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Adolescent brain development, risk-taking and vulnerability to addiction

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ABSTRACT

Adolescents (12–18 years old) and young adults (18–25 years old), are more likely than older adults to drive-or agree to be driven-recklessly or while intoxicated, to use illicit or dangerous substances and to engage in both minor and more serious antisocial behaviour. Numerous factors during adolescence may lead to or favour initiation of drug use, such as sensation-seeking, gregariousness and social conformity. These aspects, however, cannot be dissociated from the increased sex drive and quest for an integrated self. In the separation-individuation process, relationships with peers play many different roles: a field for experimentation, emotional support, a place for “projection” and “identification”, and the possibility of finding a partner. Unsurprisingly, therefore, drug use generally takes place in a group setting. Despite evidence of heightened real-world risk-taking, laboratory studies have yet to yield consistent evidence that adolescents, when on their own, are more inclined towards risky behaviour than their elders. Moreover, their comprehension and reasoning abilities in risky decision-making situations are roughly equivalent to those of adults. Structural and functional neuroimaging studies have shown that neural circuitry undergoes major reorganization during adolescence, particularly in those regions of the brain relating to executive functions, the self and social cognition, and that the “emotional brain” may play a role in that reorganization. Age-related decreases in gray matter volume mainly reflect a reduction in the number of synapses and the complexity of axonal ramifications. By 18–20 years old, most of the subcortical white matter and association pathways have reached a plateau. Risk-taking behavior and novelty-seeking may provide, with an appropriate feed back, a mechanism to optimize brain development in adolescence.

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1. Introduction

Cross sectional and, more recently, longitudinal studies have demonstrated that the prevalence of drug use increases noticeably during adolescence, peaking in late adolescence and early adulthood (Degenhardt et al., 2008; Johnston et al., 2007). For instance, in a representative sample of 8098 subjects aged 5–54 years (US National Comorbidity Survey), Wagner and Anthony (2002) estimated peak values for initiating alcohol and marijuana use at 18 years and cocaine use at 20 years, using survival analysis techniques. Individuals drink their heaviest in their late teens and early to mid-twenties, with 44% of college students displaying binge drinking every 2 weeks (Wechsler and Kuo, 2000). The natural history of tobacco smoking in adolescence is variable, with phases of cessation, reduced use and relapse. In a longitudinal study, Van De Ven et al. (2010) found that the prevalence of nicotine dependence in young adults was 16.9% for adolescent smokers. Substance

experimentation during adolescence elevates the risk of persistent substance use and substance use disorders in later life stages for all types of drugs (Palmer et al., 2009; Bauman and Phongsavan, 1999; Brook et al., 1999; Kapusta et al., 2007; Riggs et al., 2007; Winters et al., 2008). Given that increased risk-taking during adolescence (Furby and Beyth-Marom, 1992) has consistently been regarded as a major risk factor for initiating drug use during this period, we discuss how cognitive neuroscience, particularly data provided by neuroimaging studies, can complement psychoanalytic constructs and thus enhance our understanding of this subject.

2. Risk-taking during adolescence: a psychoanalytic perspective

Psychoanalytic theories of adolescence consider exploratory behaviour to be a normal, and even necessary (philosophically speaking), component of development during this period. Exploration is motivated by several concomitant factors, such as the search for a sexual partner, at a time of redefinition of the self and the quest for self-affirmation. This is set against the backdrop of a weakened sense of security, as adolescents drift away from their parents and

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start to entertain ambivalent feelings towards them. In this complex and uncomfortable context, adolescents are prone to seek an immediate solution to their internal or external conflicts and, accordingly, to favour immediate action. Although there are considerable interindividual variations in behaviour, this tendency may result in an increase in psychosocial and physical damage. For many adolescents, action serves as a major testing ground for the process of self-definition (Blos, 1967, 1980, 1989; Erikson, 1956). Adolescence is the first time that an individual's sexual identity and sense of him- or herself as a sexual being is principally measured by what he or she does, rather than simply wishes to do, and not just by what his or her parents say or how they react (Ritvo, 1971). However, this is true not only for sexual identity and behaviour, but also for a wide range of other behaviours which help to shape social identity. Both the quality of their emotional experiences (valence and intensity) and the judgments of their peers contribute to the fine-tuning of adolescents' actions and values. This process of self-definition through action ultimately makes an important contribution to the relatively stable self-representations of adulthood.

The first psychoanalytic conceptualization of adolescence (Freud, 1905) focused on the revival and transformation of infantile development and infantile conflict, both preoedipal and oedipal, by the biological event of sexual maturation. Freud regarded adolescence as a transitional period, during which new solutions to infantile internal conflicts become possible due to psychic and sexual maturation. This theory, however, had limited efficacy in the treatment of adolescent disorders. New theories subsequently emerged, mainly after the Second World War, in which narcissistic preoccupations and the construction of the self became central. In a sense, self was seen as a psychosocial processing system as it was to be in later neurocognitive constructs (Klaczynski, 2004). However, previous key concepts, such as the importance of sex drive (libido) and (unconscious) conflict theory, were retained in the psychoanalytic model. There were many similarities between the observations and key theoretical points made by the most eminent researchers of the day, such as Blos and Erikson in the United States and Winnicott in Europe. Although the impact of sexual maturation on behaviour, mood, thought and affect was confirmed by treatment, other key concepts were actively investigated, in order to improve the efficiency of the therapy. Thus, the search for a coherent identity, an integrated self, in a period of metamorphosis, correlative to new desires and new abilities, emerged as a central construct. Erikson (1956) described what he called the adolescent task of "weaving internal tastes, talents, and values together with elements of one's life history and the demands of one's culture into a coherent identity". From a developmental perspective, adolescence can be understood as "passing stages of tentative role try-outs of the new pubertal self in all its potential realizations working synergically toward a postchildhood identity" (Blos, 1962). According to Blos, this process brings in its wake a decrease in developmental plasticity, metaphorically speaking, and a growing rigidity of the personality. New findings on brain development tend to confirm this observation. This final phase of reduced plasticity corresponds to the emergence of character.

Blos (1958, 1989) emphasized another crucial point in the development of adolescents, namely the need for social recognition of their ability to function as an autonomous and personal self, in the form of "a confirmation of their gender, as manifested in social expressions, realized in fantasy, self-gratification, or bodily affective interaction with the same or other sex". Self-idealization is also a typical aspect of adolescence and serves to regulate self-esteem (Blos, 1958, 1967). This period is usually characterized by changing behaviours, accompanied by mood swings, increased withdrawal, a disposition towards social isolation, but at the same time insatiable and irrepressible gregariousness. Relationships oscillate between being active and passive and between sharing

with others, including peers and parents, and being shared by them. Winnicott (1965) emphasised the challenge faced by adolescents when they acquire the physical abilities "for genital experience and also for actual killing" that were only fantasies in their childhood. He referred to the necessity, in terms of the development of the personality structure (ego), of "experiencing instinctual drives and the object relationships that have the instinctual drives as a basis". Hence, this "experiencing", which inevitably leads to an increased rate of risky behaviour, is regarded as a component of any "healthy" adolescence.

High-risk behaviours may also be displayed by adolescents suffering from mental disorders, such as antisocial personality or affective disorders. As the causes of these types of behaviours are, to a certain extent, the same for all adolescents, they can shed light on the risky behaviours of healthy individuals. Narcissistic rage and violent behaviours, or withdrawal of cathexis, may emerge in response to disillusionment with parents, common to both healthy and vulnerable adolescents. In view of this, adolescence may be best understood through the prism of the developmental phase of early childhood.

For adolescents, an excess of activity is no more "risky" than an excess of passivity. During adolescence, the psychic conflict between the activity and passivity of the ego is reflected in an externalized conflict over action: the ego's task is to restrain and contain impulses, as well as to release and gratify them. It should be noted here that the term "ego" is sometimes used in the literature to replace "self" and refers to a construct that is indeed vaguely similar to self and not so very far removed from the cognitive concept of "central executive" (Bornstein, 2005). Similarly, there are a number of discrepancies between the terms used to characterise adolescent behaviours. For example, it is commonly said that "adolescents are characterised as impulsive" and prone to "risk-taking", with these constructs sometimes being used synonymously. However, although adolescents may be impulsive in some situations, they may also be passive and inhibited, while adults routinely react promptly and even impulsively. Rates of accidental deaths or injuries in the United States and Europe, for instance, are higher among young adults (18–25 years) than among adolescents. Peaks for drug use and dependence, although they vary according to the country being studied, often occur around or after 18 years.

When adolescents find themselves in a situation with no acceptable solution for the preservation of their self-esteem or self-identity, they may choose a risky solution. This relatively frequent attitude may be described as impulsive, but also underlines the adolescent's need to preserve his or her future, as ethical choices predominate at this stage of development. Another behaviour which may be called impulsive is "acting out", an unconscious ego defence mechanism which is brought into play when individuals engage in some kind of behaviour that serves to ease the emotional pain and anxiety associated with an unconscious conflict between their drive and their conscience.

2.1. Risk-taking alone is not a sufficient condition for addiction

Freud (1927) wrote that human beings cannot avoid using "sedatives", of which there are at least three kinds: those that decrease our suffering, those that give us substitute satisfactions and those that make us insensitive to our misery. According to this statement, every civilization uses drugs and a large number of human beings experience drugs during adulthood. In some cases, drug use is associated with mental disorders, such as antisocial behaviour disorder, posttraumatic stress disorder, depression and narcissistic personality disorder. Addiction differs from simple use or even misuse because it is a compulsive, self-maintained phenomenon. Drug use, particularly if repeated, allows individuals to ascribe less importance to relationships and decreases torments and wor-

ries about their social life. According to Freud, in a letter to Fliess dated 22 December 1897, (Freud, 1985) the prototype of addiction (“the great habit”) is masturbation, a narcissistic and mechanically driven source of satisfaction, associated with a repetitive and impoverished fantasy life, and “alcohol, morphine, tobacco are only substitutes”. When drugs gradually invade people’s lives, representations associated with the use of the toxic substance increasingly take the form of “memories in the body” (Gaddini, 1992) or “symbolic equations” (Segal, 1957), and generally obey the rules of the primary process (Freud, 1900). Freud (1912) also propounded the notion of competition between normal sexuality and the compulsion for a particular substance in the case of addiction. He later wrote that intoxication is a means of escape from pain, substituting the pleasure principle for the reality principle (Freud, 1927). According to Glover (1932b), drugs appear to obliterate instinctual tension or frustration, by “cutting off” the outside world. This accounts for the extreme sense of compulsion associated with addiction. However, as the latter is a process associated with a specific brain dysfunction that seems to be similar for adolescents and adults, it will not be studied here.

2.2. The path to addiction can be understood as resulting from an inability to tolerate affect

Although drug use is frequently initiated during adolescence, it has yet to be established whether single or even repeated use is enough for an individual to become addicted. As previously reported, the peak for drug initiation is after 17 years, depending on the substance (with the exception of tobacco), and the peak for dependence after 18 years. It could therefore be argued that addiction is primarily a phenomenon of early adulthood.

Drugs relieve psychological suffering. According to Khantzian (1997) opiates attenuate feelings of rage or violence, alcohol relieves feelings of isolation, emptiness and anxiety, and stimulants can increase hypomania, relieve depression and counteract hyperactivity and attention deficit. Although prolonged self-medication may lead to addiction, it does not appear to be the main cause. Addiction, which presupposes craving and dependence, has been linked to early developmental failures (Johnson, 1999) leading to an inability to tolerate affects and thence to regulate self-esteem or relationships (Krystal, 1982; Zinberg, 1975). To conclude, the psychoanalytical approach distinguishes between simple drug use and addiction, although their causation and maintenance may overlap. In adolescence, the former results mainly from the tendency to explore the environment with one’s peers, although a reduction in one’s active fantasy life and high levels of anxiety are often involved in addiction. Unsurprisingly, therefore, drug use generally takes place in a group setting and involves a degree of social ritualism—two elements which play a major role in combating anxiety and distress (Glover, 1932a; Johnson, 1999; Johnson et al., 2000; Khantzian, 1997; Hopper, 1981). Moreover, in the case of addiction, uncertainty in social, sexual and affective relationships tends to disappear, to be replaced by highly conventional and ritualized behaviours, leading to compulsory satisfaction. Hence, faced with the pressure of a burgeoning sex drive and the need to engage in relationships, vulnerable personalities unable to withstand deceit, distress, shame, anger and anxiety may find in addiction a substitute for real life. Self-coherence is, at least for a while, maintained with the support of the drug.

3. Risk-taking during adolescence: neuropsychological aspects

The advent of neuroimaging has profoundly modified our knowledge of adolescent brain development acquired from animal or post mortem studies.

Structural and functional neuroimaging studies have revealed that neural circuitry undergoes a major reorganization in adolescence, particularly in those regions of the brain involved in executive functions, the self and social cognition. Functional neuroimaging has shown that these regions also play a key role in the regulation of behaviour and emotion, and in the perception and evaluation of risk and reward. Accordingly, “impulsivity, risk-taking behavior, and novelty-seeking may provide a mechanism to expand the range of possibilities that will then provide the appropriate feedback for optimal sculpting of the brain” (Luna et al., 2001).

3.1. Structural neuroimaging

Most studies of structural brain development take the form of either magnetic resonance imaging (MRI) measurements of grey matter (GM) and white matter (WM) volumes or, more recently, diffusion tensor imaging (DTI) investigations of the macro- and microstructure of WM. Results are consistent, whether they are yielded by cross-sectional studies, some with large cohorts of children ($N > 200$), or by the somewhat sparser longitudinal studies, generally involving smaller samples (Gogtay et al., 2004; $N = 13$) though with some notable exceptions (Shaw et al., 2006; $N = 307$).

3.1.1. Grey matter maturation

Put succinctly, GM volume undergoes a prepubertal increase, followed by a postpubertal loss. Considerable developmental changes occur in GM volume, density and cortical thickness between childhood and adulthood. Age-related decreases in apparent GM volume mainly reflect a reduction in the number of synapses and the complexity of axonal ramifications, due to accelerated elimination or “synaptic pruning”, with an attendant increase in the degree of myelination of intracortical axons. Cortical complexity decreases during adolescence in both the left and right hemispheres (White et al., 2010). Overall, GM volumes display heterogeneous developmental trajectories across the major lobes, peaking in the frontal lobes at around 11 years, but continuing to increase in the temporal lobes until 14 years. Longitudinal studies of GM development at functionally subregional levels also point to heterochronic maturational trajectories. Typically, the primary sensorimotor cortices and the frontal and occipital poles mature first, with maturation proceeding rostrally, from the parietal areas to the frontal ones, and caudally and laterally over the parietal, occipital and, late after adolescence, temporal cortices.

The dorsolateral prefrontal cortex (DLPFC) and the superior temporal cortex, which contain association areas that integrate high-level information in several sensory modalities, are the last to mature, after 16–17 years (Gogtay et al., 2004), suggesting that the higher-order association areas only mature after the lower-order sensorimotor regions, whose functions they integrate, have matured. The DLPFC serves as the highest-order cortical area, responsible for executive functions such as motor planning, organization and regulation. It is also involved in working memory. The superior temporal gyrus (STG) has also been identified as a critical structure in social cognition. The reduction in size of the DLPFC at the end of adolescence suggests that pruning/myelination may occur in parallel (Giorgio et al., 2010; Gogtay et al., 2004). Three recent studies examined changes in regional cortical thickness in relation to various cognitive functions, namely IQ for Shaw et al. (2006), memory for Sowell et al. (2001a,b) and executive functions (inhibition, shifting and updating) for Tamnes et al. (2010). Children with the best scores demonstrated a particularly plastic cortex, with an initial accelerated and prolonged phase of cortical increase followed by a particularly vigorous phase of cortical thinning. Frontal lobe GM thinning was also more strongly predictive of memory capacity (Sowell et al., 2001a,b). GM reduction in the

frontal cortex observed between adolescence (12–16 years) and early adulthood (23–30 years) is also associated with changes in the striatum, putamen and globus pallidus-structures implicated in risk-taking. The maturation of these frontostriatal regions may be subserved by enhancing long-distance connectivity in different WM tracts, and then increasing the “fine-tuning” of neuronal connectivity. In adults, complex tasks may be accomplished more automatically, with the recruitment of phylogenetically ancient parts of the brain such as the striatum and cerebellum.

3.1.2. White matter maturation

Contrary to GM, WM volumes increase roughly linearly throughout the first four decades of life, with a peak around the mid-forties, when speed for certain fine motor skills is also optimal. [Lebel et al. \(2008\)](#)'s extremely interesting study conducted on a large sample ($N = 202$, aged 5–30 years) showed that the brain undergoes major microstructural changes during adolescence and indeed beyond, until 25 years. By 18–20 years, most of the subcortical WM and association pathways have reached a plateau. However, significant maturation has been observed between 20 and 25 years, notably of the corticospinal tract, lenticular and caudate nuclei, and thalamus. The cingulum and the uncinate fasciculus continue their maturation beyond 25 years. This study is one of several reporting nonlinear development, with frontal tracts maturing later than the more posterior ones ([Lenroot et al., 2007](#)). The exponential development of WM during adolescence may be regarded as a continuation of the exponential patterns of development observed during infancy and early childhood (during the first 5 years of life, fractional anisotropy (FA) values increase by up to 200%).

Some studies have associated DTI indices with cognitive measures, such as intellectual abilities ([Schmithorst et al., 2005](#)) and, more recently, verbal skills. In a group of 168 participants aged 8–30 years, [Tamnes et al. \(2010\)](#) found that *high verbal* abilities were associated with accelerated WM development in late adolescence/early adulthood before reaching a plateau, unlike *average verbal* abilities, which were correlated with more protracted development that continued into early adulthood. [Liston et al. \(2006\)](#) reported a relationship between frontostriatal radial diffusivities and inhibition abilities. Once more, these studies highlight the importance of the frontostriatal network in the development of executive functions.

A handful of studies have combined volume- and tract-based analyses. In 2010, Giorgio et al. reported the first longitudinal study to have focused on the adolescent period (13–18 years). Data showed that GM volumes decreased in many cortical areas, including higher-order association areas, such as the DLPFC, as well as in primary sensorimotor and sensory cortices. Conversely, WM volumes increased in several regions, notably the frontal lobe, corpus callosum and arcuate fasciculus.

In conclusion, neuroimaging studies have shown that an extensive reorganization of neural circuitry takes place during adolescence, particularly in those regions of the brain involved in executive functions, the self and social cognition. This reorganization primarily constitutes a simplification of neural circuitry and could be interpreted as the optimisation of the neural circuits involved in high-level tasks. Although the conditions governing synaptic pruning have yet to be fully elucidated, these modifications probably have an adaptive value and are determined, at least in part, by the experiences of pleasure or displeasure resulting from the various strategies used by adolescents in the new and complex tasks that they are called upon to undertake during this period. The development of WM fibres allowing faster or more intense connections between different areas of the brain could well contribute to these changes. Then again, as it is a secondary phenomenon and takes place over a protracted period, it may simply serve to estab-

lish connections between brain regions that have already undergone considerable maturation. It has been suggested that the gyrification that occurs between childhood and adolescence, as opposed to the gyrification that is observed in the first months of life and which is mainly mediated by genetics, may be influenced mainly by the environment and thus by the individual's own experiences. Studies of twins have confirmed the validity of this approach. Gyrification in adolescence ([White et al., 2010](#)) may well be triggered by the development of white matter fibre tracts connecting more or less widely separated areas of the brain. An individual's specific experiences may influence the way in which these tracts are organized.

3.1.3. Sexual dimorphism

Recent MRI studies have reported sexual dimorphism in the development of brain structure and function during adolescence ([Lenroot and Giedd, 2010](#); [Schmithorst et al., 2008](#)). First, total brain volume is about 10% greater in males, and peaks at 10.5 years in females and 14.5 in males ([Lenroot et al., 2007](#)). The GM trajectory also peaks 1–2 years earlier in females, while males may have a steeper rate of WM development during adolescence. Studies using magnetization transfer ratio (MTR) values also point to a possible sexual dimorphism during adolescence, involving an increase in axonal calibre in males ([Perrin et al., 2008](#)), as opposed to increased myelination in females ([Perrin et al., 2009](#)). Sexual dimorphism can also be observed at a regional level. The regions most frequently reported by imaging studies as displaying morphological sex differences include the basal ganglia (larger in females) and limbic structures (larger hippocampus and smaller amygdala in females). Concerning WM, a study of a large group of children and adolescents found greater FA in boys, in associative WM regions (including the frontal lobes), and greater FA in girls, in the splenium of the corpus callosum ([Schmithorst et al., 2008](#)). Increasing FA values reflect increasing myelination or increases in axonal calibre and possibly increasing fibre organization, resulting in decreased tortuosity. This variability has notable behavioural consequences. For instance, a study in 21 adolescents, looking at impulse control, found that different WM regions were associated with task performance in male and female adolescents ([Silveri et al., 2006](#)).

3.2. Functional neuroimaging: exploration and risk-taking

Neuroimaging studies can often complement or extend purely behavioural studies, which have yielded the following main findings.

3.2.1. Behavioural studies

In cognitive psychology, risk-taking has been associated with an increased tendency towards sensation-seeking and immediate reward-seeking, and a lack of inhibition ([Tamm et al., 2002](#)). Some authors, focusing on cognitive abilities, have suggested that adolescents are less *liable* to *consider* the negative repercussions of rewarded behaviour in hypothetical scenarios ([Reppucci, 1999](#)). However, this opinion is controversial and there is substantial evidence that adolescents are well aware of the risks they take, with few differences found between adolescents and adults in the spontaneous mention of the costs and benefits associated with several risky actions ([Alexander et al., 1990](#); [Beyth-Marom et al., 1993](#)). Moreover, there is little evidence of any systematic improvement in logical abilities related to decision-making past 16 years ([Overton, 1990](#)). Increasing adolescents' awareness of various risks has little impact on their decision-making outside the laboratory. Differences between adolescents and adults may rely more on the inability of the former to automatically engage in social rules. [Cauffman and Steinberg \(2000\)](#) examining how a sample of over a

thousand participants aged 12–48 years scored on “socially responsible decision-making” found that, on average, adolescents aged below 18–19 years scored significantly lower than adults. However, there were considerable interindividual differences in judgments within each adolescent age group.

These data can be more easily understood if we consider the process of socialization among adolescents, as relations with peers play a major role in the construction of the “social self”. Typical laboratory studies of risky decision-making fail to consider the social context in which risk-taking occurs in “real life” (Steinberg and Cauffman, 1996; Steinberg, 2004, 2008, 2010). In such studies, individual adolescents are presented with hypothetical dilemmas under conditions of low emotional arousal and are then asked to make and explain their decisions. In the real-world, adolescents often make decisions under conditions of emotional arousal and in peer groups. Heightened levels of susceptibility to peer influence have been shown to characterize adolescence even in laboratory studies (Steinberg and Silverberg, 1986). Gardner and Steinberg (2005) showed that the participation of peers (two friends) in a driving simulation video game led to an increase in risky driving for adolescents, but not for adults. Adolescents showed the same level of risk-taking as adults when they were alone. This has prompted some to argue that age differences in risky behaviour may be better accounted for by differences in psychosocial functioning than by differences in more cognitive aspects of risk orientation, such as risk preference (Steinberg and Cauffman, 1996).

Adolescents tend to base decisions on temporally proximal outcomes rather than on distal ones (Gardner and Herman, 1991), and in some contexts, are better motivated by reward than by negative reinforcement (Arnett, 1992; Gardner and Herman, 1991). In a psychodynamic construct, these trends reflect the complex quests undertaken by adolescents and their need to experience and socialize, at a time when the values of the past are being deeply questioned and yet the values of the future remain uncertain, and when adolescents need their actions to be validated by their peers. To put it more dramatically, actions focusing on immediate reward may also be explained by “uncertainty about the meaning and the value of life” (Winnicott, 1965).

3.2.2. Exploration and risk-taking as seen through functional neuroimaging

Structural studies have highlighted significant changes in many regions of the prefrontal cortex, notably the dorsolateral and ventromedial regions, throughout adolescence. These changes help to improve various executive functions which contribute to the regulation of affect and behaviour. The dorsolateral part of the prefrontal cortex is preferentially involved in executive processes and working memory, while the ventromedial part is involved in emotional regulation (Stuss and Alexander, 2007). For their part, functional studies point to a particularly highly developed functional link between these highly evolved structures and the limbic system during adolescence.

Studies featuring inhibition tasks can increase our understanding of impulsive behaviours. Inhibition may generally be defined as a function which, when the organism is faced with many possible responses, favours one particular response without simultaneously activating the others. Many behavioural studies have focused on cognitive control, or inhibition, using flanker, Stroop or go/no-go tasks. These tasks assess different kinds of inhibition but which all share a common mechanism, namely the inhibition of a proponent or automatic response. On the whole, children and adolescents activate a larger cerebral network to perform the tasks than adults. Thereafter, the number of brain regions that are recruited decreases with age, so that only essential regions associated with the task are activated (Durstun et al., 2002; Luna et al., 2001; see Casey et al., 2008, for review). When Luna et al. (2001)

compared three age groups, they found that adolescents displayed a greater volume of activation in the DLPFC during a response inhibition task than either younger children or older adults, suggesting a greater reliance on the frontal executive network. A recent meta-analysis of the development of executive functions using functional MRI (fMRI) highlighted the role of the dorsolateral and inferior prefrontal cortices-regions which undergo major reorganization during adolescence. We can hypothesise that synaptic pruning and relative disconnection enable regions such as the DLPFC to do the computations needed for the most efficient executive functioning, while an increase in myelination, continuing into adulthood, allows regions far from the DLPFC, such as the lateral cerebellum (Luna et al., 2001), to join in and assist in more consistent and automatic control of behaviour.

Other regions deserve further consideration. For instance, the involvement of the right anterior insular cortex is specific to adolescents as is not seen in either children or adults. This is remarkable, considering the involvement of this particular region in addiction (Naqvi and Bechara, 2009), self-regulation and executive functions.

3.2.2.1. The role of the limbic cortex in the control of risky behaviours. Hare et al. (2008) found that adolescents displayed exaggerated amygdala activity relative to children and adults during an emotional go/no-go task. They suggest that this greater activity may reflect the need to compensate for relatively weak anatomical connections between the brain regions involved in the task, through greater “top-down” executive control (Stevens et al., 2007). Conversely, the ventrolateral prefrontal cortex (VLPFC) has been shown to modulate amygdala engagement in both adolescents and adults, in order to facilitate flexible attention and behaviour when responding to environmental threats (Monk et al., 2003, 2008). The greater activity observed in the VLPFC, a region massively interconnected with the amygdala, during a go/no-go task suggests that both regions are strongly involved in this form of executive control (Stevens et al., 2007).

Wood et al. (2005) have shown that the left VLPFC mediates *positive* representations (of a concept or object) and their emotional assessment, whereas the right DLPFC mediates *negative* representations and the amygdala evaluative processing.

Casey et al. (2008) have postulated that high risk-taking during adolescence is due to discrepant development between limbic and prefrontal top-down control regions. They base their conclusions on animal studies (Laviola et al., 1999) and imaging studies (Spear, 2000, 2002; Ernst et al., 2005; Galvan et al., 2006, 2007). According to this model, adolescent behaviour is governed mainly by limbic regions, as they are functionally more mature (i.e., imbalance of limbic relative to prefrontal control), whereas in children the limbic and prefrontal regions are both still developing and in adults, these systems are fully mature. According to the authors, in emotionally salient situations, the limbic system will win over control systems in adolescents.

Although no firm conclusion can yet be drawn from these studies, it is probable that the limbic system play a major role of regulation during adolescence. However, this role looks complex. Given the need for exploratory behaviours and risk-taking, the mature limbic system may well play a positive role, regulating and moderating an immature frontal system.

3.2.2.2. The reward system: discrepant hypotheses about the role of the ventral striatum in risk-taking. In the experimental exploration of reward processing, different emotional and cognitive processes can be described. Some authors differentiate between risk-seeking (general approach to rewards) and risk-taking (positive engagement in the context of uncertainty). Other authors make a distinction between anticipation and consummation. For instance,

anticipating the opportunity to respond for monetary gain activates regions of the ventral striatum (VS), an archaic region of the brain, whereas notification of successful responses recruits a region of the medial frontal cortex (MFC), a region dedicated to complex tasks (Knutson et al., 2001a,b). The VS responds more automatically to appetitive cues (Knutson et al., 2001a), whereas the MFC appears to direct its energy towards appropriate goal objects (Elliott et al., 2000). Some studies (Spear, 2000) posit that the striatum is relatively hyporesponsive to rewards during adolescence, such that heightened reward-seeking behaviour is needed to achieve the same activation as in adults. An alternative and preferential hypothesis suggests that during adolescence, the striatal reward system is hyperresponsive, resulting in greater reward-seeking. Disproportionately increased activation of the VS motivational circuit may result from the influence of defective or immature inhibitory circuits (Chambers et al., 2003). Alternatively, adolescents may be particularly motivated by the potential for immediate reinforcement. For example, the maturation of the caudate (a subdivision of the striatum, together with the putamen) is delayed in children with disorders characterized by delayed gratification deficits (Castellanos et al., 2002).

3.2.2.3. Dopaminergic activity. Dopaminergic activity makes a considerable contribution to changes in prefrontal-striatal-limbic pathways (i.e., reward system) during adolescence. The peak observed during adolescence or early adulthood, which declines thereafter, predicts the increase in exploratory, risk-taking behaviour, and thus in reward-seeking, which cannot yet be controlled by the immature frontal regions (Wahlstrom et al., 2010). When Steinberg (2010) measured risky behaviours using laboratory paradigms, they reported a peak in performance at around 15 years. As suggested by Steinberg (2010), this temporal disjunction exerts a favourable influence from a developmental point of view. However, studies conducted on late adolescence, comparing adolescents with young adults, are too sparse for us to pinpoint the subsequent decline in risk-taking behaviours. Moreover, some individuals are more vulnerable to the potentially negative consequences of this neurobehavioural shift than others and their neural responses to rewards may be different. For instance, individuals whose genetic predispositions result in higher levels of dopamine in neural synapses, particularly in circuits involved in reward processing, demonstrate increased levels of brain activation in response to rewards (Dreher et al., 2009; Hariri, 2009). However, there are not yet any converging data on these predispositions, which may also stem from negative experiences in infancy or early childhood. Some studies, for instance, have reported contradictory data about the maturation of WM and risk-taking (Berns et al., 2009; Olson et al., 2009). Social, environmental and educational factors may also contribute to this heterogeneity, in addition to maturational ones. Hence, further studies are essential if we are to understand these apparent inconsistencies.

4. Discussion

The results of neuroimaging studies are consistent with the main concepts of psychoanalysis on adolescence, namely a transition to adulthood with a more integrated self and the development of social skills. Laboratory studies have shown that adolescents generally have a greater risk-taking propensity than adults, although there is considerable interindividual variability. While ignorance of the actual level of risk cannot be a major factor in risk-taking by typically developing adolescents, given that their knowledge of the risks is roughly similar to that of their elders (Furby and Beyth-Marom, 1992; Klaczynski, 2004), sensation-seeking and, above all, sensitivity to the peer group do seem to play an

important role, unlike in adults. As stated by Winnicott, adolescents need to gain experience of life, if they are to learn how to live and, more especially, if they are to find out whether life is worth living. They must abandon many of the childhood certainties, including the feeling of being protected by their parents, and must also de-idealize the latter. This teleological conception of action has been taken up by several researchers in the cognitive field, who see risk-taking as an adaptive mechanism allowing certain cortical structures to be optimised, particularly those involved in social cognition.

However, several important concepts specific to psychoanalysis are not used as tools for analysing action. This is particularly true of “drive”, including sex drive, which can in no way be reduced to the concept of “motivation”. Furthermore, the psychoanalytic approach focuses on cathexis. As stated by Erikson (1956), the cure process emerges amid the integration of diverse elements of personal experience, such as identity and intimacy, the past and the present, and the world of internal object representations and external relationships. Adolescents may sometimes modify the way they relate to the world through their experience of the course of treatment and through transference.

Neuroscience research tends to isolate the mechanisms of action and seek out their brain substrates. As this information does not arise from an individual's own experience, unlike that relating to a psychoanalytic cure, he or she cannot directly take this knowledge on board and integrate it into his or her psychic functioning. It can therefore be useful only as an external constraint: for example, the training, medication, or even electrical stimulation that is sometimes offered in cases of depression or addiction. Psychoanalytic referents and processes would appear to be useful tools for decoding behaviours, and possibly for modifying them at the risk-taking stage. They are, however, of little or no direct use at the addictive stage.

5. Conclusion

Psychoanalytic concepts of risk-taking in adolescents are supported by the findings of brain development studies. Risk-taking promotes the exploration of adult roles, may increase self-esteem (see Hoge and McCarthy, 1984), and promotes reproductive success. Risk-taking contributes to the efficient shaping of the most highly evolved parts of the brain that are responsible for the “sapience” which characterizes the human species.

The interrelations between cognition and emotion remain relatively poorly understood, and the study of adolescent brain development would appear to offer the best conditions for studying them. Neuroimaging studies have shown that neural circuitry undergoes major reorganization during adolescence, particularly in those regions of the brain relating to executive functions, the self and social cognition, and that the “emotional brain” may play a role in that reorganization.

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