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## **Understanding the changing adolescent brain**

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**February 2009**

### **Summary**

Recent brain imaging studies have demonstrated that the human brain continues to develop throughout the adolescent years. Although there are differences between male and female teenagers in terms of the time course of neural development, similar brain areas undergo significant restructuring in both sexes. Brain regions in which development is particularly protracted include the prefrontal cortex and the temporalparietal cortex. These regions are involved in a number of cognitive functions, including decision-making and social cognition (the understanding of other people). The development of these brain regions might contribute to behaviours typically associated with the teenage years, such as increased risk-taking, susceptibility to peer pressure, and reduced self-control. These findings have potentially important implications for how we as a society treat this age group. For example, research on decision-making and impulse control might influence questions of criminal responsibility and anti-social behaviour. Additionally, future research might play a role in shaping educational and social policy, with a view to encouraging a more socially competent and responsible generation of teenagers.

**Keywords:** brain, neuroscience, adolescence, young people, psychology, development

### **Development of the brain during adolescence**

Adolescence in humans is the period of psychological and social transition between childhood and adulthood. The beginning of adolescence, around the onset of puberty, is characterised by dramatic changes in hormone levels and, as a result, in physical appearance. This period of life is also characterised by psychological changes in terms of identity, self-consciousness and mood. After puberty, children become more aware of the opinions and emotions of both themselves and other people around them. The typical teenager is more moody and uncommunicative than a younger child (at least towards adults), and may take unnecessary risks. In addition, there are educational changes: some children go through an educational performance dip in Year 8 (age 12-13). Hormonal fluctuations alone might not account for these changes; recent neuroscience research shows that there are also dramatic transformations in the brain during adolescence.

Much has been known about early brain development since experiments on animals carried out in the 1950s and 1960s. One major developmental process affects the 'wiring' of brain cells (neurons) - the intricate network of connections (synapses) between neurons. Early in development, the brain begins to form new synapses, so that the synaptic density - the number of synapses per unit volume of brain tissue - greatly exceeds adult levels. This process of synaptic proliferation, 'synaptogenesis', lasts up to several months, depending on the species of animal (Rakic et al, 1986; Bourgeois et al, 1994).

The increase in the number of synapses is followed by a period of synaptic elimination (or pruning) in which excess connections wither away. This process is pre-programmed to a large extent - it will happen in all environments. However, the environment can also influence synaptic pruning (Hubel and Wiesel, 1964), in that frequently used connections are strengthened and infrequently used connections eliminated. Indeed, this research has been used to argue that ages zero to three represent a 'critical period' for brain development. However, this argument neglects the fact that the animals in which this early development research was carried out, such as cats and monkeys, do not go through the same extended developmental period as humans, and are sexually mature at a much younger age.

This research suggested that brain development is particularly sensitive to environmental influences very early in life. It was not until the 1970s that research on post-mortem human brains revealed that some areas of the human brain, in particular the frontal cortex, continue to develop well beyond childhood. The frontal cortex is the area responsible for cognitive abilities such as the ability to make plans, to remember to do things in the future, to multi-task, and it inhibits inappropriate behaviour (executive functions). The frontal cortex also plays an important role in self-awareness and understanding other people. Peter Huttenlocher, at the University of Chicago, collected post-mortem brains from humans of all ages and found that the frontal cortex was remarkably different in the brains of pre-pubescent children and post-pubescent adolescents (Huttenlocher et al, 1979, 1983, 1997). While in sensory brain areas such as the visual cortex, synaptogenesis and synaptic pruning occur relatively early and synaptic density has reached adult levels by mid-childhood, synaptic reorganisation in the frontal cortex continues until well into adolescence. Huttenlocher found that the number of synapses in the frontal lobe is high around puberty, after which their number decreases (due to synaptic pruning) throughout adolescence.

Another developmental mechanism that occurs for several decades in the frontal cortex is myelination. As neurons develop, they build up a layer of myelin on their axon (the long fibre transmitting signals from each brain cell). Myelin is a fatty substance that insulates the axons and vastly increases the speed of transmission of electrical impulses from neuron to neuron. Whereas sensory and motor brain regions become fully myelinated in the first few years of life, axons in some cortical regions, particularly the frontal and parietal lobes, continue to be myelinated well into adolescence in the human brain (Yakovlev and Lecours, 1967). This finding suggests that the transmission speed of neurons in these areas may increase after puberty.

### **Recent MRI studies of the developing brain**

Until recently, the structure of the human brain could be studied only after death. In recent years, non-invasive brain imaging techniques, particularly Magnetic Resonance Imaging (MRI), have enabled scientists to study development of the living human brain. In the past decade, a number of MRI studies have provided further evidence of the ongoing maturation of the cortex into adolescence and even into adulthood. These studies show that the amount of white matter in various cortical regions, including the frontal cortex and temporo-parietal cortex, increases between childhood and adulthood (Giedd et al, 1999; Paus et al, 1999, 2001; Durston et al, 2001). Myelin appears white in

MRI scans. Therefore, the increase in white matter seen to occur throughout adolescence may represent an increase in axonal myelination.

At the same time, there is a change in the volume of grey matter (made up of cell bodies, dendrites and synapses) in various cortical regions during adolescence (Giedd et al, 1999; Sowell et al, 1999; Gogtay et al, 2004). Several large MRI studies, which have acquired brain scans from hundreds of people of different ages, have consistently shown that grey matter volume in the frontal cortex increases gradually during childhood and peaks at around the onset of puberty (around 11 in girls and 12 in boys) (Giedd et al, 1999). This is followed by a gradual decrease in the volume of grey matter during adolescence and early adulthood. It has been suggested that this pattern of grey matter development may, in part, be due to an increase in the number of synapses during childhood, followed by synaptic pruning during adolescence (eg Giedd et al, 1999).

### **Cognitive development during adolescence**

The brain regions that undergo particularly protracted development during adolescence, that is prefrontal and temporo-parietal cortices, are involved in a variety of cognitive abilities, including executive functions and social cognition. In the past few years, empirical research has looked at the cognitive changes that occur during adolescence. As yet we do not know how these relate directly to the structural brain changes described above, but research in this area is progressing rapidly.

### **Development of self-concept during adolescence**

Anecdotal evidence and self-reported data indicate that children become progressively self-conscious and concerned with other people's opinions as they go through puberty and adolescence (Adams and Berzonsky, 2003). The period of adolescence seems to involve both the establishment of a sense of self as well as a process of orienting towards others. The emergence of the social self is marked by a period of heightened self-consciousness, during which adolescents become preoccupied with other people's concerns about their own actions, thoughts and appearance. Social psychological studies have investigated changes in social thinking during adolescence and emphasise that this phase is characterised by a focus on "what other people think".

Social psychologists have posited several theories regarding this apparent increase in social and emotional sensitivity. Elkind's (1967) twin constructs, the Imaginary Audience (IA) and Personal Fable (PF) have been particularly influential. According to the IA theory, adolescents believe that everyone is as concerned about their behaviour as they are, and construct an abstract (and imaginary) audience observing their every move. The PF, on the other hand, is the tendency for adolescents to believe they are unique, invulnerable, and destined for greatness. Between them, the IA and PF cover many behaviours regarded as particular to adolescence: heightened self-consciousness, increased concern with the opinions of others, and susceptibility to peer pressure (IA); and reckless behaviours such as drug use and unprotected sex (PF). Although it is generally accepted that many (though not all) adolescents go through a phase of constructing IAs and PFs, there is little consensus as to why they do so, or the underlying neural basis (Vartanian, 2000).

Elkind's (1967) own explanation was that the IA and PF arise from cognitive development between childhood and adolescence, and that this phase is characterised by 'cognitive egocentrism' ie a difficulty in differentiating one's own thoughts from those of others. The idea of a developing 'self-concept' is at the centre of many theories of adolescent social adjustment. Although the precise definition varies between studies, it is generally conceptualised as the way in which individuals view and treat themselves, and is seen as a product of interpersonal interactions (Benjamin, 1993; Ybrandt, 2008). A recent study found that having a negative self-concept (high scores on self-hate, self-

neglect and self-blame) was associated with both internalising behaviours such as depression and anxiety, and externalising behaviours such as delinquency and aggression (Ybrandt, 2008). Therefore, it is important that adolescents are supported emotionally as they develop their self-concept. While such findings have immediate real-world applicability, however, they tell us little about the underlying brain mechanisms. Furthermore, it is difficult to disentangle cause and effect. Does having a negative self-concept cause depression and anxiety, or *vice versa*? Or are both caused by a third factor?

### **The development of perspective-taking during adolescence**

The brain regions that undergo the most significant development during adolescence include those areas involved in self awareness and in the ability to understand other people's perspectives. Given that the social environment dramatically changes during adolescence, and that the brain undergoes a restructuring process, it might be expected that social cognitive abilities such as self awareness and perspective-taking develop during this period.

We recently investigated the development of perspective taking during adolescence (Choudhury et al, 2006). Pre-adolescent children (age 9 years), adolescents (age 13 years) and adults (age 24 years), were tested using a perspective-taking task. In the First Person Perspective (1PP) condition, the participant was asked to imagine how s/he would feel in various scenarios. An example of such a scenario was "You just had an argument with your best friend. How do you feel?" In the Third Person Perspective (3PP) condition, the participant was asked how someone else would feel in the same set of scenarios. The participant was asked to choose one of two possible emotions in answer to each question, as quickly as possible. The results demonstrated that the difference in reaction time (RT) between 1PP and 3PP decreased significantly with age. The difference in RT in both groups of younger participants was larger and spread almost equally in both directions, whereas among adults there was little difference in timing for 3PP and 1PP. A similar RT to 3PP and 1PP, as shown by the adult group, is likely to indicate the highest proficiency in perspective taking. In contrast, the most pronounced difference in RT between 1PP and 3PP, seen in the pre-adolescent group, would indicate relatively inefficient processing. It might be speculated therefore that, prior to adolescence, the difference in RT reflects an immature cognitive mechanism for perspective-taking. Whether this response pattern among the adolescents is a result of a relative difficulty in differentiating between the first- and third person, or because children of this age group are less inclined, or find it more difficult, to enter into another person's 'mental shoes,' requires further investigation. The differences between age groups may also be influenced by differences in social experience. Compared with children and adolescents, adults are generally more skilled at instinctively inferring the perspectives of other people. Perhaps adults show no difference between RTs for 1PP and 3PP as a result of their mature neural circuitry supporting social cognition, as well as their greater social experience.

### **Functional development of the social brain during adolescence**

Recent functional neuro-imaging studies have investigated social brain development during adolescence and there is some indication that, for social cognitive tasks, activity in the frontal cortex decreases between adolescence and adulthood. A recent fMRI study investigated the development of this ability by asking participants to think about what action they would take given a particular intention (Blakemore et al, 2007). Adolescents (aged 12-18) and adults (aged 22-37) were scanned while answering questions about intentional causality (e.g. "You want to see what's on at the cinema; do you look in a newspaper?"), or physical causality (eg "A huge tree suddenly comes crashing down in a forest; does it make a loud noise?"). Consistent with the self/social knowledge study described above, adolescents activated part of the dorsal MPFC more than did adults when thinking about their own intentions compared to during physical causality

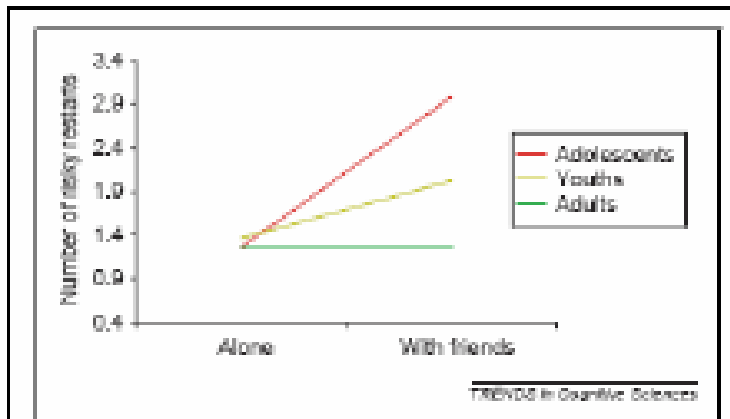
judgments. In contrast, in the same comparison (intentional – physical), adults activated part of the right superior temporal sulcus more than did adolescents.

A different fMRI study investigated the development of high level communication using an irony comprehension task and found that children (aged between 9 and 14) engaged frontal regions (medial PFC and left inferior frontal gyrus) more than did adults (Wang et al, 2006). A similar result was found in a recent fMRI study that investigated changes during adolescence of the neural processing of social emotion in the first- or third-person perspective (Burnett et al, 2008). Adult (age 22 to 32) and adolescent (age 10 to 18) participants read scenarios that described either social emotions (guilt or embarrassment) or basic emotions (fear or disgust), and were asked to imagine these scenarios happening either to themselves (self condition) or to someone else (their mother – other condition). First, activity in the dorsal MPFC during social relative to basic emotion was higher in the adolescent group than in the adult group. Second, the left temporo-parietal junction (TPJ) showed differential activity to protagonist and emotion, depending on age group. Specifically, this region differentiated better between self and other in adults than it did in adolescents, while in adolescents the left TPJ was more responsive to the difference between social and basic emotion irrespective of perspective.

These results suggest that the neural strategy for social and self understanding changes between adolescence and adulthood. Although the same neural network is active, the relative roles of the different areas change, with activity moving from anterior (medial prefrontal) regions to posterior (temporal) regions with age. One possible explanation for the decrease in prefrontal activity between adolescence and adulthood in these studies is that the PFC is still being organised during adolescence, and is therefore less efficient: more activity is required to achieve the same task (see Blakemore, 2008, for review). Further studies are needed to explore this possibility.

### **Susceptibility to peer influence**

Adolescents are particularly susceptible to peer influence (Steinberg and Silverberg, 1986). The consequences of peer influence have been well researched, both in the laboratory and in a socio-cultural context. For example, it has been found that, while adults who commit crimes do so alone, most adolescent crimes are committed with peers (Zimring, 1998). This suggests that peer influence may contribute to teenage engagement in inherently risky activity (although it may also reflect the fact that teenagers spend more time with peers than do adults). A recent laboratory study by Gardner and Steinberg (2005) looked at incidences of risky driving in a car simulation video game when adolescents and adults played either alone or with two friends present. It was found that the presence of peers led to an increase in risky driving, for example, failing to stop at a yellow traffic light, specifically in adolescents. Levels of risk taking did not differ for adult participants depending on whether they were alone or with peers, and adolescents showed the same level of risk taking as adults when they were alone. However, in the presence of peers, the number of risks taken was greatly increased (see Figure 1).



**Figure 1: The number of risks taken by adults did not differ depending on whether participants were alone or with friends. However, adolescent risk-taking increased dramatically when participants were with friends. Taken from Steinberg et al. (2005)**

These findings suggest that decision-making and planning are more fallible in adolescents when in the presence of peers. The immaturity of the PFC could explain these consequences, in that the developing system is less able to cope under added emotional pressure. This is a plausible but speculative idea which needs further work. At present, cognitive neuroscience has not addressed whether the immaturity of the PFC could also explain the susceptibility to peer pressure in the first place.

## Gender differences

Cognitive changes during adolescence may not be equally applicable to males and females, or they may follow different time courses. Anatomically, sex differences have been reported in grey and white matter volume during adolescence (Yurgelun-Todd et al, 2002), as well as in the time course of neural development (Giedd et al, 1996, 1997), with grey matter volume peaking at around age 11 in girls and age 12 in boys. Links between anatomical differences and behaviour are also apparent. A recent study (Silveri et al, 2006) looked at impulse control (the ability to control and regulate behaviour), and found that different regions of white matter were associated with task performance in male and female teenagers. The findings suggest subtle differences in the brain networks recruited for cognitive control by males and females during development. Such gender differences at the neural level may help to explain behavioural differences in executive processes such as decision-making and risk assessment. For example, several studies have found that, relative to females, male adolescents give more weight to the potential benefit of a risk than its potential costs (Gardner and Steinberg, 2005), and are also more prone to risk-taking in the presence of peers (Parsons et al, 2000).

Gender differences in social behaviour have also been well documented during the adolescent years. For example, young adolescent females are much more likely to use social aggression such as ostracism during interpersonal interaction (Cairns et al, 1989), while males tend to use physical aggression. Additionally, teenage girls who have a negative self-concept (high levels of self-hate, self-neglect and self-blame) are more likely to engage in internalising behaviours, ie depression, anxiety and withdrawn behaviour, while boys tend to engage in more outwardly aggressive externalising behaviours (Moffitt et al, 2001; Roussos et al, 2001).

The next step is to link these social observations with what we are learning about the brain. Brain development patterns may shed light on gender-related differences in the

onset of various mental illnesses (Silveri et al, 2006; Kovacs et al, 2003; Evenson et al, 1993). This is especially likely given that the tendency for certain disorders to be more prevalent in one gender than the other first emerges during adolescence (Angold et al, 2004), for example, higher incidences of depression/anxiety in females. However, psychosocial factors such as gender expectations and differential exposure to social stressors (Kendler et al, 2001) may be important in explaining gender differences in both clinical and typical populations. An important goal, therefore, for cognitive neuroscience is to integrate research on the brain with findings from the social and behavioural sciences.

## **Implications for society and future developments**

The teenage years are a time of marginalisation for many, and it could be argued that highlighting differences in behaviour and neuro-anatomy merely serves to increase the sense in which members of this age group are not yet fully active members of society. However, despite meeting the material needs of this age group better than at any previous point in human history, many developed countries, including the UK, are seeing rising rates of mental illness, disaffection and criminal behaviour (UNICEF, 2007). Improving knowledge of adolescent development at the neural, as well as psychosocial, level will only increase the chances of helping those who need it.

In practical terms, research on the development of the neural structures underlying the appraisal of risk and reward may have implications for the criminal justice system (Blakemore and Choudhury, 2006; Greene and Cohen, 2004). Additionally, recent efforts have been made to integrate findings about brain development into educational policy, both for special educational needs, such as autism and dyslexia, and for typical development (Goswami, 2006). One potentially positive implication of the neural development occurring during adolescence is that the teenage brain is well adapted to learning. Although a 'Year 8 dip' in academic performance has been reported, this might correspond, at least in part, to the reorganisation of the brain so that it can learn more efficiently. Appropriate education is crucial during the adolescent years. The data suggest that it is not too late for those still struggling with educational attainment.

An important next step is to extend these efforts to the pastoral side of education, in order to inform anti-bullying and extra-curricular policies. One purely speculative possibility is that, just as the environment influences synaptic pruning in the first few years of life, so might it have an impact on the pruning that occurs in the frontal cortex during adolescence. There are no tools as yet to look at pruning in the living human brain. However, if the environment influences synaptic pruning during adolescence, this has implications for what kind of experiences adolescents should encounter, both academically and socially. Secondary school is often socially stressful (Erath et al, 2007), just at the time when the social brain is undergoing profound development. Provide a social environment at school that is more in line with neural maturation might be useful. It might be fruitful to include in the curriculum some teaching on the changes occurring in the brain during adolescence. Adolescents might be very interested to learn about the changes that are going on in their brains.

Medical policy could also benefit from research on the adolescent brain. For example, treatment of substance abuse disorders may require modification for this population in light of the differences in risk and reward circuitry. Similarly, mood disorders such as depression and anxiety may differ between adolescence and adulthood due to differences affecting regulation and emotional sensitivity. Implications are also raised for young people who take recreational drugs such as cannabis, as the effects they have on the developing teenage brain are likely to be different to those on the adult brain, and may have longer term consequences. Indeed, regular cannabis use is associated with a significant increase in the risk of a later schizophrenia diagnosis, and this risk is even

higher if the onset of use occurs during adolescence (Arseneault et al, 2004). This may well be because the brain is more vulnerable to the effects of the drug during development (Pope et al, 2003). Education of young people based on new findings about the brain may act as a more effective deterrent against heavy and regular use than current techniques.

## **Conclusions**

Research on neuro-cognitive development during adolescence is still a relatively new field. However, in the past few years there have been some important developments. Research is currently exploring how the brain changes and how these changes might help to explain certain aspects of typically teenage behaviour, such as risk taking and emerging competence in interpersonal interactions. In turn, these findings might contribute to improving the quality of education and pastoral care for this age group, and may also have implications for the way young people are seen in the eyes of the law and are treated by the medical profession. In all, the research discussed throughout this review serves to highlight that adolescents are a distinct sector of society with specific needs.

## **Acknowledgements**

*Our research is funded by the Royal Society, the Wellcome Trust and the BBSRC. SJB is a Royal Society University Research Fellow. SB is funded by the Wellcome Trust four year PhD programme in neuroscience at UCL. CS is funded by a BBSRC PhD studentship.*

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*This document has been commissioned as part of the UK Department for Children, Schools and Families' Beyond Current Horizons project, led by Futurelab. The views expressed do not represent the policy of any Government or organisation.*