci. Off. J. Soc. Neurosci. 33, 16249–16261. https://doi.org/10.1523/JNEUROSCI.2345-13.2013.
Schlegel, A., Barry III, H., 1991. Adolescence: an Anthropological Inquiry. Free Press, New York, NY, US.
Scholl, B., Pattadkal, J.J., Dilly, G.A., Priebe, N.J., Zemelman, B.V., 2015. Local integration accounts for weak selectivity of mouse neocortical parvalbumin interneurons. Neuron 87, 424–436. https://doi.org/10.1016/j.neuron.2015.06.030.
Schultz, W., Dayan, P., Montague, P.R., 1997. A neural substrate of prediction and reward. Science 275, 1593–1599.
Selemon, L.D., 2013. A role for synaptic plasticity in the adolescent development of executive function. Transl. Psychiatry 3, e238. https://doi.org/10.1038/tp.2013.7.
Shafee, R., Buckner, R.L., Fischl, B., 2015. Gray matter myelination of 1555 human brains using partial volume corrected MRI images. NeuroImage 105, 473–485. https://doi.org/10.1016/j.neuroimage.2014.10.054.
Shao, F., Han, X., Shao, S., Wang, W., 2013. Adolescent social isolation influences cognitive function in adult rats. Neural Regen. Res. 8, 1025–1030. https://doi.org/10.3969/j.issn.1673-5374.2013.11.008.
Shepard, R., Page, C.E., Coutellier, L., 2016. Sensitivity of the prefrontal GABAergic system to chronic stress in male and female mice: relevance for sex differences in stress-related disorders. Neuroscience 332, 1–12. https://doi.org/10.1016/j.neuroscience.2016.06.038.
Shulman, E.P., Smith, A.R., Silva, K., Icenogle, G., Duell, N., Chein, J., Steinberg, L., 2016. The dual systems model: review, reappraisal, and reaffirmation. Dev. Cognit. Neurosci. 17, 103–117. https://doi.org/10.1016/j.dcn.2015.12.010.
Silveri, M.M., Sneider, J.T., Crowley, D.J., Covell, M.J., Acharya, D., Rosso, I.M., Jensen, J.E., 2013. Frontal lobe γ-aminobutyric acid levels during adolescence: associations with impulsivity and response inhibition. Biol. Psychiatry, Depression: Risk, Rhythms, and Response Vol. 74. pp. 296–304. https://doi.org/10.1016/j.biopsych.2013.01.033.
Simmonds, D.J., Hallquist, M.N., Asato, M., Luna, B., 2014. Developmental stages and sex differences of white matter and behavioral development through adolescence: a longitudinal diffusion tensor imaging (DTI) study. NeuroImage 92, 356–368. https://doi.org/10.1016/j.neuroimage.2013.12.044.
Simmonds, D.J., Hallquist, M.N., Luna, B., 2017. Protracted development of executive and mnemonic brain systems underlying working memory in adolescence: A longitudinal fMRI study. NeuroImage. https://doi.org/10.1016/j.neuroimage.2017.01.016.
Snyder, K.P., Barry, M., Valentino, R.J., 2014. Cognitive impact of social stress and coping strategy throughout development. Psychopharmacology (Berl.) 232, 185–195. https://doi.org/10.1007/s00213-014-3654-7.
Sohrabji, F., Lewis, D.K., 2006. Estrogen–BDNF interactions: implications for neurodegenerative diseases. Front. Neuroendocrinol. Estrogen Growth Fact. Brain Funct. 27, 404–414. https://doi.org/10.1016/j.yfrne.2006.09.003.
Sowell, E.R., Thompson, P.M., Holmes, C.J., Jernigan, T.L., Toga, A.W., 1999. In vivo evidence for post-adolescent brain maturation in frontal and striatal regions. Nat. Neurosci. 2, 859–861.
Sowell, E.R., Thompson, P.M., Toga, A.W., 2004. Mapping changes in the human cortex throughout the span of life. Neuroscientist 10, 372–392.
Spear, L.P., 2000. Neurobehavioral changes in adolescence. Curr. Dir. Psychol. Sci. 9, 111–114.
Spinka, M., Newberry, R.C., Bekoff, M., 2001. Mammalian play: training for the unexpected. Q. Rev. Biol. 76, 141–168.
Stansfield, K.H., Kirstein, C.L., 2006. Effects of novelty on behavior in the adolescent and adult rat. Dev. Psychobiol. 48, 10–15. https://doi.org/10.1002/dev.20127.
Steinberg, L., 2008. A social neuroscience perspective on adolescent risk-taking. Dev. Rev. 28, 78–106.
Steullet, P., Cabungcal, J.-H., Cuénod, M., Do, K.Q., 2014. Fast oscillatory activity in the anterior cingulate cortex: dopaminergic modulation and effect of perineuronal net loss. Front. Cell. Neurosci. 8, 244. https://doi.org/10.3389/fncel.2014.00244.
Sturman, D.A., Moghaddam, B., 2011. The neurobiology of adolescence: changes in brain architecture, functional dynamics, and behavioral tendencies. Neurosci. Biobehav. Rev. 35, 1704–1712. https://doi.org/10.1016/j.neubiorev.2011.04.003.
Sugiyama, S., Di Nardo, A.A., Aizawa, S., Matsuo, I., Volovitch, M., Prochiantz, A., Hensch, T.K., 2008. Experience-dependent transfer of Otx2 homeoprotein into the visual cortex activates postnatal plasticity. Cell 134, 508–520. https://doi.org/10.1016/j.cell.2008.05.054.
Sur, M., Nagakura, I., Chen, N., Sugihara, H., 2013. Mechanisms of plasticity in the developing and adult visual cortex. Prog. Brain Res. 207, 243–254. https://doi.org/10.1016/B978-0-444-63327-9.00002-3.
Takesian, A.E., Hensch, T.K., 2013. Balancing plasticity/stability across brain development. Prog. Brain Res. 207, 3–34. https://doi.org/10.1016/B978-0-444-63327-9.00001-1.
Tamnes, C.K., Fjell, A.M., Westlye, L.T., Østby, Y., Walhovd, K.B., 2012. Becoming consistent: developmental reductions in intraindividual variability in reaction time are related to white matter integrity. J. Neurosci. 32, 972–982. https://doi.org/10.1523/JNEUROSCI.4779-11.2012.
Tarazi, F.I., Baldessarini, R.J., 2000. Comparative postnatal development of dopamine D (1), D(2) and D(4) receptors in rat forebrain. Int. J. Dev. Neurosci. 18, 29–37.
Tarazi, F.I., Tomasini, E.C., Baldessarini, R.J., 1998. Postnatal development of dopamine D4-like receptors in rat forebrain regions: comparison with D2-like receptors. Brain Res. Dev. Brain Res. 110, 227–233.
Telzer, E.H., 2016. Dopaminergic reward sensitivity can promote adolescent health: a new perspective on the mechanism of ventral striatum activation. Dev. Cognit. Neurosci. 17, 57–67. https://doi.org/10.1016/j.dcn.2015.10.010.
Thomason, M.E., Race, E., Burrows, B., Whitfield-Gabrieli, S., Glover, G.H., Gabrieli, J.D.E., 2009. Development of spatial and verbal working memory capacity in the human brain. J. Cognit. Neurosci. 21, 316–332. https://doi.org/10.1162/jocn.2008.21028.
Toyoizumi, T., Miyamoto, H., Yazaki-Sugiyama, Y., Atapour, N., Hensch, T.K., Miller, K.D., 2013. A theory of the transition to critical period plasticity: inhibition selectively suppresses spontaneous activity. Neuron 80, 51–63. https://doi.org/10.1016/j.neuron.2013.07.022.
Tseng, K.Y., O'Donnell, P., 2004. Dopamine-glutamate interactions controlling prefrontal cortical pyramidal cell excitability involve multiple signaling mechanisms. J. Neurosci. 24, 5131–5139.
Tseng, K.Y., O'Donnell, P., 2005. Post-pubertal emergence of prefrontal cortical up states induced by D1-NMDA co-activation. Cereb. Cortex 15, 49–57.
Tseng, K.Y., O'Donnell, P., 2007. Dopamine modulation of prefrontal cortical interneurons changes during adolescence. Cereb. Cortex 17, 1235–1240.
Tucker, D.M., Poulsen, C., Luu, P., 2015. Critical periods for the neurodevelopmental processes of externalizing and internalizing. Dev. Psychopathol. 27, 321–346. https://doi.org/10.1017/S0954579415000024.
Uhlhaas, P.J., Singer, W., 2011. The development of neural synchrony and large-scale cortical networks during adolescence: relevance for the pathophysiology of schizophrenia and neurodevelopmental hypothesis. Schizophr. Bull. 37, 514–523. https://doi.org/10.1093/schbul/sbr034.
Uhlhaas, P.J., Roux, F., Singer, W., Haenschel, C., Sireteanu, R., Rodriguez, E., 2009. The development of neural synchrony reflects late maturation and restructuring of functional networks in humans. Proc. Natl. Acad. Sci. U. S. A. 106, 9866–9871.
Uhlhaas, P.J., Roux, F., Rodriguez, E., Rotarska-Jagiela, A., Singer, W., 2010. Neural synchrony and the development of cortical networks. Trends Cognit. Sci. 14, 72–80.
van Kerkhof, L.W., Damsteegt, R., Trezza, V., Voorn, P., Vanderschuren, L.J., 2013. Social play behavior in adolescent rats is mediated by functional activity in medial prefrontal cortex and striatum. Neuropsychopharmacology 38, 1899–1909. https://doi.org/10.1038/npp.2013.83.
Wahlstrom, D., Collins, P., White, T., Luciana, M., 2010. Developmental changes in dopamine neurotransmission in adolescence: behavioral implications and issues in assessment. Brain Cognit. 72, 146–159. https://doi.org/10.1016/j.bandc.2009.10.013.
Walhovd, K.B., Tamnes, C.K., Bjørnerud, A., Due-Tønnessen, P., Holland, D., Dale, A.M., Fjell, A.M., 2014. Maturation of cortico-subcortical structural networks—segregation and overlap of medial temporal and fronto-striatal systems in development. Cereb. Cortex. https://doi.org/10.1093/cercor/bht424. bht424.
Wang, X.H., Jenkins, A.O., Choi, L., Murphy, E.H., 1996. Altered neuronal distribution of parvalbumin in anterior cingulate cortex of rabbits exposed in utero to cocaine. Exp. Brain Res. 112, 359–371.
Wang, Y.-C., Ho, U.-C., Ko, M.-C., Liao, C.-C., Lee, L.-J., 2012. Differential neuronal changes in medial prefrontal cortex, basolateral amygdala and nucleus accumbens after postweaning social isolation. Brain Struct. Funct. 217, 337–351. https://doi.org/10.1007/s00429-011-0355-4.
Webster, M.J., Weickert, C.S., Herman, M.M., Kleinman, J.E., 2002. BDNF mRNA expression during postnatal development, maturation and aging of the human prefrontal cortex. Brain Res. Dev. Brain Res. 139, 139–150.
Weickert, C.S., Webster, M.J., Gondipalli, P., Rothmond, D., Fatula, R.J., Herman, M.M., Kleinman, J.E., Akil, M., 2007. Postnatal alterations in dopaminergic markers in the human prefrontal cortex. Neuroscience 144, 1109–1119.
Weickert, C.S., Fung, S.J., Catts, V.S., Schofield, P.R., Allen, K.M., Moore, L.T., Newell, K.A., Pellen, D., Huang, X.-F., Catts, S.V., Weickert, T.W., 2013. Molecular evidence of N-methyl-D-aspartate receptor hypofunction in schizophrenia. Mol. Psychiatry 18, 1185–1192. https://doi.org/10.1038/mp.2012.137.
Wieck, A., Andersen, S.L., Brenhouse, H.C., 2013. Evidence for a neuroinflammatory mechanism in delayed effects of early life adversity in rats: relationship to cortical NMDA receptor expression. Brain Behav. Immun. 28, 218–226. https://doi.org/10.

1016/j.bbi.2012.11.012.
Wiesel, T.N., Hubel, D.H., 1963. Single-cell responses in striate cortex of kittens deprived of vision in one eye. J. Neurophysiol. 26, 1003–1017.
Willing, J., Cortes, L.R., Brodsky, J.M., Kim, T., Juraska, J.M., 2017. Innervation of the medial prefrontal cortex by tyrosine hydroxylase immunoreactive fibers during adolescence in male and female rats. Dev. Psychobiol. 59, 583–589. https://doi.org/10.1002/dev.21525.
Xu, H., Zhang, Y., Zhang, F., Yuan, S., Shao, F., Wang, W., 2016. Effects of duloxetine treatment on cognitive flexibility and BDNF expression in the mPFC of adult male mice exposed to social stress during adolescence. Front. Mol. Neurosci. 9. https://doi.org/10.3389/fnmol.2016.00095.
Yakovlev, P.I., Lecours, A.R., Minkowski, A., 1967. The myelogenetic cycles of regional maturation of the brain. Regional Development of the Brain in Early Life. Blackwell Scientific, Oxford, pp. 3–70.
Yamamoto, J., Suh, J., Takeuchi, D., Tonegawa, S., 2014. Successful execution of working memory linked to synchronized high-frequency gamma oscillations. Cell 157, 845–857. https://doi.org/10.1016/j.cell.2014.04.009.
Yang, E.-J., Lin, E.W., Hensch, T.K., 2012. Critical period for acoustic preference in mice. Proc. Natl. Acad. Sci. U. S. A. 109 (Suppl. 2), 17213–17220. https://doi.org/10.1073/pnas.1200705109.
Zald, D.H., Cowan, R.L., Riccardi, P., Baldwin, R.M., Ansari, M.S., Li, R., Shelby, E.S., Smith, C.E., McHugo, M., Kessler, R.M., 2008. Midbrain dopamine receptor availability is inversely associated with novelty-seeking traits in humans. J. Neurosci. Off. J. Soc. Neurosci. 28, 14372–14378. https://doi.org/10.1523/JNEUROSCI.2423-08.2008.
Zehr, J.L., Van Meter, P.E., Wallen, K., 2005. Factors regulating the timing of puberty onset in female rhesus monkeys (*Macaca mulatta*): role of prenatal androgens, social rank, and adolescent body weight. Biol. Reprod. 72, 1087–1094. https://doi.org/10.1095/biolreprod.104.027755.
Zhang, Z., Jiao, Y.-Y., Sun, Q.-Q., 2011. Developmental maturation of excitation and inhibition balance in principal neurons across four layers of somatosensory cortex. Neuroscience 174, 10–25. https://doi.org/10.1016/j.neuroscience.2010.11.045.