



Changing brains: how longitudinal functional magnetic resonance imaging studies can inform us about cognitive and social-affective growth trajectories

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Brain imaging studies have demonstrated widespread changes in brain networks which support cognitive and social-affective development. These conclusions, however, are largely based on cross-sectional comparisons, which limits the possibility to investigate growth trajectories and detect individual changes. Understanding individual growth patterns is crucial if we want to ultimately understand how brain development is sensitive to environmental influences such as educational or psychological interventions or childhood maltreatment. Recently, longitudinal brain imaging studies in children and adolescents have taken the first steps into examining cognitive and social-affective brain functions longitudinally with several compelling findings. First, longitudinal measurements show that activations in some brain regions, such as the prefrontal, temporal, and parietal cortex, are relatively stable over time and can be used as predictors for cognitive functions, whereas activations in other brain regions, such as the amygdala and ventral striatum, are much more variable over time. Second, developmental studies reveal how these changes are related to age, puberty, and changes in performance. These findings have implications for understanding how environmental factors influence brain development. An important future direction will be to examine individual characteristics (e.g., genetic, temperamental, personality) which make individuals differentially susceptible to their environment. © 2014 John Wiley & Sons, Ltd.

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INTRODUCTION

Between childhood and early adulthood, many significant physical, social, cognitive, and emotional changes take place,^{1,2} which are accompanied by changes in brain structure, function, and connectivity.^{3,4} First, behavioral cross-sectional research has demonstrated developmental improvements in cognitive control functions during childhood and adolescence.⁵ Consistent with these

developmental improvements, cross-sectional functional brain imaging studies have shown that regions in the lateral prefrontal cortex (PFC), anterior cingulate cortex (ACC)/supplementary motor area (SMA), and parietal cortex show a protracted development with respect to performance on these cognitive control tasks, such as in the domains of working memory,⁶ inhibition,⁷ interference suppression,⁸ and performance monitoring.⁹ Second, mid adolescence is characterized by an increase in sensitivity to social-affective influences on behavior, such as increased risk-taking in the presence of peers,¹⁰ which is accompanied by elevated neural responses in subcortical brain regions involved in reward and emotion detection and their connections.¹¹

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Cross-sectional neuroimaging studies including children, adolescents, and adults have shown that adolescents show stronger activity in the ventral striatum during reward tasks^{12,13} and in the amygdala when processing fearful faces^{14,15} compared to children and adults. Together, these findings have been interpreted in terms of heightened sensitivity of subcortical brain regions in mid adolescence, possibly related to the onset of puberty, and protracted development of cortical brain regions.¹⁶

Despite recent progress in understanding how brain maturation is mapped to the development of cognitive and social-affective functions, much less is known about how the maturation of brain function develops over time within individuals. Thus, although cross-sectional studies provide important starting points for understanding brain development, longitudinal studies are of key importance to advance our understanding of individual trajectories of cognitive control and social-affective sensitivities.⁴ In this review, we describe the first set of studies examining brain development using longitudinal measurements, which have revealed that some areas are relatively stable over time (i.e., showing test–retest stability), whereas other areas show much more variation over time. These differences in test–retest stability have important implications for interpreting neural activation as either a stable trait marker for individual characteristics or as reflecting state-like influences related to effort, stress, training, or intervention.

LONGITUDINAL BRAIN IMAGING STUDIES

Longitudinal functional magnetic resonance imaging (fMRI) studies allow us to overcome several problems which are typically associated with cross-sectional comparisons. First, longitudinal studies suffer less from potential cohort effects and therefore reduce sampling bias. Second, longitudinal studies can address the question of trait-like stability versus state-like variability of behavior and neural activity. Third, longitudinal studies allow for detecting individual patterns which are of crucial importance when trying to understand the interactions between individual characteristics and environmental influences. Fourth, cross-sectional studies are not suitable for testing mediations models,¹⁷ for example, when the goal is to test if a mediator variable (e.g., processing speed) explains the relation between age and an outcome variable (e.g., working memory). Thus, to test causal factors in development, it is crucial that the study has a within-person longitudinal design.

Ultimately, these longitudinal studies will be important to detect deviances in developmental slopes when development is going astray, such as when children develop mental disorders as anxiety, depression or attention deficit hyperactivity disorder (ADHD), or show impairments in cognitive functions.

There are now several studies which have used longitudinal approaches in the domains of cognitive control and social-affective development, which are described in the following sections (summarized in Table 1). Before we go on describing the studies that have been conducted, several methodological considerations need to be taken into account. First of all, in longitudinal studies, one key potential problem for interpretation of the results is how to disentangle normal development from practice effects, or other aspects related to repeated testing. Second, fMRI studies make use of contrasts, which makes it difficult to track down the exact source of time effects, i.e., as time effects could for example indicate a change in the ‘baseline control condition’ or in the ‘active experimental condition’. Methodological considerations for interpretation of longitudinal brain imaging studies are summarized in Box 1.

LONGITUDINAL BRAIN IMAGING STUDIES OF COGNITIVE CONTROL DEVELOPMENT

The development of cognitive control, specifically working memory and inhibition, has probably received most attention in developmental neuroimaging research using cross-sectional designs. These studies have implicated a network of lateral PFC and parietal cortex areas that differ depending on age.^{20,21}

The first study which tracked developmental change longitudinally made use of a go/nogo task and studied the development of neural regions supporting response inhibition in seven children who participated in the study at age 9 and 11 years.²² Behaviorally, mean reaction times to ‘go’ trials decreased, whereas there was no change in inhibition accuracy over time (93.5% correct at age 9 and 98.2% correct at age 11). The authors found that ventral lateral PFC, a region which is involved in successful response inhibition was recruited more at age 11 than at age 9, suggesting an increase in task-related neural recruitment. They also reported that children at age 9 recruited a more widespread area in the lateral PFC compared to when they were age 11, suggesting a shift from diffuse to focal activation. A second study focused on older adolescents and examined the neural development of working memory in 10 females at age 15 and 18 years.²³ Participants performed an *n*-back

TABLE 1 | Overview of longitudinal brain imaging studies

	Ages T1	Ages T2		Time	fMRI Paradigm
Longitudinal fMRI studies					
<i>Cognitive control</i>					
Durston	9 years	11 years	$n = 7$	2.1 years	Go/Nogo
Finn	15 years	18 years	$n = 10$	3 years	Working memory
Koolschijn	8–24 years	11–27 years	$n = 32$	3.5 years	Perf. monitoring
Ordaz	9–26 years	10–26 years	$n = 123$	Variable	Inhibition of saccades
Emerson	4–9 years	4–9 years	$N = 17$	1–2 years	Numerical processing
Dumontheil	6–18 years	8–20 years	$n = 44$	2 years	Working memory
<i>Mentalizing</i>					
Overgaauw	10–16 years	12–18 years	$n = 32$	2 years	Mentalizing
Pfeifer	10 years	13 years	$N = 27$	3 years	Self processing
<i>Faces</i>					
Pfeifer	10 years	13 years	$N = 38$	3 years	Emotional faces
Spielberg	11–12 years	13–14 years	$N = 38$	2 years	Emotional faces
Van den Bulk	12–19 years	12–19 years	$n = 27/22$	3/6 months	Emotional faces
<i>Rewards</i>					
Lamm	13–18 years	18–20 years	$n = 22$	Variable	Reward/loss anticipation
VanDuijvenvoorde	10–16 years	12–19 years	$n = 31$	2.13 years	Rewards

fMRI, functional magnetic resonance imaging.

task and were faster to respond to targets when they were 18 years compared to when they were 15 years, whereas accuracy did not change over time. The neuroimaging findings revealed that participants recruited dorsal lateral PFC, a region known to be involved in working memory,²⁴ to a similar extent at ages 15 and 18 years, suggesting no additional neural recruitment of dorsal lateral PFC in late adolescence. However, they found that adolescents at the age of 15 recruited the hippocampus, a region known for its role in memory,²⁴ more compared with those at 18 years, possibly indicating greater effort in younger adolescents. Together, these early longitudinal studies with relatively small samples suggested an early developmental increase in ventral lateral PFC related to inhibitory control and a stable developmental pattern in dorsal lateral PFC related to working memory in later adolescence. In addition, these studies indicated increased specialization of neural networks with increasing age.

The relation between brain activity and cognitive control across development was studied in greater detail in two longitudinal fMRI studies which examined behavioral and neural changes across the larger age range of childhood to adulthood. The first study examined change in performance monitoring in 32 participants between ages 8 and 27 years, with a 3.5 year gap between the first and the second measurement.²⁵ Participants had to sort stimuli in one of four locations and had to use feedback

(positive or negative) to learn the correct rule and change behavior when the prior rule was no longer correct (mirroring the Wisconsin Card Sorting Task). Performance improved considerably between ages 8 and 14 years, after which it stabilized (see Figure 2b). Neuroimaging analyzes revealed that all participants recruited the dorsal lateral PFC to a greater extent when demands on performance monitoring increased. However, only performance improvement over time, not age change per se, was associated with activation change in dorsal lateral PFC (see Figure 2c). Thus, those participants who showed a large change in performance (poor performance at the first measurement, good performance at the second measurement) also showed a large change in activation in dorsal lateral PFC (low activation at the first measurement, higher activation at the second measurement), whereas those participants who did not show a large performance change also did not show a large change in neural recruitment. Thus, taking these prior studies together suggest that changes in brain activation in cognitive control are driven by both age and performance changes over time.

An important question concerns how stable brain activation was in these networks over time, which informs us about whether neural activation is an individual index of a general trait or may change over time. To address this question the study²⁵ also analyzed reliability of neural activity

BOX 1

CONSIDERATIONS FOR LONGITUDINAL BRAIN IMAGING STUDIES

Longitudinal brain imaging studies have several advantages, such as the possibility to track individual patterns. Yet, several methodological considerations need to be taken into account.

1. fMRI studies make use of contrasts, such as when a difficult task (A) is contrasted against an easy task (B), resulting in differences in activation [A–B]. The longitudinal comparison then involves a contrast of [A–B] at time point 2 versus [A–B] at time point 1. An important consideration concerns that possible changes can be associated with increases/decreases for task A, but also with increases/decreases for task B, or with both.
2. An approach which is often used in longitudinal studies is to compare brain activity in a certain brain region (region of interest) at time point 1 with brain activity in the same region at time point 2 (see Figure 1). When an analysis shows a main effect of time, this could indicate that the activation levels increase over time for the majority of individuals (upper panel), whereas the absence of a time effect indicates no change (bottom panel). However, so far less attention is devoted to the variance within individuals. Latent growth modeling (also referred to as multilevel model for change) makes use of two or more time-points to investigate individual differences in intercepts (i.e., starting points) and slopes (i.e., patterns). That is, it can be the case that patterns are stable over time with varying intercepts but stable slopes (left panel) or it can be the case these patterns show large intra-individual variability with varying intercepts and varying slopes, for example due to time-dependent differences in responsiveness (right panel). Examining both within subjects test–retest stability (stability of the intercept) and within subjects main effects of time (slopes) is therefore informative for unraveling effects of age (i.e., time), and stability of the neural signal. Latent growth modeling has been widely used in structural brain analyzes,¹⁸ and see Ref 19 for an illustration of this approach in functional brain development analyzes.
3. It is likely that changes in a certain brain region do not occur in isolation, but are part

of developmental changes within a larger network (e.g., diffuse spread of activation to more localized activity, or vice versa). As such, longitudinal brain imaging analyzes require not only a focus on a priori selected regions, but also explorative (connectivity) analyzes which can detect change in a wider network of areas.

within individuals over time and indicated that activity in dorsal lateral PFC and parietal cortex showed modest to good test–retest stability within participants over time when participants were between ages 14 and 27 years, even over periods of more than 3 years. In contrast, for participants between ages 8 and 14 years, the period during which performance increased, this test–retest stability was much lower. This latter finding is consistent with the hypothesis that increases in cognitive control performance and associated neural recruitment is most pronounced in childhood,²⁰ and suggests that after the age of 14 activation patterns are stable.

Similar findings were reported in a recent study which examined behavior and neural changes in cognitive control across the whole age period of childhood to adulthood. This study tested 123 participants between ages 9 and 26 years who participated 2–5 times in the fMRI study (302 sessions in total), which allowed for the latent modeling of growth functions.¹⁹ Participants performed an oculomotor tasks which involved prosaccades (eye movements to a target location) and antisaccades (inhibition of eye movements to a target location). Using latent growth curve modeling, the authors showed that antisaccade errors decreased over time. The neuroimaging findings were analyzed in terms of motor control (prosaccades), executive control (antisaccades), and error monitoring (failed saccades). The authors observed a developmental decrease in activation in dorsal lateral PFC, a region related to executive control. The most robust developmental increase over time was observed in activation in ACC during error monitoring of failed antisaccades, such that with increasing age the ACC was more active when monitoring errors.

This study also addressed the question of test–retest reliability over time and showed modest to good test–retest reliability in the PFC, ACC, and parietal cortex, but poor reliability in the putamen, a region of the basal ganglia often implicated in cognitive control.¹⁹ Thus, these two cognitive control studies which examined test–retest reliability reported modest to good reliability for several cortical

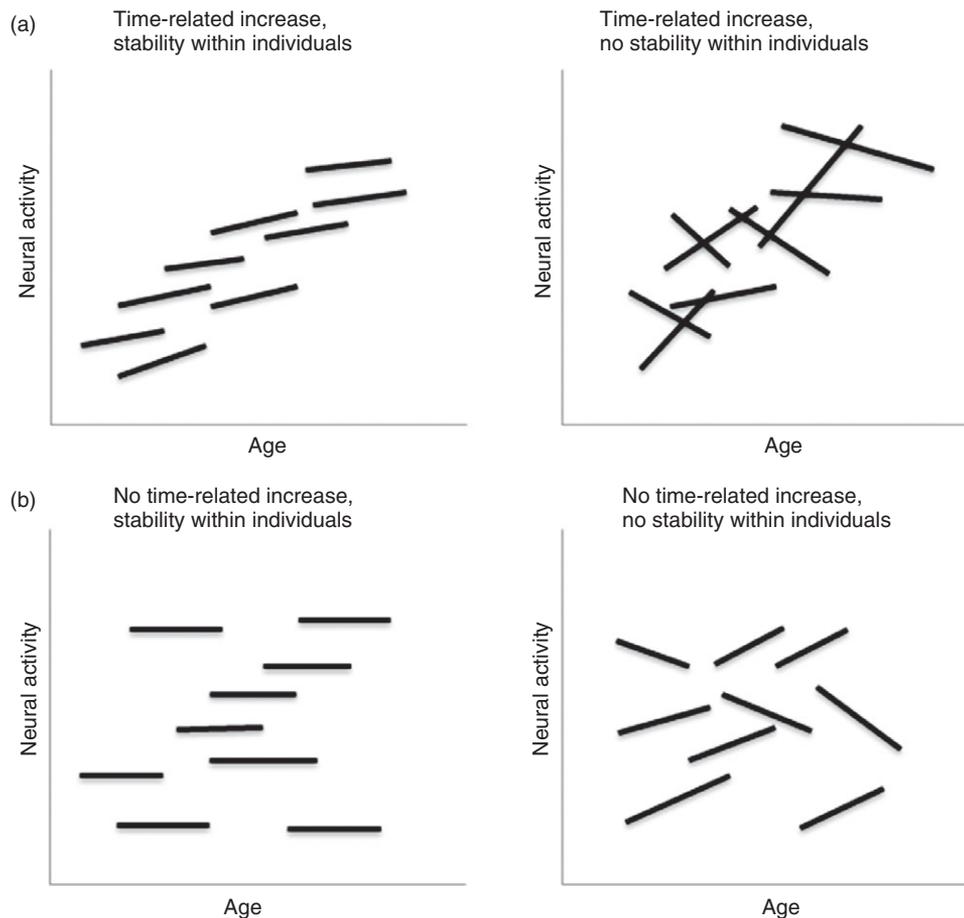


FIGURE 1 | Examples of longitudinal brain patterns. Neural changes can be characterized by the absence or presence of time/age-related changes, and the absence or presence of stability over time.

regions associated with inhibition and performance monitoring, but poor test–retest reliability for subcortical regions. An important question concerns what determines differences in brain activity between individuals.^{19,25} One important contributor is effort, or behavioral performance, given that there was an association between task performance and brain activity.²⁵

Finally, stability, and change was also detected in a longitudinal study using a numerical processing task, a process which has previously been related to cognitive control. This study included 17 children between ages 4 and 9 years who were tested twice in a period of 2–3 years using fMRI.²⁶ This study reported general increases in numerical processing between the two testing sessions and furthermore, they found that intraparietal sulcus (IPs) was uniquely involved in this process. Interestingly, the longitudinal comparisons revealed high test–retest correlation in right IPS, suggesting stability over time, whereas left IPS change over time correlated with improvement in performance over time.

Thus, also for the IPS region there were interesting indices of both stability and performance-related change.

One possibility is that changes in activation in lateral PFC, parietal cortex, and ACC during cognitive control tasks are dependent on individual genetic differences, for example related to COMT genotype, a gene that is involved in the regulation of the dopamine system.²⁷ This question was tested in a longitudinal behavioral and brain imaging study which examined 260 participants who were tested twice behaviorally, and 44 participants who were tested twice or three times using fMRI between ages 6 and 18 years. In the context of a working memory task which was relatively easy, carriers of the Val/Val COMT genotype showed a developmental increase in neural activation in ventral lateral PFC and angular gyrus, whereas the Met/Met carriers did not. However, Met/Met carrying individuals showed a steeper increase in performance over time than Val/Val carriers in a more challenging working memory task in which they could not easily reach ceiling levels.²⁷ One possibility is that

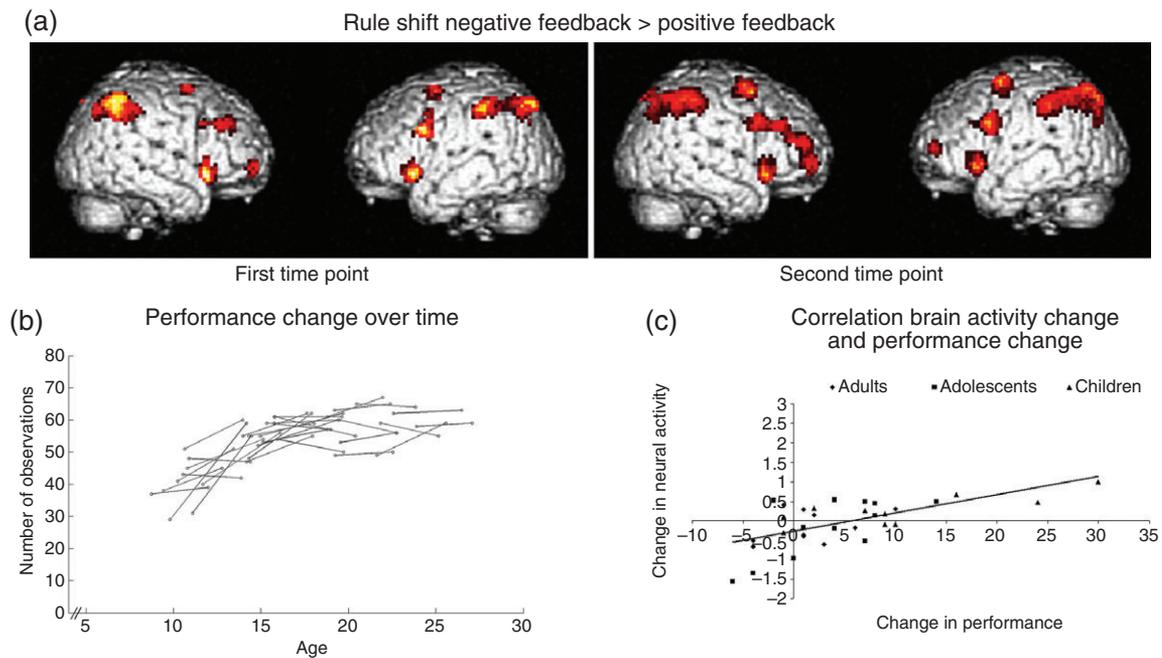


FIGURE 2 | Longitudinal brain activity during performance monitoring.²⁵ (a) A set of lateral prefrontal cortex (PFC) and parietal cortex regions was more active when processing feedback signaling a rule shift in comparison with positive feedback, at both the first and the second time point. (b) Performance increased rapidly in childhood and early adolescence after which it stabilized. (c) Brain activity in lateral PFC was correlated with performance changes over time.

the dopamine changes are non-linear and affect performance and brain activity differently depending on whether the task is relatively easy (the fMRI task) or tap the individual's maximal performance in terms of difficulty (behavioral tasks). These findings provide some interesting starting points for future studies examining how individual genetic differences may shape the developmental trajectories within the brain.

A final question concerns whether brain activation indices can also predict future development of cognitive functions. That is to say, fMRI measures may provide a more direct evaluation of the neural substrate involved in a certain process and may therefore have additional predictive value for developmental trajectories, for example involving school performance.

The relation between neural activity related to cognitive control and arithmetic, an important school-based outcome, was addressed in a longitudinal study. The researchers analyzed whether brain activity during a working memory task has additional predictive power for arithmetic performance 2 years later above the behavioral measures. Consistent with their prior findings, working memory demands were associated with increased activation in the lateral PFC and IPS.²⁸ Furthermore, consistent with earlier behavioral studies,²⁹ working memory performance

predicted arithmetic performance 2 years later. Crucially, adding activation in IPS to the regression model showed that arithmetic performance 2 years later could be predicted better. These findings are important in showing that brain imaging data are not only a neural correlate of behavior, but can also provide additional information above behavioral indices.

LONGITUDINAL BRAIN IMAGING STUDIES OF SOCIAL-COGNITIVE DEVELOPMENT

Brain regions involved in social-cognitive functioning partly overlap with brain areas implicated in cognitive control (such as the lateral PFC and parietal cortex) but also involve other brain regions [such as the temporal pole, the superior temporal sulcus (STS), and the dorsal medial PFC], which have together been referred to as social brain regions.³ A typical task that shows recruitment of this social brain network is the Reading the Mind in the Eyes, in which participants have to make a selection of mental states displayed by the eye region of a face.³⁰ Using the Reading the Mind in the Eyes Task, a longitudinal study analyzed neural responses during task performance in 32 participants between ages 10 and 16 years and 2 years later

at ages 12–18 years.³¹ Behaviorally, accuracy in the Reading the Mind in the Eyes condition (also referred to as the mentalizing condition) did not change over time and correlated from session 1 to session 2, suggesting that participants performed equally well at both time points. In the Reading the Mind in the Eyes condition, participants showed increased activation in the bilateral ventral lateral PFC, STS, and temporal poles. The longitudinal comparison showed that within individuals there was stability over time in the recruitment of the ventral lateral PFC and temporal cortex (specifically the STS), such that signal strength for the experimental condition relative to the control condition at the first measurement correlated with signal strength in the same contrast at the second measurement. In contrast, neural activity in the medial PFC decreased over time, consistent with prior cross-sectional studies.^{30,32,33} There was, however, no significant association between performance change and change in neural activity, which leaves open the question whether performance and neural activation provide separate complementary information about the ability to reason about intentions, or if there are additional factors driving both patterns.

The question of change in the mentalizing areas of the brain was also addressed in a study in which 27 children were tested at age 10 and 13 years, and were asked to make evaluations about themselves and about Harry Potter. Making evaluations about self ('self' mentalizing) was associated with increased activation in medial PFC whereas making evaluations about Harry Potter ('other' mentalizing) was associated with activation in posterior cingulate cortex and temporal parietal junction. This study did not report test–retest stability measurements, but the whole brain contrast suggested no change in neural activity between age 10 and 13 years in the dorsal medial PFC and TPJ. A region in ventral medial PFC, however, was associated with an increase in activation in relation to an increase in self-reported puberty over time.³⁴ Future studies should examine the developmental patterns of these subregions in medial PFC in more detail.

Taken together, these findings show that at least for activation in ventral lateral PFC (specifically inferior frontal gyrus) and STS, the activity patterns in social-cognitive tasks have commonalities with the activity pattern in non-social tasks, such as working memory and inhibition tasks, showing relative stability within individuals over time. In addition, the studies reveal longitudinal change in medial PFC. Future studies should examine the direction of change in relation to performance.²⁵

LONGITUDINAL BRAIN IMAGING STUDIES OF SOCIAL-AFFECTIVE DEVELOPMENT: FACES

On the basis of cross-sectional studies, it was previously argued that adolescent development is characterized not only by protracted development of the lateral PFC, temporal cortex, and parietal cortex, but also by heightened sensitivity of subcortical brain regions in response to (social-)affective stimuli and their connections.¹⁶ Evidence for this hypothesis comes from cross sectional studies which have reported that, for example, adolescents show stronger amygdala responses to emotional faces.^{14,15} This same question was addressed longitudinally by examining developmental changes in 38 children at age 10 and 13 years.³⁵ This age range was chosen because it is assumed that brain regions which respond to emotional faces show heightened sensitivity when entering adolescence.³⁶ In this study, participants watched neutral, angry, fearful, sad, and happy faces without behavioral requirements, and showed activation in the amygdala, ventral striatum, and ventromedial PFC in response to viewing faces. They further showed that especially activity in the ventral striatum and the ventral medial PFC increased over time, whereas activation in the amygdala did not change, although test–retest reliability was not specifically measured in this study. More specific analyses revealed that amygdala activity increased only when participants were viewing sad faces, but not for the other emotional or neutral faces.

These researchers related the changes in neural activity in response to viewing emotional faces to changes in self-reported resistance to peer influence and observed that an increase in ventral striatum activity to emotional faces was associated with an *increase* in resistance to peer influence and *decrease* in self-reported risky behavior.³⁵ Although possibly not predicted beforehand, these findings were interpreted to suggest that ventral striatum activity may have a role in developing skills for healthy interpersonal functioning. Affective displays by peers can strongly impact behavior and as such a stronger emotional responses to emotional faces may be associated with improved social behavior.

To test the role of puberty, and more specifically pubertal hormones, a recent study examined change in amygdala and striatum activation in 38 participants 2 years apart.³⁷ They selected 11–12-year-old girls and 12–13-year-old boys because this narrow age range allowed them to separate effects of age and puberty. Participants viewed angry, fearful, and neutral faces in a blocked design and had to select which of

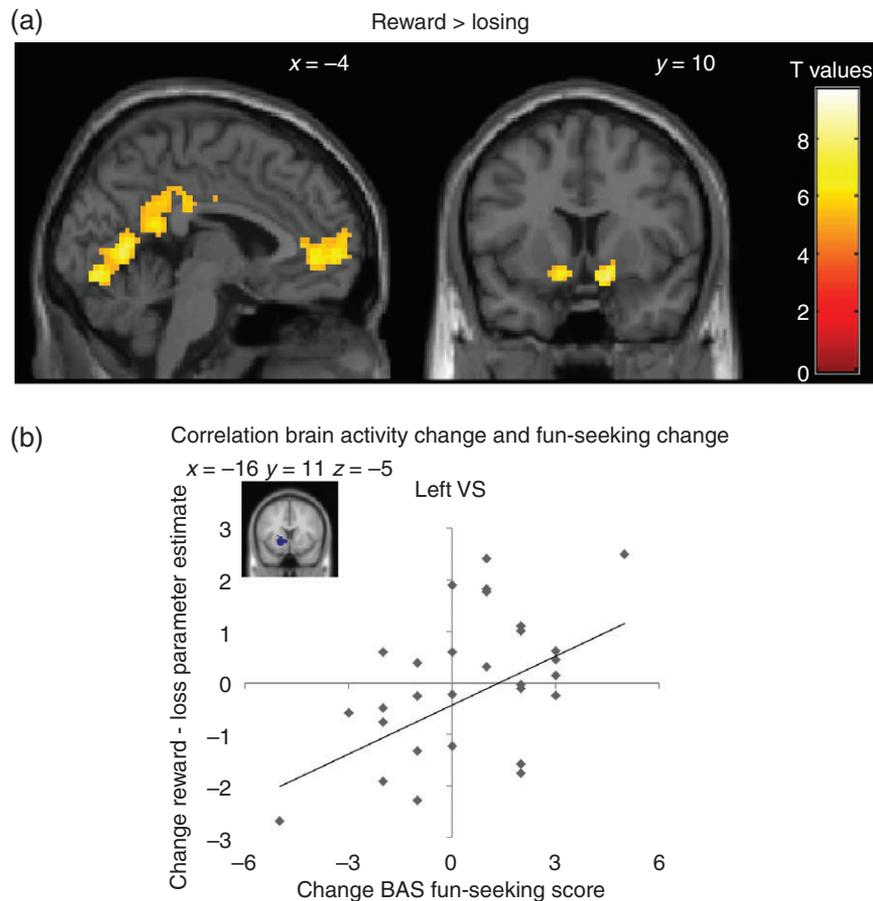


FIGURE 3 | Longitudinal brain activity when receiving rewards.⁴¹ (a) The bilateral ventral striatum, medial prefrontal cortex (PFC), and precuneus were more active when receiving rewards relative to losses in a gambling task. (b) Longitudinal change in brain activity following rewards was correlated with longitudinal change in fun-seeking.

two faces at the bottom of the screen matched a target face presented at the top half of the screen. There was no significant change in reaction time to faces over time. In terms of neural activity, increase in testosterone levels was positively correlated with increase in amygdala and nucleus accumbens to fearful faces. These findings were interpreted to suggest that subcortical brain regions previously associated with threat (amygdala) and reward processing (nucleus accumbens) were related to change in testosterone levels, highlighting again that puberty may be an important driving force for the observed increase in subcortical activation in adolescence.³⁷

Altogether, amygdala response was found to be variable over time, possibly indexing emotional responsiveness at that time. This was also concluded in a longitudinal study in which 27 adolescents between ages 12 and 19 years were scanned twice, and 22 of those three times within a 6 month time window.³⁸ Participants were asked to view emotional faces and give responses to specific questions related to their

emotional state (e.g., how happy are you?). The results from the whole brain comparison revealed strong activity in the amygdala when viewing emotional faces, but no change over time, mirroring the effects reported earlier.³⁵ In addition, an analysis of test–retest reliability of neural activity was performed by comparing signal strength per individual, focusing on the amygdala, lateral PFC, and occipital cortex (the latter as a control region). Test–retest reliability was high for occipital cortex, moderate for lateral PFC, but low for amygdala activity. So far, it is unknown whether this is mainly due to the smaller size of the amygdala versus the lateral PFC, or if this is indicative of more state-dependent influences, for example in emotional state, which may be highly variable over time.

Together, these findings indicate that amygdala activity and ventral striatum/nucleus accumbens activity when viewing emotional faces is not by definition stronger when children become older, but may depend on individual characteristics, such as the stage

of pubertal development. In addition, activity in amygdala may be situation-dependent, so that adolescents may show stronger amygdala reactivity during or immediately after stressful circumstances (e.g., romantic break up, conflicts with parents), which may normalize once the situation is stabilized.³⁷

LONGITUDINAL BRAIN IMAGING STUDIES OF SOCIAL-AFFECTIVE DEVELOPMENT: REWARDS

A further way in which heightened reactivity of subcortical brain regions to (social-)affective stimuli has been studied is by examining neural responses to anticipation and receipt of risk and rewards. Cross-section comparisons have been inconclusive with respect to whether adolescents show heightened or reduced activation in the dorsal and ventral striatum when *anticipating* rewards or losses. A longitudinal study compared neural activation when anticipating reward and losses in the Monetary Incentive Delay (MID) task in 22 adolescents between ages 13 and 18 years and again when participants were between ages 18 and 20 years. The results showed that with increasing age, adolescents became less accurate in anticipating losses and showed more activation in the dorsal striatum when anticipating gains and losses. This study only examined mean changes across the group and did not examine stability of behavior or neural signals over time.³⁹

Cross-sectional comparison studies have further shown that adolescents typically show higher activity in the ventral striatum to *receiving* rewards than children and adults.⁴⁰ A longitudinal study addressed the question whether the ventral striatum changed in activity when receiving rewards in a gambling task.⁴¹ In total, 31 participants were scanned twice, once between 10 and 16 years and once again between 12 and 19 years, with an average time interval of 2 years. Participants played a gambling task where each choice could be followed by rewards or losses and the critical contrast concerned reward > loss. There was no general increase or decrease in risk taking behavior over time, but risk taking behavior at measurement 1 correlated with risk taking behavior 2 years later. Even though both the ventral striatum and the ventral medial PFC showed robust activity in response to receiving rewards (see also Ref 13), there was no significant change in activation over time, and correlations between activity at both measurements were low.

However, this study also showed that change in ventral striatum activity in response to reward over time was positively correlated with the change

in self-reported fun seeking over time (see Figure 3). Thus, those individuals showing an increase in fun seeking over time, also showed more ventral striatum activation to rewards over time. These findings suggest that the ventral striatum, similar to the amygdala, may be more dependent on the emotional state. Future longitudinal studies with larger samples and participants of varying ages are necessary to unravel the dynamics of age increases and decreases in relation to anticipation and receipt of rewards in risk taking tasks.

CONCLUSION

Why do some children adapt better to environmental change than others? What are the neural predictors for positive and negative developmental outcomes? The longitudinal fMRI data reported in this review provide several important conclusions for moving the field toward detecting developmental change and unraveling predictors for change.

The longitudinal fMRI studies available to date suggest that several cortical brain areas show stability over time when performing cognitive tasks, at least for late adolescents and adults, and that activity patterns are related to task performance. It is often assumed based on structural brain imaging data that the cortical regions, especially regions implicated in cognitive control, show the most protracted developmental trajectories.^{42,43} The findings reviewed in this paper based on longitudinal fMRI studies suggest that developmental changes can occur within relative stability, that is to say, within a certain window of opportunity there may be changes in the slope of the time course while the windows (i.e., the intercepts) may differ between individuals.⁴⁴ As such, the developmental trajectory of an individual, especially in relation to behavior, yields much more information in understanding change compared to single time points.

The activation patterns in subcortical brain regions were found to be more variable over time. The relative instability of subcortical brain regions, such as the amygdala, may seem surprising given the consistent findings from prior studies reporting an adolescent peak in activity in these areas.^{11,40} One explanation for this may be that some adolescents have temperaments, or hormonal changes, that make them more sensitive to (social-)affective influences than others. Even though on average adolescents may show heightened sensitivity in this network, there are marked individual differences with some adolescents showing neural responses similar to children and/or adults, and others showing heightened emotional responses. It should be taken into account that

these differences might in part reflect differences in measurement reliability of cortical versus subcortical brain regions. In addition, this may also be due to actual relative instability of subcortical brain regions.

Future longitudinal studies should test if social-affective fluctuations are specific for some individuals but not for others, and should test whether some individuals show more fluctuations in social-affective sensitivity than others, taking into account personality characteristics as well as the effects of (early) life experiences. Prior longitudinal brain imaging studies have not yet examined in great detail individual differences in responses to childhood experiences but it is likely that these

experiences explain variability in responsiveness to social-affective cues. An important direction for future research will be to get a better understanding of individual differences in the developmental window of opportunity, for example, caused by individual differences in temperament or genetic influences in combination with different early life experiences. This may inform us on why some children show negative or positive developmental trajectories, or recover better or worse from adverse environmental circumstances than others.⁴⁵ Unraveling these sensitivities will be of great importance for tracking developmental change and eventually tailor home environments and school interventions to the needs of individual children.

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