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Longitudinal structural and functional
brain development in childhood and adolescence

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Abstract

The development of the human brain involves a prolonged course of maturation, enabling us to learn to navigate our complex social environments. Here, we give short introductions to post-mortem and animal studies on postnatal brain development and selected methodological considerations for longitudinal developmental neuroimaging. We then describe typical developmental changes in brain structure and function from childhood to adulthood. We focus on measurements derived from magnetic resonance imaging (MRI) and on longitudinal data. Specifically, we discuss brain structural development based on morphometry and diffusion tensor imaging (DTI) studies, and functional development based on resting-state and task-based functional MRI. Finally, we highlight selected current overarching research questions and argue that an important step in answering these questions is to study individual differences in longitudinal brain development.

Introduction

The brain undergoes profound development from birth to adulthood. Developmental changes range from growth in overall size to subtle functional reorganization and can be observed on a microcellular scale as well as by analysing brain images acquired by Magnetic Resonance Imaging (MRI). The changing nature of the brain during the first two decades of life suggests that environmental inputs could impact developmental trajectories. The concept of brain plasticity refers to the brain's ability and potential to change. This ability is inherent in the brain – that is, the brain is constantly changing in response to the environment. However, the brain is more capable of change during specific periods of life than at others, and it is well known that the developing brain, compared to the adult brain, is most plastic. In this chapter, we first introduce key findings from post-mortem and animal studies on postnatal brain development and discuss selected methodological considerations for MRI studies on human brain development. We then focus on and discuss typical development of brain structure and function from childhood to early adulthood, as well as the cognitive relevance of these changes.

Post-mortem and animal studies

Starting in the womb, and continuing in the first years of life, the brain overproduces synaptic connections between neurons (Huttenlocher 1984). Neurons are located in several parts of the brain, including the cerebral cortex, which forms the thin outer layer of the brain. The process of overproducing synaptic connections between neurons is intrinsically regulated, and is not thought to be influenced by environmental experiences (Huttenlocher and Dabholkar 1997). Different regions of the cerebral cortex demonstrate different trajectories of synaptic overproduction within the first few years, correlating to the overall functionality of that brain region. For example, as visual competency increases between the ages of 2-8 months, so does

the proliferation of connections between brain cells in the region of the cortex that processes vision (Huttenlocher 1984).

As the human brain continues to mature, its overabundance of synaptic connections diminishes, leaving the adult human brain with roughly 60% of the synaptic connections that were present during infancy (Huttenlocher and Dabholkar 1997). The elimination of many of these connections can be influenced by environmental factors. For example, a child who develops amblyopia through congenital strabismus can still attain proper vision through intervention, but only if this intervention occurs before the age of 5 years. The synaptic density in the visual cortex diminishes to adult levels around the age of 5 years, which marks the end of a period of heightened plasticity in the visual system (Huttenlocher 1984). The studies that have identified these sensitive periods where the brain adapts to certain environmental inputs (or the lack of environmental inputs) are largely laboratory studies conducted on animals. While it is possible to measure periods of sensitivity to environmental influences in humans (for example clinical phenomena like interventions for strabismus), the only studies in humans capable of examining the underpinning cellular processes involve collecting samples of post-mortem human brain tissue.

Post-mortem work has also provided evidence that some brain regions continue to gain myelin, a fatty electrically insulating layer around the axons of neurons, into the second and even third decade of life (Benes 1989; Yakovlev and Lecours 1967). Yakovlev and Lecours (1967) theorized that protracted changes in white matter development parallel the changes in behaviour that occur in later stages of development. Although constrained by small sample sizes, these foundational studies challenged prevailing ideas that brain development is complete by early childhood, and spurred subsequent work investigating brain changes

beyond the first decade of life. Comparative studies of primates add to this picture; the human brain undergoes a more prolonged developmental course compared to other species, including primates (Leigh 2004). For example, myelination of the human brain continues beyond adolescence, whereas degree of myelination in the chimpanzee brain reaches adult levels at roughly the same time as the animal becomes sexually mature (Miller et al. 2012). Much of the potential – and many of the vulnerabilities – of our brains will depend on transactional processes between this prolonged maturation and our experiences.

In vivo neuroimaging

Although post-mortem and animal studies took some of the first steps in our understanding of both the microscopic and macroscopic changes occurring in the brain across development, MRI has, in many contexts, become the instrument of choice to measure changes in both brain structure and brain function. MRI technologies allow us the ability to examine how the brain of living, developing, individuals change across age. Furthermore, compared to other common in vivo imaging methods, MRI offers high spatial resolution (typically 1mm³ for structural and 2mm³ for functional) and decent temporal resolution (down to a measurement every second). While MRI technology cannot measure the number of synaptic connections between brain cells or amount of myelin, we can quantify larger anatomical changes, as well as a proximal measure of brain activity. Thus, with MRI, scientists can link developmental changes in cognition, emotions and behaviour to changes occurring in the brain. For example, the powerful magnetic fields within the MRI machine are able to detect the level of blood flow in the different regions of the brain. Because of this ability to detect blood flow, the parts of the brain that require more energy during a certain cognitive task or behaviour can be identified using MRI. However, most MRI studies are unable to specify what brain chemicals (neurotransmitters) are being released.

Early important structural and functional MRI studies quantitatively comparing children and adults, i.e. cross-sectional studies, were published in the 1990s (e.g., Giedd et al. 1996; Jernigan and Tallal 1990; Reiss et al. 1996; Sowell et al. 1999; Thomas et al. 1999). Since then, a large number of cross-sectional and an increasing number of longitudinal investigations have examined brain developmental trajectories across the first decades of life using different MRI methods. Through these studies we have learned that the human brain undergoes not only a protracted development, with aspects of our brain maturing into the third decade of life, but that this development is tissue-specific, multifaceted, regional and coordinated.

Magnetic resonance imaging (MRI) of longitudinal brain development

MRI methods

MRI is a collection of imaging techniques that uses strong magnetic fields, electric field gradients and radio waves to produce high quality images of living organs. Because tissues differ in their magnetic properties, protocols designed to create anatomical images of the brain are based on signal intensities and contrasts that distinguish between grey matter, white matter, and cerebrospinal fluid, as well as different brain structures. Other protocols, like diffusion MRI (dMRI) which quantifies preferences of randomly diffusing water molecules to move in different directions, can create images to probe tissue microstructural properties. Functional MRI (fMRI) techniques on the other hand, can be used to produce images that reflect physiological processes that accompany neural activity. FMRI measures changes in blood flow and oxygenation, which vary based on the processing demands placed on the brain region. FMRI is typically used to investigate blood-oxygen-level dependent (BOLD) signals that are temporally correlated with experimental conditions or stimuli or specific

responses (task-fMRI), or to investigate spontaneous fluctuations in BOLD signals during task-free states, so-called resting-state fMRI.

Challenges and limitations

A core challenge with neuroimaging studies in general is that it is difficult to ascribe individual differences or longitudinal changes in imaging phenotypes from e.g. anatomical MRI, DTI or fMRI scans to specific cellular and molecular properties or events (Lerch et al. 2017; Zatorre, Fields, and Johansen-Berg 2012). Concerning brain development in particular, there are several hypotheses about the central involved mechanisms (Crone and Ridderinkhof 2011; Paus 2013). One hypothesis is that the early increases and later reductions in grey matter volume may partly relate to initial overproduction and subsequent pruning of synaptic connections, respectively. However, given that synaptic boutons comprise only a fraction of grey matter volume, and even when synapses are particularly dense, they are estimated to represent less than 1.5% of cortical volume (Bourgeois and Rakic 1993), it is unlikely that the marked decreases in cortical volume observed across adolescence are mainly reflective of synaptic pruning. A speculative alternative hypothesis is that synaptic pruning is also accompanied by a reduction in the number of cortical glial cells, and that these events together account for some of the reductions in cortical grey matter volume observed during development (K. L. Mills and Tamnes 2014). Growth of subcortical white matter and reduction in grey matter likely also relate to continued myelination, both in white matter and intracortically, as well as increases in axon diameter and changes in fibre packing density (Paus 2010). Undoubtedly, there is a myriad of both parallel and interacting cellular processes underlying the observed changes in imaging measured across childhood and adolescence. The relative roles of specific cellular processes for developmental changes in

brain structure, microstructure and activation patterns are likely also age-dependent, with different contributions for instance in infancy and during adolescence.

The current developmental neuroimaging literature largely consists of studies either on infancy or late childhood and adolescence, while few studies have investigate the period between infancy and school age (Brown and Jernigan 2012). The main reason for this is that young children are likely to move while inside the MRI scanner, which results in poor image quality. In contrast, older children and adolescents can be instructed to stay still, and MRI examinations of infants can, with good timing and some luck, be performed for non-clinical purposes during natural sleep after feeding. Studies of infants and young children, however, have specific major challenges, including image registration, choice of atlases, the large scale of anatomical changes, and the change of image intensity contrasts (Cusack, McCuaig, and Linke 2017; Phan et al. 2017).

In all developmental neuroimaging studies, preparing the participant and behavioural interventions such as movie watching and friendly feedback during acquisition (Greene et al. 2018) are important in order to reduce motion and optimize data quality. Additionally, quality control procedures, both pre- and post-processing, are of great importance for the resulting data quality (Vijayakumar et al. 2017). It has for instance been shown that post-processing quality control, in the form of exclusion of scans defined as quality control failures on the basis of visual inspection and review of extreme values, has a large impact on identified developmental trajectories for cortical thickness (Ducharme et al. 2016). While the biases introduced by motion-related artefacts has received substantial attention in the developmental fMRI literature (Power, Schlaggar, and Petersen 2015; Fair et al. 2012), effect of subtle motion on structural measures have also increasingly been recognized as potentially

impacting models of structural brain development (Alexander-Bloch et al. 2016; Yendiki et al. 2014). In order to improve reproducibility and effectiveness, well-documented and standardized (Backhausen et al. 2016) or automated (e.g. Esteban et al. 2017; Klapwijk et al. 2018) quality control procedures have recently been developed and are increasingly used.

Finally, there are also a number of considerations and challenges that are specific for longitudinal neuroimaging studies. These issues are associated with different stages of the research process, from study design and participant attrition, to data processing and statistical analysis (Tamnes, Roalf, et al. 2017; Telzer et al. 2018; Vijayakumar et al. 2017; King et al. 2017). While the most commonly used software for structural MRI have developed features specifically for longitudinal data (e.g. FreeSurfer, Reuter et al. 2012; ANTS Tustison et al. 2017), most available software packages for fMRI analysis does not include longitudinal processing or longitudinal statistical analyses. Hopefully, future programs will close the gap between the modelling capabilities of current software and the models that are necessary to answer longitudinal developmental questions (Madhyastha et al. 2017).

Structural brain development

Brain and tissue volumes

The brain changes throughout life, but it is clear that, besides during the prenatal period, the changes observed during the first few postnatal years qualitatively and quantitatively far exceeds the changes seen across the rest of the lifespan (Gilmore, Knickmeyer, and Gao 2018). A cross sectional study found that whole brain volume increases by 101% in the first year and then an additional 15% in the second year (Knickmeyer et al. 2008). A later longitudinal study further mapped these very rapid changes in brain morphology in early infancy by examining a large group of newborns aged 2 to 90 days old (Holland et al. 2014). The results showed that the brain's total volume increases approximately by a staggering *one*

percent per day in the period immediately after birth (Holland et al. 2014). In contrast to the increase in volume observed in early childhood, a multi-sample longitudinal study found that whole brain volume reduces in size during adolescence (K. L. Mills et al. 2016). When these findings are considered alongside those from a meta-analysis of longitudinal studies, it appears that whole brain volume increases until around age 13 years, then decreases until some point in the early twenties, after which it remains relatively stable until it later begins to decrease again (Hedman et al. 2012).

Importantly, volumetric development of the two main tissue types of the brain, grey matter and white matter, follow distinct developmental trajectories. Grey matter, i.e. the cerebral and cerebellar cortex and distinct subcortical structures, is composed of neuronal bodies, glial cells, dendrites, blood vessels, extracellular space and both unmyelinated and myelinated axons. Similar to whole brain volume, cortical grey matter volume increases rapidly after birth, approximately doubling in size in the first year of life (Gilmore et al. 2012). It then reaches its greatest volume in childhood, and decreases in late childhood and throughout adolescence, before stabilizing in young adulthood (Lebel and Beaulieu 2011; K. L. Mills et al. 2016). Unlike earlier characterizations of cortical grey matter volume reaching a “peak” at a specific age in late childhood or early adolescence (Giedd et al. 1999; Lenroot et al. 2007), it is likely that cortical grey matter reaches its highest volume in early childhood and plateaus for a number of years before it begins to decrease in late childhood (Gilmore, Knickmeyer, and Gao 2018).

In contrast to cortical grey matter volume, cerebral white matter, which occupies almost half of the human brain and consists largely of organized myelinated axons, continues to increase in volume from birth and across the second decade of life before stabilizing at some point in

the late teens or early twenties (Lebel and Beaulieu 2011; K. L. Mills et al. 2016; Knickmeyer et al. 2008). In addition to the tissue specific patterns described above, there are also regional and component specific differences in brain developmental timing and pace.

Regional patterns of development in the cerebral cortex

An important addition to the general patterns described above is that the cerebral cortex does not develop uniformly, but with regional patterns. For example, the parietal lobes and lateral occipital cortices show larger volumetric reductions in late childhood and early adolescence, whereas the medial frontal cortex and anterior temporal cortex pick up the pace in the teen years (Tamnes et al. 2013). Development of the cerebral cortex thus appears to generally follow a posterior–anterior pattern, with relatively late development of anterior brain regions in the frontal and temporal cortices.

Because the cerebral cortex morphometrically is a layer of tissue enveloping the cerebrum, it can be measured in terms of its distinct components: thickness and surface area. Importantly, cortical thickness and surface area are phylogenetically (Geschwind and Rakic 2013) and genetically (Kremen et al. 2013) distinct, and they are increasingly used metrics instead of cortical volume (Winkler et al. 2010). Cortical thickness and surface area are also ontogenetically distinct. In the first two years of life, both cortical thickness and surface area increase over time, although with a much larger increase in the latter (Lyall et al. 2015). From mid-childhood to adulthood, they show different developmental trajectories. Results from recent longitudinal studies suggest a monotonic decline for cortical thickness, while surface area increases in childhood and then slightly decreases during adolescence (K. L. Mills, Lalonde, et al. 2014; Tamnes, Herting, et al. 2017; Vijayakumar et al. 2016; Wierenga, Langen, Oranje, et al. 2014). Greater cortical volumes and surface areas are, on average,

observed in boys compared to girls, but relatively smaller and few sex differences are observed for cortical thickness, or for developmental change in any of these cortical measures (K. L. Mills, Lalonde, et al. 2014; Vijayakumar et al. 2016). While surface area has been found to be the primary determinant of individual differences in cortical volume in adults, and also the main driving factor for cortical volume increases in the early years of life (Lyll et al. 2015), the dominant contributor to cortical volume reductions between late childhood and early adulthood is cortical thinning (Tamnes, Herting, et al. 2017). The developmental patterns of cortical thinning from childhood to early adulthood are similar between homologous and contiguous regions, as well as between the core nodes of the default mode network: the medial prefrontal cortex and medial posterior cortex (Khundrakpam et al. 2017).

The human cortex is highly convoluted, with approximately one third of the surface exposed on gyri and two-thirds buried within sulci, and developmental changes related to this feature can be measured using a global (whole brain) or local gyrification index. During the first two years of life, the global gyrification index increases around 25%, with substantial regional heterogeneity (Li et al. 2014). Local changes in gyrification are stronger for association cortices in infancy, and regions located in sensorimotor, auditory, and visual cortices show relatively less change in gyrification (Li et al. 2014). Global gyrification decreases between childhood and young adulthood (Alemán-Gómez et al. 2013; Raznahan et al. 2011). One longitudinal study demonstrated that the cortex “flattens” during adolescence, mostly due to decreases in sulcal depth and increases in sulcal width (Alemán-Gómez et al. 2013). As seen in infancy, changes in gyrification vary across the cortex during childhood and adolescence, with regions in medial prefrontal cortex, occipital cortex, and temporal cortex undergoing little to no change between ages 6-30 years (Mutlu et al. 2013). However, similar to what has been found in whole brain (Raznahan et al. 2011) and lobar-level (Alemán-Gómez et al.

2013) analyses, linear decreases in local gyrification are observed across the majority of the cortex (Mutlu et al. 2013).

Subcortical structures

The growth rates of subcortical grey matter structures in infancy are similar to that of cortical volume, except that the hippocampus appears to show a somewhat slower growth than other subcortical structures (Gilmore et al. 2012; Gilmore, Knickmeyer, and Gao 2018). Several subcortical structures and cortical infolds also show substantial structural change between childhood and young adulthood, although generally at a lower rate than is observed in the cortex (Tamnes et al. 2013). Longitudinal studies of children and adolescents have found that the thalamus, pallidum, amygdala, caudate, putamen, and nucleus accumbens all show significant changes in volume across the second decade of life (Goddings et al. 2014; Herting et al. 2018; Wierenga, Langen, Ambrosino, et al. 2014). The caudate, putamen and nucleus accumbens decrease at a near linear rate during this time, whereas the amygdala, thalamus and pallidum demonstrate non-linear increases in volume. Findings for the hippocampus have been inconsistent, but recent studies, including a multisite longitudinal developmental study (Herting et al. 2018) and a large longitudinal study (Tamnes et al. 2018), demonstrate a non-linear developmental trajectory with subtle increases into mid-adolescence and subsequent decreases. Together, these developmental findings for subcortical structures are in contradiction with hypotheses and developmental models that assume that subcortical structures are mature by adolescence, as it is now clear that these regions are still undergoing structural development throughout the second decade of life. Males on average consistently show larger subcortical volumes than females (Wierenga, Bos, et al. 2018), but findings are less clear for sex differences in their developmental trajectories (Herting et al. 2018).

White matter microstructure

In addition to volumetric studies, white matter development is often investigated with dMRI. The most typical quantification of dMRI is achieved in a tensor model and this is referred to as diffusion tensor imaging (DTI). Several indices can be derived; fractional anisotropy (FA) is used as a measure of the directionality of diffusion, mean diffusivity (MD) reflects the overall magnitude of diffusion, whilst axial (AD) and radial diffusivity (RD) are diffusivity along and across the longest axis of the diffusion tensor, respectively. These indices can be analysed on a voxel-wise basis or in regions of interest, or with tractography techniques to reconstruct long-range connections, yielding possibilities for inferring patterns of structural connectivity. The major white matter fibre pathways in the brain are present and identifiable at birth, but rapid changes in DTI indices are seen across infancy (Qiu, Mori, and Miller 2015). A longitudinal study of infants ranging from 2 weeks to 2 years (scanned annually) found that over the first two years of life, FA in ten major tracts increased by 16-55%, RD decreased by 24-46%, and AD decreased by 13-28%, with faster changes in the first year than in the second (Geng et al. 2012).

In addition to the early changes in fibre integrity that have been observed, longitudinal DTI studies have documented consistent patterns of continued development of white matter microstructure in later childhood and adolescence. These studies have demonstrated that, with increasing age, FA increases, while MD and RD decreases, in most white matter regions, but the results for AD are less consistent (Lebel and Deoni 2018). In preschool and the early school years, FA showed linear increase over time for most white matter regions, while MD and RD showed linear decreases (Krogsrud et al. 2016). Lebel and Beaulieu (2011) studied a much broader age-range, 5-32 years, and found that almost all tracts

investigated showed nonlinear developmental trajectories, with decelerating increases for FA and decelerating decreases for MD, primarily due to decreasing RD.

There are also regional differences in white matter microstructure development. Consistent with the posterior–anterior cortical grey matter developmental pattern, a pattern of maturation in which major tracts with frontotemporal connections develop more slowly than other tracts has emerged (Lebel et al. 2008). Of the major fibre bundles, the cingulum, implicated in cognitive control, and the uncinate fasciculus, implicated in emotion and episodic memory, appear to be among those with the most prolonged development (Lebel et al. 2012; Olson et al. 2015).

DTI has also been used to measure changes in brain connectivity across the brain. One longitudinal study found that only a small percentage of connections changed structurally between the ages of 15-19 years, and that these connections were largely between “hub” regions of the brain (Baker et al. 2015). Specifically, connections between subcortical hubs decreased across late adolescence and connections between frontal–subcortical and frontal–parietal hubs increased across late adolescence (Baker et al. 2015). A recent study replicated and extended these findings in two independent longitudinal datasets with participants ranging from ages 4 to 13 years (Wierenga, van den Heuvel, et al. 2018). As observed in Baker et al., 2015, the hub regions of the brain showed the most substantial changes in connectivity between childhood and early adolescence (Wierenga, van den Heuvel, et al. 2018). Further, this study found that white matter tracts connecting distal regions of the brain demonstrated larger developmental changes in FA than white matter tracts connecting proximal brain regions (Wierenga, van den Heuvel, et al. 2018).

The brain is highly organised, and the layout is often described as highly efficient in regards to signalling (Achard and Bullmore 2007). A longitudinal study of twins aged 9-15 years demonstrated that the efficiency of the brain's structural connections is highly heritable, and that this efficiency increases across early adolescence (Koenis et al. 2015). A follow-up study of the same cohort demonstrated that global efficiency of the brain's structural connections follows a non-linear trajectory, increasing between 10-13 years before stabilising between ages 12-18 years (Koenis et al. 2017). This study also found that adolescents with more efficient structural brain networks (both local and global) had higher IQs, and that the coupling between structural network efficiency and IQ increased with age (Koenis et al. 2017). Further, the increased correlation between structural network efficiency and IQ observed with age appeared to be under strong genetic control (Koenis et al. 2017).

Structural brain development and cognition

What are the functional consequences of the prolonged structural development of the human brain? One of the main characteristics of the brain during development is its plasticity, or capacity for change in response to external influences, which can range from concerted interventions to everyday behaviours. There have only been a few studies that have measured the impact of interventions on brain structure during development. One recent study investigated how a reading intervention impacted the integrity of white matter tracts in children aged 7-12 years (Huber et al. 2018). This novel study identified struggling readers and assigned them to either an 8-week reading intervention or school as usual, and the students were scanned four times: once at baseline, after 2.5 weeks of intervention, after 5 weeks of intervention, and after the intervention had been completed (Huber et al. 2018). This intensive longitudinal study allowed the researchers to observe the rapid changes that occurred in white matter tracts, including the left arcuate fasciculus and inferior longitudinal

fasciculus – tracts which connect a core network of brain regions involved in reading and word comprehension (Huber et al. 2018).

While intervention studies are crucial to fully understand how environmental factors can impact the developing brain, some characteristics of the environment (e.g. socioeconomic status) cannot be manipulated in experimental studies. There have been a few observational studies investigating the impact of the environment on brain development. One longitudinal study of children aged 11-20 years examined the interacting effects of parenting style and socioeconomic disadvantage on structural brain development (Whittle et al. 2017). In this study, socioeconomic disadvantage measured at the neighbourhood-level was related to differences in volumetric brain development in the amygdala and temporal lobes, more specifically with greater increases in amygdala volumes and relatively increased cortical thickening longitudinally. Furthermore, positive parenting strategies attenuated the effects of socioeconomic disadvantage on brain development in some regions (Whittle et al. 2017).

There have been several studies investigating how changes in brain structure correlate with changes in cognitive abilities or behaviours. For example changes in cortical thickness in prefrontal cortical regions during adolescence have been associated with developmental improvements in aspects of cognitive control, including proactive control (Vijayakumar et al. 2014a), and cognitive reappraisal strategies (Vijayakumar et al. 2014b). Further, individual differences in developmental changes in DTI indices relate to cognitive development across ages 8-28 years (Simmonds et al. 2014). In this study, earlier white matter development in adolescence was associated with faster and more efficient behavioural responding and better inhibitory control, whereas later (delayed) white matter development was associated with poorer performance, suggesting that the timing of developmental changes in white matter

microstructure is important for cognitive development (Simmonds et al. 2014). A separate longitudinal DTI study examined the relationship between temporal discounting and frontostriatal circuitry in individuals between the ages of 8-26, and found that greater frontostriatal white matter integrity was related to the preference for waiting for larger reward during this age period (Achterberg et al. 2016).

Functional brain development

Compared to structural brain development, there have been fewer longitudinal investigations of functional brain development utilizing either task-based or resting-state fMRI techniques, and the majority include only two time points per participant. The current section focuses exclusively on longitudinal fMRI studies and does not cover the large number of cross-sectional fMRI studies that have correlated brain responses, or functional connectivity, with age, cognition, or behaviour during developmental periods.

Developmental changes in functional connectivity

The first longitudinal study to investigate developmental changes in the brain's functional organisation did not use data acquired during the canonical "resting-state" when participants usually rest quietly with eye's closed or fixated on a cross-hair, but rather examined functional connectivity while participants listened passively to meaningless speech (Sherman et al. 2014). As with previous cross-sectional studies investigating age-related differences in functional brain networks (Fair et al. 2007, 2009, 2008), this study demonstrated that the integration (within-network connectivity) and segregation (between-network connectivity) of the default mode and central executive networks changes between childhood and early adolescence. Specifically, core nodes within each of these networks became more strongly

connected to their respective networks, and less connected with the other network, between the ages of 10 and 13 years (Sherman et al. 2014).

A recent study that made use of publicly available datasets found that the brain's functional organization remained stable from adolescence to early adulthood (Horien et al. 2017).

Despite the availability of longitudinal resting state datasets for developing populations, in addition to the datasets that have been acquired but not publicly shared, not much is published on this topic. There are a few studies comparing the development of resting state functional brain connectivity between clinical groups (e.g. B. D. Mills et al. 2017; Jalbrzikowski et al. 2017), but fewer studies investigating typically developmental trajectories of functional brain organisation or connectivity between predefined regions.

Developmental changes in functional brain organisation can also be related to cognitive processes and behaviours assessed outside of the scanner. A recent longitudinal study demonstrated that individual differences in functional brain organisation can account for behavioural changes in temporal discounting with age (Anandakumar et al. 2018). In this study, functional connections that could explain temporal discounting changes above age were first identified in a longitudinal sample of 7-15 year olds, and then confirmed in an independent cross-sectional sample. For both samples, connectivity strength within and between valuation and cognitive control systems accounted for variance in temporal discounting behaviour that was not explained by age (Anandakumar et al. 2018). Specifically, greater connectivity strength between cognitive control regions, as well as between cognitive control and valuation regions, was related to a preference for waiting for a larger reward. In contrast, greater connectivity strength between valuation network regions was related to a preference for taking an immediate, smaller, reward.

In a study that combined three longitudinal datasets spanning ages 6-22 years, functional connectivity strength between regions of the lateral frontoparietal network showed a nonlinear pattern, with minimal change in late childhood but a pronounced change in the transition into adolescence (Wendelken et al. 2017). Further, the functional connectivity strength within this network was associated with reasoning ability in adolescents and adults (Wendelken et al. 2017).

Developmental changes in neural responses during task fMRI

One of the first longitudinal fMRI investigations of brain development demonstrated that neural responses to social stimuli continue to change between childhood and adolescence (Pfeifer et al. 2011). Between the ages of 10 and 13 years, children begin to show greater neural activity in the ventral striatum and ventromedial prefrontal cortex while looking at faces in general, whereas the anterior temporal cortex showed greater neural activity in particular for emotional faces (Pfeifer et al. 2011). The longitudinal design of this study also provided the opportunity to understand how changes in neural responsivity in socioemotional situations relate to emotion-regulation capacities. The authors demonstrated that heightened ventral striatal activity across this age period was correlated with decreasing susceptibility (i.e., increasing resistance) to peer influence (Pfeifer et al. 2011).

Another longitudinal study examined non-linear changes in neural recruitment during an inhibitory control task across ages 9-26 years (Ordaz et al. 2013). Inhibitory control continued to improve throughout adolescence, but recruitment of brain regions involved in motor response control did not show developmental changes, suggesting that brain functioning regarding this aspect of inhibitory control matures earlier - in late childhood

(Ordaz et al. 2013). However, activation in certain executive control regions decreased with age until adolescence, and error processing activation in the dorsal anterior cingulate cortex showed continued increases all the way into young adulthood and was associated with task performance (Ordaz et al. 2013). By taking a longitudinal approach, the study provides strong evidence that the continued maturation of error-processing abilities underlies the protracted development of inhibitory control over adolescence.

There has been one longitudinal study that has examined the impact of puberty on the capacity to experience (some) fear-evoking experiences as an exciting thrill (Spielberg et al. 2014). This study demonstrated that increases in testosterone over a two-year period of pubertal maturation was positively related to recruitment of both the amygdala and nucleus accumbens when perceiving stimuli typically associated with threat (Spielberg et al. 2014). The level of recruitment of these regions was further related to greater approach behaviour – in this case, responding faster to threatening faces (Spielberg et al. 2014). Overall, the authors suggest that the experience of threat shifts to a more complex process during pubertal maturation, which is specifically associated with changing testosterone levels.

There are developmental increases in the dorsal striatum, but not ventral striatum, during the anticipation of rewards or losses during adolescence, which, interestingly, doesn't differ between reward and loss conditions (Lamm et al. 2014). A separate study found that a network of brain regions involved in processing reward (including the ventral striatum and medial prefrontal cortex) are consistently recruited in response to rewards over the course of adolescence, and the propensity to engage in risky behaviour is positively correlated with reward-related activation within this reward-related network (van Duijvenvoorde et al. 2014). Further, this study did not find evidence for a “peak” in the brain's response to rewards in mid-adolescence (van Duijvenvoorde et al. 2014). However, a subsequent study with a larger

sample, which examined longitudinal changes in neural responses to rewards during a laboratory risk-taking task across ages 8-27 years, did find evidence for heightened activity in the nucleus accumbens in response to rewards during adolescence, as compared to in both childhood and adulthood (Braams et al. 2015). All in all, these discrepant findings could be resolved through replication efforts as more datasets examining longitudinal studies of functional brain development are acquired.

Conclusions and Future Directions

Thanks to two decades of advances in neuroimaging acquisition and analysis and an increasing number of longitudinal studies, we have gained new insight into how the human brain, both in terms of structural architecture and functional activation patterns, develops throughout childhood and adolescence. This fundamental knowledge opens up many novel research questions that are currently being pursued. How are the brain structural and functional developmental changes related, and how do they jointly support development of cognition and emotion (Fengler, Meyer, and Friederici 2016; Ullman, Almeida, and Klingberg 2014)? How do early influences and novel social experiences characteristic of the adolescent period affect neurocognitive development (Blakemore and Mills 2014; McLaughlin, Sheridan, and Nelson 2017)? What brain measures demonstrate a differential developmental pattern when comparing females and males, and what are the roles of puberty and specific hormonal changes in these differential patterns (Herting and Sowell 2017; Wierenga, Bos, et al. 2018)? How do the genetic, social and neural dimensions together augment risk or promote resilience for emerging mental health problems observed from childhood to young adulthood (Alnæs et al. 2018; Bos et al. 2018; Kaufmann et al. 2017)?

A critical premise for answering many of these questions, is that we need to move beyond a focus on averages and towards studying variability and individual differences (Fisher,

Medaglia, and Jeronimus 2018; Foulkes and Blakemore 2018). Patterns of structural brain development have been linked to individual differences in psychological traits (Ferschmann et al. 2018), as well as intelligence (Schnack et al. 2014). Several studies have demonstrated that patterns of structural brain development are not the same for everyone within a group, e.g. boys (Wierenga et al., n.d.), or children with a specific clinical diagnosis (Bethlehem et al. 2018; Alexander-Bloch et al. 2014), or at an individual level (K. L. Mills, Goddings, et al. 2014). Both structural and functional longitudinal neuroimaging studies indicate substantial individual differences in brain developmental trajectories, but few studies have formally evaluated individual differences in slopes and tried to relate these to other variables of interest (but some are starting to, see: (Becht et al. 2018). Large longitudinal datasets or datasets with many timepoints, such as the Adolescent Brain Cognitive Development (ABCD) study, and both exploratory and hypothesis-driven studies are needed to achieve this.

References

- Achard, Sophie, and Ed Bullmore. 2007. "Efficiency and Cost of Economical Brain Functional Networks." *PLOS Computational Biology* 3 (2): e17. <https://doi.org/10.1371/journal.pcbi.0030017>.
- Achterberg, Michelle, Jiska S. Peper, Anna C. K. van Duijvenvoorde, René C. W. Mandl, and Eveline A. Crone. 2016. "Frontostriatal White Matter Integrity Predicts Development of Delay of Gratification: A Longitudinal Study." *Journal of Neuroscience* 36 (6): 1954–61. <https://doi.org/10.1523/JNEUROSCI.3459-15.2016>.
- Alemán-Gómez, Yasser, Joost Janssen, Hugo Schnack, Evan Balaban, Laura Pina-Camacho, Fidel Alfaro-Almagro, Josefina Castro-Fornieles, et al. 2013. "The Human Cerebral Cortex Flattens during Adolescence." *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience* 33 (38): 15004–10. <https://doi.org/10.1523/JNEUROSCI.1459-13.2013>.
- Alexander-Bloch, Aaron F., Liv Clasen, Michael Stockman, Lisa Ronan, Francois Lalonde, Jay Giedd, and Armin Raznahan. 2016. "Subtle In-Scanner Motion Biases Automated Measurement of Brain Anatomy from in Vivo MRI." *Human Brain Mapping* 37 (7): 2385–97. <https://doi.org/10.1002/hbm.23180>.
- Alexander-Bloch, Aaron F., Philip T. Reiss, Judith Rapoport, Harry McAdams, Jay N. Giedd, Ed T. Bullmore, and Nitin Gogtay. 2014. "Abnormal Cortical Growth in Schizophrenia Targets Normative Modules of Synchronized Development." *Biological Psychiatry, Brain Development and Connectivity in Schizophrenia*, 76 (6): 438–46. <https://doi.org/10.1016/j.biopsych.2014.02.010>.
- Alnæs, Dag, Tobias Kaufmann, Nhat Trung Doan, Aldo Córdova-Palomera, Yunpeng Wang, Francesco Bettella, Torgeir Moberget, Ole A. Andreassen, and Lars T. Westlye. 2018. "Association of Heritable Cognitive Ability and Psychopathology With White Matter Properties in Children and Adolescents." *JAMA Psychiatry* 75 (3): 287–95. <https://doi.org/10.1001/jamapsychiatry.2017.4277>.
- Anandakumar, Jeya, Kathryn Mills, Eric Earl, Lourdes Irwin, Oscar Miranda-Dominguez, Damion V. Demeter, Alexandra Walton-Weston, Sarah Karalunas, Joel Nigg, and Damien A. Fair. 2018. "Individual Differences in Functional Brain Connectivity Predict Temporal Discounting Preference in the Transition to Adolescence." *BioRxiv*, January, 255679. <https://doi.org/10.1101/255679>.
- Backhausen, Lea L., Megan M. Herting, Judith Buse, Veit Roessner, Michael N. Smolka, and Nora C. Vetter. 2016. "Quality Control of Structural MRI Images Applied Using FreeSurfer-A Hands-On Workflow to Rate Motion Artifacts." *Frontiers in Neuroscience* 10: 558. <https://doi.org/10.3389/fnins.2016.00558>.
- Baker, Simon T. E., Dan I. Lubman, Murat Yücel, Nicholas B. Allen, Sarah Whittle, Ben D. Fulcher, Andrew Zalesky, and Alex Fornito. 2015. "Developmental Changes in Brain Network Hub Connectivity in Late Adolescence." *Journal of Neuroscience* 35 (24): 9078–87. <https://doi.org/10.1523/JNEUROSCI.5043-14.2015>.
- Becht, Andrik I., Marieke G.N. Bos, Stefanie A. Nelemans, Sabine Peters, Wilma A.M. Vollebergh, Susan J.T. Branje, Wim H.J. Meeus, and Eveline A. Crone. 2018. "Goal-Directed Correlates and Neurobiological Underpinnings of Adolescent Identity: A Multimethod Multisample Longitudinal Approach." *Child Development* 0 (0). <https://doi.org/10.1111/cdev.13048>.
- Benes, F. 1989. "Myelination of Cortical-Hippocampal Relays during Late Adolescence." *Schizophrenia Bulletin* 15 (4): 585–93.
- Bethlehem, Richard A. I., Jakob Seidlitz, Rafael Romero-Garcia, and Michael V. Lombardo. 2018. "Using Normative Age Modelling to Isolate Subsets of Individuals with Autism Expressing Highly Age-Atypical Cortical Thickness Features." *BioRxiv*, January, 252593. <https://doi.org/10.1101/252593>.
- Blakemore, Sarah-Jayne, and Kathryn L. Mills. 2014. "Is Adolescence a Sensitive Period for Sociocultural Processing?" *Annual Review of Psychology* 65: 187–207. <https://doi.org/10.1146/annurev-psych-010213-115202>.

- Bos, Marieke G. N., Sabine Peters, Ferdi C. van de Kamp, Eveline A. Crone, and Christian K. Tamnes. 2018. "Emerging Depression in Adolescence Coincides with Accelerated Frontal Cortical Thinning." *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, March. <https://doi.org/10.1111/jcpp.12895>.
- Bourgeois, Jean-Pierre, and Pasko Rakic. 1993. "Changes of Synaptic Density in the Primary Visual Cortex of the Macaque Monkey from Fetal to Adult Stage." *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience* 13 (7): 2801–20.
- Braams, Barbara R., Anna C. K. van Duijvenvoorde, Jiska S. Peper, and Eveline A. Crone. 2015. "Longitudinal Changes in Adolescent Risk-Taking: A Comprehensive Study of Neural Responses to Rewards, Pubertal Development, and Risk-Taking Behavior." *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience* 35 (18): 7226–38. <https://doi.org/10.1523/JNEUROSCI.4764-14.2015>.
- Brown, Timothy T., and Terry L. Jernigan. 2012. "Brain Development during the Preschool Years." *Neuropsychology Review* 22 (4): 313–33. <https://doi.org/10.1007/s11065-012-9214-1>.
- Crone, Eveline A., and K. Richard Ridderinkhof. 2011. "The Developing Brain: From Theory to Neuroimaging and Back." *Developmental Cognitive Neuroscience* 1 (2): 101–9. <https://doi.org/10.1016/j.dcn.2010.12.001>.
- Cusack, Rhodri, Olivia McCuaig, and Annika C. Linke. 2017. "Methodological Challenges in the Comparison of Infant fMRI across Age Groups." *Developmental Cognitive Neuroscience*, November. <https://doi.org/10.1016/j.dcn.2017.11.003>.
- Ducharme, Simon, Matthew D. Albaugh, Tuong-Vi Nguyen, James J. Hudziak, J. M. Mateos-Pérez, Aurelie Labbe, Alan C. Evans, Sherif Karama, and Brain Development Cooperative Group. 2016. "Trajectories of Cortical Thickness Maturation in Normal Brain Development--The Importance of Quality Control Procedures." *NeuroImage* 125 (January): 267–79. <https://doi.org/10.1016/j.neuroimage.2015.10.010>.
- Duijvenvoorde, Anna C. K. van, Zdeňka A. Op de Macks, Sandy Overgaauw, Bregtje Gunther Moor, Ronald E. Dahl, and Eveline A. Crone. 2014. "A Cross-Sectional and Longitudinal Analysis of Reward-Related Brain Activation: Effects of Age, Pubertal Stage, and Reward Sensitivity." *Brain and Cognition* 89 (August): 3–14. <https://doi.org/10.1016/j.bandc.2013.10.005>.
- Esteban, Oscar, Daniel Birman, Marie Schaer, Oluwasanmi O. Koyejo, Russell A. Poldrack, and Krzysztof J. Gorgolewski. 2017. "MRIQC: Advancing the Automatic Prediction of Image Quality in MRI from Unseen Sites." *PloS One* 12 (9): e0184661. <https://doi.org/10.1371/journal.pone.0184661>.
- Fair, Damien A., Alexander L. Cohen, Nico U. F. Dosenbach, Jessica A. Church, Francis M. Miezin, Deanna M. Barch, Marcus E. Raichle, Steven E. Petersen, and Bradley L. Schlaggar. 2008. "The Maturing Architecture of the Brain's Default Network." *Proceedings of the National Academy of Sciences* 105 (10): 4028–32. <https://doi.org/10.1073/pnas.0800376105>.
- Fair, Damien A., Alexander L. Cohen, Jonathan D. Power, Nico U. F. Dosenbach, Jessica A. Church, Francis M. Miezin, Bradley L. Schlaggar, and Steven E. Petersen. 2009. "Functional Brain Networks Develop from a 'Local to Distributed' Organization." *PLOS Computational Biology* 5 (5): e1000381. <https://doi.org/10.1371/journal.pcbi.1000381>.
- Fair, Damien A., Nico U. F. Dosenbach, Jessica A. Church, Alexander L. Cohen, Shefali Brahmabhatt, Francis M. Miezin, Deanna M. Barch, Marcus E. Raichle, Steven E. Petersen, and Bradley L. Schlaggar. 2007. "Development of Distinct Control Networks through Segregation and Integration." *Proceedings of the National Academy of Sciences* 104 (33): 13507–12. <https://doi.org/10.1073/pnas.0705843104>.
- Fair, Damien A., Joel T. Nigg, Swathi Iyer, Deepti Bathula, Kathryn L. Mills, Nico U. F. Dosenbach, Bradley L. Schlaggar, et al. 2012. "Distinct Neural Signatures Detected for ADHD Subtypes after Controlling for Micro-Movements in Resting State Functional Connectivity MRI Data." *Frontiers in Systems Neuroscience* 6: 80. <https://doi.org/10.3389/fnsys.2012.00080>.
- Fengler, Anja, Lars Meyer, and Angela D. Friederici. 2016. "How the Brain Attunes to Sentence Processing: Relating Behavior, Structure, and Function." *NeuroImage* 129 (April): 268–78. <https://doi.org/10.1016/j.neuroimage.2016.01.012>.
- Ferschmann, Lia, Anders M. Fjell, Margarete E. Vollrath, Håkon Grydeland, Kristine B. Walhovd, and Christian K. Tamnes. 2018. "Personality Traits Are Associated With Cortical

- Development Across Adolescence: A Longitudinal Structural MRI Study.” *Child Development* 89 (3): 811–22. <https://doi.org/10.1111/cdev.13016>.
- Fisher, Aaron J., John D. Medaglia, and Bertus F. Jeronimus. 2018. “Lack of Group-to-Individual Generalizability Is a Threat to Human Subjects Research.” *Proceedings of the National Academy of Sciences*, June, 201711978. <https://doi.org/10.1073/pnas.1711978115>.
- Foulkes, Lucy, and Sarah-Jayne Blakemore. 2018. “Studying Individual Differences in Human Adolescent Brain Development.” *Nature Neuroscience* 21 (3): 315–23. <https://doi.org/10.1038/s41593-018-0078-4>.
- Geng, Xiujuan, Sylvain Gouttard, Anuja Sharma, Hongbin Gu, Martin Styner, Weili Lin, Guido Gerig, and John H. Gilmore. 2012. “Quantitative Tract-Based White Matter Development from Birth to Age 2years.” *NeuroImage* 61 (3): 542–57. <https://doi.org/10.1016/j.neuroimage.2012.03.057>.
- Geschwind, Daniel H., and Pasko Rakic. 2013. “Cortical Evolution: Judge the Brain by Its Cover.” *Neuron* 80 (3): 633–47. <https://doi.org/10.1016/j.neuron.2013.10.045>.
- Giedd, Jay N., J Blumenthal, N O Jeffries, F X Castellanos, H Liu, A Zijdenbos, T Paus, A C Evans, and J L Rapoport. 1999. “Brain Development during Childhood and Adolescence: A Longitudinal MRI Study.” *Nature Neuroscience* 2 (10): 861–63. <https://doi.org/10.1038/13158>.
- Giedd, Jay N., J W Snell, N Lange, J C Rajapakse, B J Casey, P L Kozuch, A C Vaituzis, et al. 1996. “Quantitative Magnetic Resonance Imaging of Human Brain Development: Ages 4-18.” *Cerebral Cortex (New York, N.Y.: 1991)* 6 (4): 551–60.
- Gilmore, John H., Rebecca C. Knickmeyer, and Wei Gao. 2018. “Imaging Structural and Functional Brain Development in Early Childhood.” *Nature Reviews Neuroscience* 19 (3): 123–37. <https://doi.org/10.1038/nrn.2018.1>.
- Gilmore, John H., Feng Shi, Sandra L. Woolson, Rebecca C. Knickmeyer, Sarah J. Short, Weili Lin, Hongtu Zhu, Robert M. Hamer, Martin Styner, and Dinggang Shen. 2012. “Longitudinal Development of Cortical and Subcortical Gray Matter from Birth to 2 Years.” *Cerebral Cortex (New York, N.Y.: 1991)* 22 (11): 2478–85. <https://doi.org/10.1093/cercor/bhr327>.
- Goddings, Anne-Lise, Kathryn L. Mills, Liv S. Clasen, Jay N. Giedd, Russell M. Viner, and Sarah-Jayne Blakemore. 2014. “The Influence of Puberty on Subcortical Brain Development.” *NeuroImage* 88 (March): 242–51. <https://doi.org/10.1016/j.neuroimage.2013.09.073>.
- Greene, Deanna J., Jonathan M. Koller, Jacqueline M. Hampton, Victoria Wesevich, Andrew N. Van, Annie L. Nguyen, Catherine R. Hoyt, et al. 2018. “Behavioral Interventions for Reducing Head Motion during MRI Scans in Children.” *NeuroImage* 171 (May): 234–45. <https://doi.org/10.1016/j.neuroimage.2018.01.023>.
- Hedman, Anna M, Neeltje E M van Haren, Hugo G Schnack, René S Kahn, and Hilleke E Hulshoff Pol. 2012. “Human Brain Changes across the Life Span: A Review of 56 Longitudinal Magnetic Resonance Imaging Studies.” *Human Brain Mapping* 33 (8): 1987–2002. <https://doi.org/10.1002/hbm.21334>.
- Herting, Megan M., Cory Johnson, Kathryn L. Mills, Nandita Vijayakumar, Meg Dennison, Chang Liu, Anne-Lise Goddings, et al. 2018. “Development of Subcortical Volumes across Adolescence in Males and Females: A Multisample Study of Longitudinal Changes.” *NeuroImage* 172 (May): 194–205. <https://doi.org/10.1016/j.neuroimage.2018.01.020>.
- Herting, Megan M., and Elizabeth R. Sowell. 2017. “Puberty and Structural Brain Development in Humans.” *Frontiers in Neuroendocrinology* 44: 122–37. <https://doi.org/10.1016/j.yfrne.2016.12.003>.
- Holland, Dominic, Linda Chang, Thomas M. Ernst, Megan Curran, Steven D. Buchthal, Daniel Alicata, Jon Skranes, et al. 2014. “Structural Growth Trajectories and Rates of Change in the First 3 Months of Infant Brain Development.” *JAMA Neurology* 71 (10): 1266–74. <https://doi.org/10.1001/jamaneurol.2014.1638>.
- Horien, Corey, Xilin Shen, Dustin Scheinost, and R. Todd Constable. 2017. “Individual Connectomes Are Unique and Stable in the Developing Brain from Adolescence to Young Adulthood.” *BioRxiv*, December, 238113. <https://doi.org/10.1101/238113>.

- Huber, Elizabeth, Patrick M. Donnelly, Ariel Rokem, and Jason D. Yeatman. 2018. "Rapid and Widespread White Matter Plasticity during an Intensive Reading Intervention." *Nature Communications* 9 (1): 2260. <https://doi.org/10.1038/s41467-018-04627-5>.
- Huttenlocher, Peter R. 1984. "Synapse Elimination and Plasticity in Developing Human Cerebral Cortex." *American Journal of Mental Deficiency* 88 (5): 488–96.
- Huttenlocher, Peter R., and A S Dabholkar. 1997. "Regional Differences in Synaptogenesis in Human Cerebral Cortex." *The Journal of Comparative Neurology* 387 (2): 167–78.
- Jalbrzikowski, Maria, Bart Larsen, Michael N. Hallquist, William Foran, Finnegan Calabro, and Beatriz Luna. 2017. "Development of White Matter Microstructure and Intrinsic Functional Connectivity Between the Amygdala and Ventromedial Prefrontal Cortex: Associations With Anxiety and Depression." *Biological Psychiatry* 82 (7): 511–21. <https://doi.org/10.1016/j.biopsych.2017.01.008>.
- Jernigan, T. L., and P. Tallal. 1990. "Late Childhood Changes in Brain Morphology Observable with MRI." *Developmental Medicine and Child Neurology* 32 (5): 379–85.
- Kaufmann, Tobias, Dag Alnæs, Nhat Trung Doan, Christine Lycke Brandt, Ole A. Andreassen, and Lars T. Westlye. 2017. "Delayed Stabilization and Individualization in Connectome Development Are Related to Psychiatric Disorders." *Nature Neuroscience* 20 (4): 513–15. <https://doi.org/10.1038/nn.4511>.
- Khundrakpam, Budhachandra S., John D. Lewis, Seun Jeon, Penelope Kostopoulos, Yasser Itturia Medina, François Chouinard-Decorte, and Alan C. Evans. 2017. "Exploring Individual Brain Variability during Development Based on Patterns of Maturational Coupling of Cortical Thickness: A Longitudinal MRI Study." *Cerebral Cortex (New York, N.Y.: 1991)*, December. <https://doi.org/10.1093/cercor/bhx317>.
- King, Kevin M., Andrew K. Littlefield, Connor J. McCabe, Kathryn L. Mills, John Flournoy, and Laurie Chassin. 2017. "Longitudinal Modeling in Developmental Neuroimaging Research: Common Challenges, and Solutions from Developmental Psychology." *Developmental Cognitive Neuroscience*, November. <https://doi.org/10.1016/j.dcn.2017.11.009>.
- Klapwijk, Eduard T., Ferdi van de Kamp, Mara van der Meulen, Sabine Peters, and Lara M. Wierenga. 2018. "Qoala-T: A Supervised-Learning Tool for Quality Control of Automatic Segmented MRI Data." *BioRxiv*, March, 278358. <https://doi.org/10.1101/278358>.
- Knickmeyer, Rebecca C., Sylvain Gouttard, Chaeryon Kang, Dianne Evans, Kathy Wilber, J. Keith Smith, Robert M. Hamer, Weili Lin, Guido Gerig, and John H. Gilmore. 2008. "A Structural MRI Study of Human Brain Development from Birth to 2 Years." *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience* 28 (47): 12176–82. <https://doi.org/10.1523/JNEUROSCI.3479-08.2008>.
- Koenis, Marinka M. G., Rachel M. Brouwer, Martijn P. van den Heuvel, René C. W. Mandl, Inge L. C. van Soelen, René S. Kahn, Dorret I. Boomsma, and Hilleke E. Hulshoff Pol. 2015. "Development of the Brain's Structural Network Efficiency in Early Adolescence: A Longitudinal DTI Twin Study." *Human Brain Mapping* 36 (12): 4938–53. <https://doi.org/10.1002/hbm.22988>.
- Koenis, Marinka M. G., Rachel M. Brouwer, Suzanne C. Swagerman, Inge L. C. van Soelen, Dorret I. Boomsma, and Hilleke E. Hulshoff Pol. 2017. "Association between Structural Brain Network Efficiency and Intelligence Increases during Adolescence." *Human Brain Mapping*, November. <https://doi.org/10.1002/hbm.23885>.
- Kremen, William S., Christine Fennema-Notestine, Lisa T. Eyler, Matthew S. Panizzon, Chi-Hua Chen, Carol E. Franz, Michael J. Lyons, Wesley K. Thompson, and Anders M. Dale. 2013. "Genetics of Brain Structure: Contributions from the Vietnam Era Twin Study of Aging." *American Journal of Medical Genetics. Part B, Neuropsychiatric Genetics: The Official Publication of the International Society of Psychiatric Genetics* 162B (7): 751–61. <https://doi.org/10.1002/ajmg.b.32162>.
- Krogsrud, Stine K., Anders M. Fjell, Christian K. Tamnes, Håkon Grydeland, Lia Mork, Paulina Due-Tønnessen, Atle Bjørnerud, et al. 2016. "Changes in White Matter Microstructure in the Developing Brain--A Longitudinal Diffusion Tensor Imaging Study of Children from 4 to 11years of Age." *NeuroImage* 124 (Pt A): 473–86. <https://doi.org/10.1016/j.neuroimage.2015.09.017>.

- Lamm, C., B. E. Benson, A. E. Guyer, K. Perez-Edgar, N. A. Fox, D. S. Pine, and M. Ernst. 2014. "Longitudinal Study of Striatal Activation to Reward and Loss Anticipation from Mid-Adolescence into Late Adolescence/Early Adulthood." *Brain and Cognition* 89 (August): 51–60. <https://doi.org/10.1016/j.bandc.2013.12.003>.
- Lebel, Catherine, and Christian Beaulieu. 2011. "Longitudinal Development of Human Brain Wiring Continues from Childhood into Adulthood." *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience* 31 (30): 10937–47. <https://doi.org/10.1523/JNEUROSCI.5302-10.2011>.
- Lebel, Catherine, and Sean Deoni. 2018. "The Development of Brain White Matter Microstructure." *NeuroImage*, January. <https://doi.org/10.1016/j.neuroimage.2017.12.097>.
- Lebel, Catherine, M Gee, R Camicioli, M Wieler, W Martin, and Christian Beaulieu. 2012. "Diffusion Tensor Imaging of White Matter Tract Evolution over the Lifespan." *NeuroImage* 60 (1): 340–52. <https://doi.org/10.1016/j.neuroimage.2011.11.094>.
- Lebel, Catherine, L Walker, A Leemans, L Phillips, and Christian Beaulieu. 2008. "Microstructural Maturation of the Human Brain from Childhood to Adulthood." *NeuroImage* 40 (3): 1044–55. <https://doi.org/10.1016/j.neuroimage.2007.12.053>.
- Leigh, S. R. 2004. "Brain Growth, Life History, and Cognition in Primate and Human Evolution." *American Journal of Primatology* 62 (3): 139–64. <https://doi.org/10.1002/ajp.20012>.
- Lenroot, Rhoshel K, Nitin Gogtay, Deanna K Greenstein, Elizabeth Molloy Wells, Gregory L Wallace, Liv S Clasen, Jonathan D Blumenthal, et al. 2007. "Sexual Dimorphism of Brain Developmental Trajectories during Childhood and Adolescence." *NeuroImage* 36 (4): 1065–73. <https://doi.org/10.1016/j.neuroimage.2007.03.053>.
- Lerch, Jason P., André J. W. van der Kouwe, Armin Raznahan, Tomáš Paus, Heidi Johansen-Berg, Karla L. Miller, Stephen M. Smith, Bruce Fischl, and Stamatios N. Sotiropoulos. 2017. "Studying Neuroanatomy Using MRI." *Nature Neuroscience* 20 (3): 314–26. <https://doi.org/10.1038/nn.4501>.
- Li, Gang, Li Wang, Feng Shi, Amanda E. Lyall, Weili Lin, John H. Gilmore, and Dinggang Shen. 2014. "Mapping Longitudinal Development of Local Cortical Gyrification in Infants from Birth to 2 Years of Age." *Journal of Neuroscience* 34 (12): 4228–38. <https://doi.org/10.1523/JNEUROSCI.3976-13.2014>.
- Lyall, Amanda E., Feng Shi, Xiujuan Geng, Sandra Woolson, Gang Li, Li Wang, Robert M. Hamer, Dinggang Shen, and John H. Gilmore. 2015. "Dynamic Development of Regional Cortical Thickness and Surface Area in Early Childhood." *Cerebral Cortex (New York, N.Y.: 1991)* 25 (8): 2204–12. <https://doi.org/10.1093/cercor/bhu027>.
- Madhyastha, Tara, Matthew Peverill, Natalie Koh, Connor McCabe, John Flournoy, Kate Mills, Kevin King, Jennifer Pfeifer, and Katie A. McLaughlin. 2017. "Current Methods and Limitations for Longitudinal fMRI Analysis across Development." *Developmental Cognitive Neuroscience*, November. <https://doi.org/10.1016/j.dcn.2017.11.006>.
- McLaughlin, Katie A., Margaret A. Sheridan, and Charles A. Nelson. 2017. "Neglect as a Violation of Species-Expectant Experience: Neurodevelopmental Consequences." *Biological Psychiatry* 82 (7): 462–71. <https://doi.org/10.1016/j.biopsych.2017.02.1096>.
- Miller, Daniel J., Tetyana Duka, Cheryl D. Stimpson, Steven J. Schapiro, Wallace B. Baze, Mark J. McArthur, Archibald J. Fobbs, et al. 2012. "Prolonged Myelination in Human Neocortical Evolution." *Proceedings of the National Academy of Sciences* 109 (41): 16480–85. <https://doi.org/10.1073/pnas.1117943109>.
- Mills, Brian D., Oscar Miranda-Dominguez, Kathryn L. Mills, Eric Earl, Michaela Cordova, Julia Painter, Sarah L. Karalunas, Joel T. Nigg, and Damien A. Fair. 2017. "ADHD and Attentional Control: Impaired Segregation of Task Positive and Task Negative Brain Networks." *Network Neuroscience* 02 (02): 200–217. https://doi.org/10.1162/netn_a_00034.
- Mills, Kathryn L, Anne-Lise Goddings, Liv S. Clasen, Jay N. Giedd, and Sarah-Jayne Blakemore. 2014. "The Developmental Mismatch in Structural Brain Maturation during Adolescence." *Developmental Neuroscience* 36 (3–4): 147–60. <https://doi.org/10.1159/000362328>.
- Mills, Kathryn L, Anne-Lise Goddings, Megan M. Herting, Rosa Meuwese, Sarah-Jayne Blakemore, Eveline A. Crone, Ronald E. Dahl, et al. 2016. "Structural Brain Development between

- Childhood and Adulthood: Convergence across Four Longitudinal Samples.” *NeuroImage* 141 (November): 273–81. <https://doi.org/10.1016/j.neuroimage.2016.07.044>.
- Mills, Kathryn L, François Lalonde, Liv S Clasen, Jay N. Giedd, and S J Blakemore. 2014. “Developmental Changes in the Structure of the Social Brain in Late Childhood and Adolescence.” *Social Cognitive and Affective Neuroscience* 9 (1): 123–31. <https://doi.org/10.1093/scan/nss113>.
- Mills, Kathryn L, and Christian K. Tamnes. 2014. “Methods and Considerations for Longitudinal Structural Brain Imaging Analysis across Development.” *Developmental Cognitive Neuroscience* 9 (July): 172–90. <https://doi.org/10.1016/j.dcn.2014.04.004>.
- Mutlu, A Kadir, Maude Schneider, Martin Debbané, Deborah Badoud, Stephan Eliez, and Marie Schaer. 2013. “Sex Differences in Thickness, and Folding Developments throughout the Cortex.” *NeuroImage* 82 (November): 200–207. <https://doi.org/10.1016/j.neuroimage.2013.05.076>.
- Olson, Ingrid R., Rebecca J. Von Der Heide, Kylie H. Alm, and Govinda Vyas. 2015. “Development of the Uncinate Fasciculus: Implications for Theory and Developmental Disorders.” *Developmental Cognitive Neuroscience* 14 (Supplement C): 50–61. <https://doi.org/10.1016/j.dcn.2015.06.003>.
- Ordaz, Sarah J, William Foran, Katerina Velanova, and Beatriz Luna. 2013. “Longitudinal Growth Curves of Brain Function Underlying Inhibitory Control through Adolescence.” *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience* 33 (46): 18109–24. <https://doi.org/10.1523/JNEUROSCI.1741-13.2013>.
- Paus, T. 2010. “Growth of White Matter in the Adolescent Brain: Myelin or Axon?” *Brain and Cognition* 72 (1): 26–35. <https://doi.org/10.1016/j.bandc.2009.06.002>.
- . 2013. “How Environment and Genes Shape the Adolescent Brain.” *Hormones and Behavior*, April. <https://doi.org/10.1016/j.yhbeh.2013.04.004>.
- Pfeifer, Jennifer H, Carrie L Masten, William E Moore 3rd, Tasha M Oswald, John C Mazziotta, Marco Iacoboni, and Mirella Dapretto. 2011. “Entering Adolescence: Resistance to Peer Influence, Risky Behavior, and Neural Changes in Emotion Reactivity.” *Neuron* 69 (5): 1029–36. <https://doi.org/10.1016/j.neuron.2011.02.019>.
- Phan, Thanh Vân, Dirk Smeets, Joel B. Talcott, and Maaïke Vandermosten. 2017. “Processing of Structural Neuroimaging Data in Young Children: Bridging the Gap between Current Practice and State-of-the-Art Methods.” *Developmental Cognitive Neuroscience*, August. <https://doi.org/10.1016/j.dcn.2017.08.009>.
- Power, Jonathan D., Bradley L. Schlaggar, and Steven E. Petersen. 2015. “Recent Progress and Outstanding Issues in Motion Correction in Resting State fMRI.” *NeuroImage* 105 (January): 536–51. <https://doi.org/10.1016/j.neuroimage.2014.10.044>.
- Qiu, Anqi, Susumu Mori, and Michael I. Miller. 2015. “Diffusion Tensor Imaging for Understanding Brain Development in Early Life.” *Annual Review of Psychology* 66 (January): 853–76. <https://doi.org/10.1146/annurev-psych-010814-015340>.
- Raznahan, Armin, Phillip Shaw, Francois Lalonde, Mike Stockman, Gregory L. Wallace, Dede Greenstein, Liv Clasen, Nitin Gogtay, and Jay N. Giedd. 2011. “How Does Your Cortex Grow?” *The Journal of Neuroscience* 31 (19): 7174–77. <https://doi.org/10.1523/JNEUROSCI.0054-11.2011>.
- Reiss, A. L., M. T. Abrams, H. S. Singer, J. L. Ross, and M. B. Denckla. 1996. “Brain Development, Gender and IQ in Children. A Volumetric Imaging Study.” *Brain: A Journal of Neurology* 119 (Pt 5) (October): 1763–74.
- Reuter, Martin, Nicholas J Schmansky, H Diana Rosas, and Bruce Fischl. 2012. “Within-Subject Template Estimation for Unbiased Longitudinal Image Analysis.” *NeuroImage* 61 (4): 1402–18. <https://doi.org/10.1016/j.neuroimage.2012.02.084>.
- Schnack, Hugo G, Neeltje E M van Haren, Rachel M Brouwer, Alan Evans, Sarah Durston, Dorret I Boomsma, René S Kahn, and Hilleke E Hulshoff Pol. 2014. “Changes in Thickness and Surface Area of the Human Cortex and Their Relationship with Intelligence.” *Cerebral Cortex (New York, N.Y.: 1991)*, January. <https://doi.org/10.1093/cercor/bht357>.
- Sherman, Lauren E., Jeffrey D. Rudie, Jennifer H. Pfeifer, Carrie L. Masten, Kristin McNealy, and Mirella Dapretto. 2014. “Development of the Default Mode and Central Executive Networks

- across Early Adolescence: A Longitudinal Study.” *Developmental Cognitive Neuroscience* 10 (October): 148–59. <https://doi.org/10.1016/j.dcn.2014.08.002>.
- Simmonds, Daniel J., Michael N. Hallquist, Miya Asato, and Beatriz Luna. 2014. “Developmental Stages and Sex Differences of White Matter and Behavioral Development through Adolescence: A Longitudinal Diffusion Tensor Imaging (DTI) Study.” *NeuroImage*. <https://doi.org/10.1016/j.neuroimage.2013.12.044>.
- Sowell, E. R., P. M. Thompson, C. J. Holmes, T. L. Jernigan, and A. W. Toga. 1999. “In Vivo Evidence for Post-Adolescent Brain Maturation in Frontal and Striatal Regions.” *Nature Neuroscience* 2 (10): 859–61. <https://doi.org/10.1038/13154>.
- Spielberg, Jeffrey M., Thomas M. Olino, Erika E. Forbes, and Ronald E. Dahl. 2014. “Exciting Fear in Adolescence: Does Pubertal Development Alter Threat Processing?” *Developmental Cognitive Neuroscience* 8 (April): 86–95. <https://doi.org/10.1016/j.dcn.2014.01.004>.
- Tamnes, Christian K., Marieke G. N. Bos, Ferdi C. van de Kamp, Sabine Peters, and Eveline A. Crone. 2018. “Longitudinal Development of Hippocampal Subregions from Childhood to Adulthood.” *Developmental Cognitive Neuroscience* 30 (April): 212–22. <https://doi.org/10.1016/j.dcn.2018.03.009>.
- Tamnes, Christian K., Megan M. Herting, Anne-Lise Goddings, Rosa Meuwese, Sarah-Jayne Blakemore, Ronald E. Dahl, Berna Güroğlu, et al. 2017. “Development of the Cerebral Cortex across Adolescence: A Multisample Study of Inter-Related Longitudinal Changes in Cortical Volume, Surface Area, and Thickness.” *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience* 37 (12): 3402–12. <https://doi.org/10.1523/JNEUROSCI.3302-16.2017>.
- Tamnes, Christian K., David R. Roalf, Anne-Lise Goddings, and Catherine Lebel. 2017. “Diffusion MRI of White Matter Microstructure Development in Childhood and Adolescence: Methods, Challenges and Progress.” *Developmental Cognitive Neuroscience*, December. <https://doi.org/10.1016/j.dcn.2017.12.002>.
- Tamnes, Christian K., Kristine B. Walhovd, Anders M. Dale, Ylva Østby, Håkon Grydeland, George Richardson, Lars T. Westlye, et al. 2013. “Brain Development and Aging: Overlapping and Unique Patterns of Change.” *NeuroImage* 68C (March): 63–74. <https://doi.org/10.1016/j.neuroimage.2012.11.039>.
- Telzer, Eva H., Ethan M. McCormick, Sabine Peters, Danielle Cosme, Jennifer H. Pfeifer, and Anna C. K. van Duijvenvoorde. 2018. “Methodological Considerations for Developmental Longitudinal fMRI Research.” *Developmental Cognitive Neuroscience*, February. <https://doi.org/10.1016/j.dcn.2018.02.004>.
- Thomas, K. M., S. W. King, P. L. Franzen, T. F. Welsh, A. L. Berkowitz, D. C. Noll, V. Birmaher, and B. J. Casey. 1999. “A Developmental Functional MRI Study of Spatial Working Memory.” *NeuroImage* 10 (3 Pt 1): 327–38. <https://doi.org/10.1006/nimg.1999.0466>.
- Tustison, Nicholas J., Andrew J. Holbrook, Brian B. Avants, Jared M. Roberts, Philip A. Cook, Zachariah M. Reagh, James R. Stone, Daniel L. Gillen, and Michael A. Yassa. 2017. “The ANTs Longitudinal Cortical Thickness Pipeline.” *BioRxiv*, July, 170209. <https://doi.org/10.1101/170209>.
- Ullman, Henrik, Rita Almeida, and Torkel Klingberg. 2014. “Structural Maturation and Brain Activity Predict Future Working Memory Capacity during Childhood Development.” *Journal of Neuroscience* 34 (5): 1592–98. <https://doi.org/10.1523/JNEUROSCI.0842-13.2014>.
- Vijayakumar, Nandita, Nicholas B. Allen, George Youssef, Meg Dennison, Murat Yücel, Julian G. Simmons, and Sarah Whittle. 2016. “Brain Development during Adolescence: A Mixed-Longitudinal Investigation of Cortical Thickness, Surface Area, and Volume.” *Human Brain Mapping*, March. <https://doi.org/10.1002/hbm.23154>.
- Vijayakumar, Nandita, Kathryn L. Mills, Aaron F. Alexander-Bloch, Christian K. Tamnes, and Sarah Whittle. 2017. “Structural Brain Development: A Review of Methodological Approaches and Best Practices.” *Developmental Cognitive Neuroscience*, November. <https://doi.org/10.1016/j.dcn.2017.11.008>.
- Vijayakumar, Nandita, Sarah Whittle, Murat Yücel, Meg Dennison, Julian Simmons, and Nicholas B. Allen. 2014a. “Prefrontal Structural Correlates of Cognitive Control during Adolescent

- Development: A 4-Year Longitudinal Study.” *Journal of Cognitive Neuroscience* 26 (5): 1118–30. https://doi.org/10.1162/jocn_a_00549.
- . 2014b. “Thinning of the Lateral Prefrontal Cortex during Adolescence Predicts Emotion Regulation in Females.” *Social Cognitive and Affective Neuroscience* 9 (11): 1845–54. <https://doi.org/10.1093/scan/nst183>.
- Wendelken, Carter, Emilio Ferrer, Simona Ghetti, Stephen K. Bailey, Laurie Cutting, and Silvia A. Bunge. 2017. “Frontoparietal Structural Connectivity in Childhood Predicts Development of Functional Connectivity and Reasoning Ability: A Large-Scale Longitudinal Investigation.” *Journal of Neuroscience* 37 (35): 8549–58. <https://doi.org/10.1523/JNEUROSCI.3726-16.2017>.
- Whittle, Sarah, Nandita Vijayakumar, Julian G. Simmons, Meg Dennison, Orli Schwartz, Christos Pantelis, Lisa Sheeber, Michelle L. Byrne, and Nicholas B. Allen. 2017. “Role of Positive Parenting in the Association Between Neighborhood Social Disadvantage and Brain Development Across Adolescence.” *JAMA Psychiatry* 74 (8): 824–32. <https://doi.org/10.1001/jamapsychiatry.2017.1558>.
- Wierenga, Lara M., Marieke G. N. Bos, Elisabeth Schreuders, Ferdi vd Kamp, Jiska S. Peper, Christian K. Tamnes, and Eveline A. Crone. 2018. “Unraveling Age, Puberty and Testosterone Effects on Subcortical Brain Development across Adolescence.” *Psychoneuroendocrinology* 91 (May): 105–14. <https://doi.org/10.1016/j.psyneuen.2018.02.034>.
- Wierenga, Lara M., Martijn P. van den Heuvel, Bob Oranje, Jay N. Giedd, Sarah Durston, Jiska S. Peper, Timothy T. Brown, Eveline A. Crone, and The Pediatric Longitudinal Imaging, Neurocognition, and Genetics Study. 2018. “A Multisample Study of Longitudinal Changes in Brain Network Architecture in 4-13-Year-Old Children.” *Human Brain Mapping* 39 (1): 157–70. <https://doi.org/10.1002/hbm.23833>.
- Wierenga, Lara M., Marieke Langen, Sara Ambrosino, Sarai van Dijk, Bob Oranje, and Sarah Durston. 2014. “Typical Development of Basal Ganglia, Hippocampus, Amygdala and Cerebellum from Age 7 to 24.” *NeuroImage* 96 (August): 67–72. <https://doi.org/10.1016/j.neuroimage.2014.03.072>.
- Wierenga, Lara M., Marieke Langen, Bob Oranje, and Sarah Durston. 2014. “Unique Developmental Trajectories of Cortical Thickness and Surface Area.” *NeuroImage* 87 (February): 120–26. <https://doi.org/10.1016/j.neuroimage.2013.11.010>.
- Wierenga, Lara M., Joseph A. Sexton, Petter Laake, Jay N. Giedd, and Christian K. Tamnes. n.d. “A Key Characteristic of Sex Differences in the Developing Brain: Greater Variability in Brain Structure of Boys than Girls.” *Cerebral Cortex*, 1–11. <https://doi.org/10.1093/cercor/bhx154>.
- Winkler, Anderson M, Peter Kochunov, John Blangero, Laura Almasy, Karl Zilles, Peter T Fox, Ravindranath Duggirala, and David C Glahn. 2010. “Cortical Thickness or Grey Matter Volume? The Importance of Selecting the Phenotype for Imaging Genetics Studies.” *NeuroImage* 53 (3): 1135–46. <https://doi.org/10.1016/j.neuroimage.2009.12.028>.
- Yakovlev, P.A., and I.R. Lecours. 1967. “The Myelogenetic Cycles of Regional Maturation of the Brain.” In *Regional Development of the Brain in Early Life.*, edited by Alexandre Minkowski. Oxford: Blackwell.
- Yendiki, Anastasia, Kami Koldewyn, Sita Kakunoori, Nancy Kanwisher, and Bruce Fischl. 2014. “Spurious Group Differences Due to Head Motion in a Diffusion MRI Study.” *NeuroImage* 88: 79–90. <https://doi.org/10.1016/j.neuroimage.2013.11.027>.
- Zatorre, Robert J., R. Douglas Fields, and Heidi Johansen-Berg. 2012. “Plasticity in Gray and White: Neuroimaging Changes in Brain Structure during Learning.” *Nature Neuroscience* 15 (4): 528–36. <https://doi.org/10.1038/nn.3045>.

Figure 1. Methods to examine structural brain changes with MRI.

(A) Horizontal slice of T1 image showing a whole brain segmentation used for volumetric analyses and (B) a left lateral view of an averaged parcellated cerebral cortex used for surface-based analyses, both from FreeSurfer. (C) Horizontal slice of TBSS mean FA white matter skeleton overlaid on a mean FA map and (D) a left lateral view of a 3D rendering of probabilistic fibre tracts from the Mori atlas.

Figure 2. Structural brain developmental trajectories.

Developmental trajectories for global measures for cerebral cortical volume, cerebral white matter volume, cortical surface area, and mean cortical thickness, adapted from Tamnes et al, 2017 and Mills et al., 2016. The coloured lines represent the GAMM fitting while the lighter coloured areas correspond to the 95% confidence intervals. Pink, NIMH Child Psychiatry Branch, Bethesda, Maryland, USA; purple, Pittsburgh Cohort, Pittsburgh, Pennsylvania, USA; blue, NeuroCognitive Development dataset, Oslo, Norway; green, Braintime dataset, Leiden, The Netherlands.