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Opinion

Adolescence as a Sensitive Period of Brain Development

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Most research on sensitive periods has focussed on early sensory, motor, and language development, but it has recently been suggested that adolescence might represent a second 'window of opportunity' in brain development. Here, we explore three candidate areas of development that are proposed to undergo sensitive periods in adolescence: memory, the effects of social stress, and drug use. We describe rodent studies, neuroimaging, and large-scale behavioural studies in humans that have yielded data that are consistent with heightened neuroplasticity in adolescence. Critically however, concrete evidence for sensitive periods in adolescence is mostly lacking. To provide conclusive evidence, experimental studies are needed that directly manipulate environmental input and compare effects in child, adolescent, and adult groups.

Trends

Recently the idea that adolescence may be a sensitive period of development has gained traction in the literature.

Adolescence is characterised by changes in brain structure and function, particularly in regions of the cortex that are involved in higher-level cognitive processes such as memory, for which capacity may be heightened in adolescence.

Heightened plasticity may not only result in increased opportunities for development but also in increased vulnerabilities. Data from rodents show effects of social isolation and reduced fear extinction that are consistent with adolescence as a sensitive period for the development of mental illness.

Adolescent sensitive periods are likely to be characterised by large individual differences. Rodent data indicate that individuals who are exposed to drugs such as cannabis during adolescence may experience detrimental effects on cognitive functioning.

Defining Plasticity and Sensitive Periods

In the 1960s, Wiesel and Hubel investigated the effect of monocular deprivation for 1–4 months after eye opening. Neurons in the corresponding visual cortex subsequently lost responsiveness to stimuli directed towards the previously deprived eye and started responding preferentially to the nondeprived eye [1,2]. Monocular deprivation in the first 3 months of life was also associated with atrophy in cells in the thalamus receiving input from the deprived eye. Recovery from this atrophy was very limited, even after 5 years of light exposure. In contrast, monocular deprivation after 3 months of age produced virtually no physiological, morphological, or behavioural effects [3,4]. The findings from these studies were taken as evidence that the first few months of life form a sensitive period for perceptual development, during which neuronal plasticity is heightened [5].

Plasticity describes the ability of the nervous system to adapt its structure and function in response to environmental demands, experiences, and physiological changes [6]. The human brain retains a baseline level of plasticity throughout life – this is known as experience-dependent plasticity, and underlies all learning [7]. Plasticity during sensitive periods, by contrast, is experience-expectant – an organism 'expects' to be exposed to a particular stimulus during this time [7].

Sensitive periods were originally referred to as 'critical periods'. This term is used less frequently now, because it has since become clear that some recovery of function may be possible even outside the time window of highest sensitivity. In the case of visual development, later research on monocular deprivation in kittens showed that animals can be trained to use the initially deprived eye after it is uncovered, and this can bring about a certain level of recovery [8].

Studies on sensitive periods of the visual system in humans have relied on naturally occurring instances of visual deprivation in individuals born with cataracts, which occlude the lens of the eye. Sight may be regained after cataract reversal procedures. Cataract reversal studies indicate differences among sensitive periods for normal visual development, periods of sensitivity to deprivation, and periods of recovery from deprivation [9]. For visual acuity, for instance, the

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period of visually-driven typical development extends over the first 7 years of life, but individuals remain sensitive to deprivation up to 10 years of age and some recovery of function may be possible throughout life [10].

Language development, too, generally shows heightened plasticity in childhood [11,12], although there is no single sensitive period for language. Different linguistic abilities are acquired by partly separable neural systems, and these might differ in their response to deprivation and periods of heightened plasticity [13]. Congenital deafness, for instance, is associated with altered processing of grammatical information while semantic processing appears to be insensitive to auditory deprivation [14]. This highlights the specificity of sensitive periods.

Work on molecular mechanisms underlying early sensitive periods has shown that the balance of excitatory and inhibitory neurotransmission is a trigger of heightened plasticity and that molecular 'brakes' usually limit plasticity at the end of sensitive periods [15]. The timing of onset and offset of sensitive periods is malleable. Studies with monkeys have demonstrated that the face-sensitive period at the beginning of life can be extended by 2 or more years if infant monkeys are not exposed to face stimuli during this time. Face deprivation, therefore, delays the onset of the sensitive period [16]. The end of a sensitive period may in some cases be self-generated: learning may drive the commitment of neural structures, effectually reducing plasticity [17,18]. Face perception undergoes perceptual narrowing, for instance, during which individuals become better at processing the category of faces they are most exposed to at the expense of categories they see less frequently, producing effects such as the own-race bias of face perception [19]. Another explanation for the end of sensitive periods is that neuroplasticity is not actually reduced but, instead, there is less, or less varied, environmental stimulation [18].

Most studies on sensitive periods have concentrated on early childhood, whereas experience-expectant plasticity in later developmental periods have been somewhat neglected. Researchers have started to consider the possibility that adolescence represents a 'second period of heightened malleability' (Steinberg, 2014 [20], p. 9; also see [21,22]). Adolescence, the period of life that starts at puberty and ends at the point at which an individual attains an independent role in society [23], is characterised by marked changes in brain structure and function (Box 1). In this opinion article, we explore three areas of adolescent development that are proposed to be characterised by heightened plasticity: memory, social processing, and the effects of drug use. We argue that advances in developmental studies have yielded intriguing data that are consistent with heightened plasticity in adolescence. However, despite recent advances, concrete evidence for sensitive periods is mostly lacking.

What Evidence Would Be Consistent with Adolescence Being a Sensitive Period?

If adolescence were indeed a sensitive period, certain patterns in the developmental data would be expected. First, the impact of a specific stimulus on brain and behaviour should be higher in

Box 1. Neurocognitive Development in Adolescence

White and grey matter show complex patterns of change over the lifespan [24,76,77]. White matter volume and integrity increase throughout childhood and adolescence into adulthood in many cortical regions [77]. Grey matter volume, in contrast, increases from infancy through childhood, then declines throughout adolescence and into the twenties [78,79]. These changes are particularly pronounced in the frontal, parietal, and temporal regions during adolescence [24].

The ongoing development in white and grey matter during adolescence is accompanied by changes in cognitive function, including improvements in intelligence quotient (IQ) [80], working memory (WM) [81,82], and problem solving [83]. Social cognition also undergoes pronounced changes during this period of life, including significant improvements in perspective taking [84] and face processing [85]. Risk-taking and sensation-seeking behaviours decrease from adolescence to adulthood [86,87].

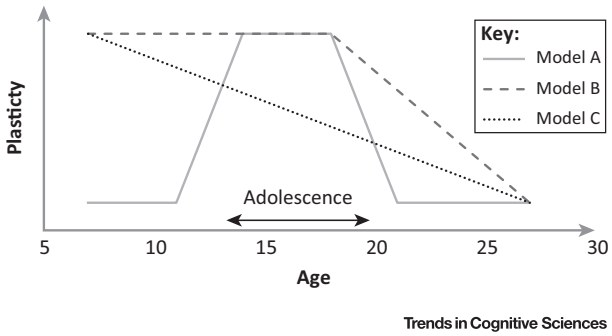

Figure 1. Models of Plasticity in Adolescence. Adolescence may be a stand-alone period of heightened plasticity (A) or form a continuous sensitive period with childhood (B). Alternatively, plasticity may decline continuously from childhood through adolescence and into adulthood (C). Adapted for adolescence from [88].

adolescence than before or after. For that reason, studies comparing children, adolescents, and adults are needed. Only if all of these age groups are considered is it possible to assess whether adolescence is a stand-alone period of heightened plasticity (Figure 1, Model A), a continuous sensitive period with childhood (Figure 1, Model B), or does not represent a sensitive period at all (Figure 1, Model C).

As a result of the differences in the timing of maturation of different brain regions and circuits [24], considerable variation in the onset and off-set of sensitive periods for different stimuli would be expected. Just as early development is characterised by multiple sensitive periods [9,13], adolescence is not proposed to be a sensitive period *per se*; instead, it is proposed that there are certain periods in adolescence during which a specific input from the environment is expected.

If certain environmental stimuli indeed have a heightened impact during this time, we would expect there to be enhanced learning, particularly of late-maturing skills. This will be discussed in the following section on memory. A lack of stimulation or aberrant stimulation would also be expected to have a disproportionate effect during this time. This feature of sensitive periods will be discussed in the section on the effects of social stress.

Adolescent plasticity might differ from plasticity early in development because, unlike babies and young children, adolescents are more likely and able to actively choose the environmental stimuli they experience. Generally, during childhood, environments are more structured by parents or caregivers, while adolescents have more autonomy to choose what to experience and with whom [25]. We might thus expect a large degree of individual differences in sensitive periods in adolescence and some sensitive periods may only ever be experienced by a subset of adolescents. This will be discussed in the section on the effects of drug use.

Adolescence as a Sensitive Period for Memory

At age 35, we are more likely to recall autobiographical memories from ages 10 to 30 years than memories prior or subsequent to this period, a phenomenon referred to as the 'reminiscence bump' [26]. The reminiscence bump is remarkably robust and shows a similar pattern when tested with different mnemonic tests and in different cultures [26,27]. In addition to autobiographical events, the recall of music, books, films, and public events from adolescence is also superior compared with from other periods of life [28,29]. Even mundane events that happened in adolescence and early adulthood appear to be over-represented in memory, suggesting that mnemonic capacity is heightened during this time of life [30]. For example, a large-scale study showed a peak of other aspects of memory such as verbal and visuospatial memory between 14 and 26 years of age [31]. While these data are suggestive of sensitive periods, training studies are needed to provide experimental evidence for sensitive periods for memory.

Box 2. Education in Adolescence

It has been estimated that 40% of the world's teenagers do not have access to secondary school education [89]. Even in countries that have compulsory education, schooling often ends between 14 and 16 years of age [90]. In Western countries, such as the UK or USA, much attention and resources have been devoted to early development, sometimes creating the impression that experiences in the first few years of life alone determine lifelong health, education, and social outcomes [91,92]. This status quo is now changing, however, and heightened awareness is emerging of the importance of later stages in development. A recent World Health Organisation report argues for the importance of adolescence for world-wide health [93] and a UK Royal Society report underscored the significance of STEM (Science, Technology, Engineering, and Maths) subjects education post-16 years for the national economy [94].

Training studies are available for working memory (WM), the ability to store and manipulate information [32]. Simple aspects of WM, such as delayed spatial recall, may reach maturity in childhood [33]. More complex WM abilities, such as strategic self-guided spatial search, continue to improve during early adolescence [33]. Such complex WM tasks recruit frontal regions that show particularly protracted development throughout adolescence [34] (Box 1).

There is some evidence for plasticity of WM in development. For children and young adolescents, gains in n-back type WM training, but not knowledge-based training, transferred to improvements in fluid intelligence [35]. Improvements were sustained over a 3-month period during which time no further training was implemented. WM training may be effective in adolescents with poor executive functioning, as well as in typically-developing controls [36]. However, we do not yet know how effects of training differ in adolescents as compared with children or adults. Studies in which children, adolescents, and adults undergo cognitive training and the effects are compared with active control groups that receive placebo training will be particularly informative in determining whether adolescence represents a sensitive period for WM development [37]. Such studies might directly inform educational interventions and policies (Box 2).

Adolescence as a Sensitive Period for the Effects of Stress on Mental Health

Many mental illnesses have their onset in adolescence and early adulthood [38,39]. A longitudinal study showed that 73.9% of adults with a mental disorder received a diagnosis before 18 years of age and 50.0% before 15 years of age [40]. It is thought that psychiatric disorders may in part be triggered by stress exposure in childhood or adolescence [41]. Social stress in particular is thought to have a disproportionate impact during this time [41]. The experience of acculturation stress attributable to migration, for example, predicts longitudinally internalising symptoms such as depression and anxiety in adolescence [42]. There is evidence, too, however, that bullying in childhood (age 7 or 11) also has lasting effects on physical and mental health in adulthood [43].

Rodent studies provide the opportunity to manipulate experimentally exposure to social stress, and have offered valuable insights into the deleterious effects of stress in adolescence. Adolescence in female rats lasts approximately from postnatal day (PND) 30 to 60, and from PND 40 to 80 in males. In female mice, adolescence lasts from PND 20 to 40, and from PND 25 to 55 in males [44]. It should be noted that there is considerable variation in the age of rodents classified as adolescent or adult in the literature [44]. Adolescent rats subjected to repeated defeat by a dominant individual have been shown to present with different behavioural patterns (more avoidance rather than aggression), and recover less from renewed stress, compared with adult rats. Exposure to stress in adolescence (compared with adulthood) in rats was also associated with less neuronal activation in areas of the prefrontal cortex, cingulate, and thalamus [45]. This study did not include juveniles, limiting conclusions for sensitive periods.

The absence of any social stimulation can have deleterious effects as well. Social isolation in male and female rats has been shown to have irreversible effects on some aspects of exploratory

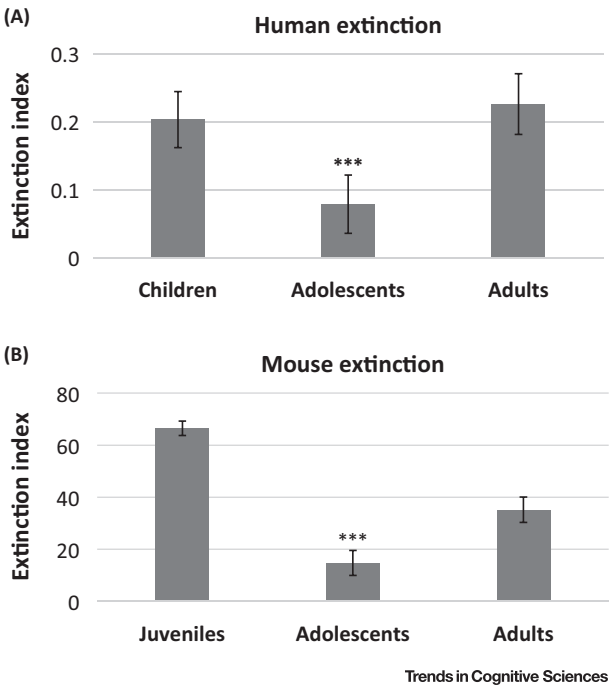

Figure 2. Fear Extinction Learning in Mice and Humans across Development. Mean indices for fear extinction learning with standard error bars in humans (A) and mice (B) for children or juveniles, adolescents, and adults. ***$P < 0.001$ for an attenuation in fear extinction compared with other age groups. Adapted and reprinted from [50] with permission from the National Academy of Sciences.

behaviour, but only if the isolation occurred between PND 25 and 45, but not before or after [46]. This therefore appears to be a vulnerable period for social deprivation in rats. While this paradigm has not been directly translated to humans, studies have shown that human adolescents show greater levels of anxiety in response to social exclusion than do adults [47,48]. Social exclusion is also linked to the development of social anxiety in human adolescence [49]. Providing evidence for the effects of social isolation across development in humans is not only important from a theoretical perspective but might also help develop and time mental health interventions aimed at strengthening resilience to social exclusion.

Adolescence may also be a sensitive period for recovery from the experience of social stress [50]. Fear extinction learning is key for a healthy response to stress, for example [51]. For psychiatric conditions such as post-traumatic stress disorder (PTSD), stress persists even though the stressor is no longer present. Fear extinction learning has been found to be attenuated in adolescence as compared with childhood and adulthood – both in humans and in mice (Figure 2) [50]. The rodent data in the study indicated that a lack of synaptic plasticity in the ventromedial prefrontal cortex during adolescence is associated with decreased fear extinction. This implies that desensitisation treatments, which are based on the principles of fear extinction learning, may be less effective in adolescence, and highlights the need for the development of alternative treatment approaches for this age group. The particular strength of this study lies in the fact that it included child, adolescent, and adult age groups, as well as providing neural evidence in rodents. The results suggest that adolescence may be a sensitive, or vulnerable, period for recovery from stress.

Adolescence as a Sensitive Period for the Effects of Drug Use

Adolescence is a time of heightened engagement in risky health behaviours, such as unsafe sexual behaviour, dangerous driving, and experimenting with alcohol and other drugs [52,53]. This increase in risk-taking behaviour might be partly mediated by the increase in time spent with friends rather than family [54]. When together with their friends, adolescents are more likely to engage in risky behaviour than when alone [55]. Young adolescents appear to be particularly

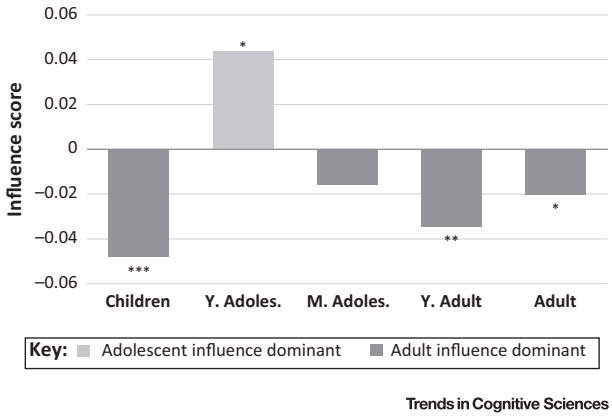

Figure 3. Effect of Social Influence on Risk Ratings. A total of 563 participants rated the riskiness of everyday situations – before and after they were informed about the ratings of other people, either adults or teenagers [56]. An index of conformity to other people's ratings is shown, depending on the origin of the social influence (adults or teenagers) across five age groups: children (aged 8 to 11), young adolescents (Y. Adoles., aged 12 to 14), mid-adolescents (M. Adoles., aged 15 to 18), young adults (Y. Adult, aged 19 to 25), and adults (aged 26 and over). ***$P < 0.001$, **$P < 0.01$, *$P < 0.05$ significant difference in social influence effect between social influence origin (adults compared with teenagers) in each age group. Young adolescents' risk ratings were more influenced by teenagers' ratings than by adults' ratings. Data published in [56].

susceptible to peer influence on risk perception, compared with other age groups (Figure 3) [56]. This study measured the degree of social influence on risk perception in different age groups and found that, whereas children, young adults, and adults were more influenced by adults' opinions about risk, young adolescents were more influenced by the opinions of teenagers compared with the opinions of adults. Mid-adolescents showed no difference in the level of influence by adults' and teenagers' opinions about risks, suggesting that this is a transitional stage in development.

When with peers, adolescents are more likely to engage in risky behaviours such as drug use [57]. Adolescents whose friends regularly consume tobacco, alcohol, and cannabis are more likely to use drugs themselves, for example [58]. Cannabis is one of the most widely recreationally used drugs among adolescents and adults in the USA and UK [59,60]. It has been estimated that 15.2% of Europeans aged 15 to 24 have used cannabis in the last year and 8% in the last month [61]. Cannabinoid exposure during early adolescence is thought to result in lasting changes in brain structure and cognitive deficits, possibly making adolescence a vulnerable period for its effects [62,63].

Recreational cannabis use before the age of 18 (but not in adulthood) or heavy use at any age has been linked to grey matter atrophy in the adult temporal pole, parahippocampal gyrus, and insula [64]. Longitudinal data have indicated that self-reported persistent cannabis use between 13 and 15 years is associated with a significant decline in IQ [65]. The longer the period of cannabis consumption, the greater the decline in IQ [65]. This decline in IQ was found to be more pronounced in participants who used cannabis before the age of 18 as compared with those who started to use cannabis after 18. These findings suggest that the developing brain of adolescents might be particularly sensitive to the adverse consequences of cannabis use. It should be noted, however, that alternative explanations, such as pre-existing mood or anxiety disorders mediating both cannabis use and cognitive problems, cannot be ruled out in this study [66]. These studies also did not include younger age groups, and it is possible that the developing brain during childhood would show a similar or even greater sensitivity to cannabis than in adolescence. Even if that were the case, however, such sensitivities would not usually be expressed in humans because adolescence or adulthood will usually be the first potential point of contact with recreational drugs.

Molecular and cellular data on the effects of cannabis in adolescence are sparse but there is some indirect evidence for heightened sensitivity. It has been shown that cannabis affects the endocannabinoid system, which, along with other neurotransmitter systems (e.g., the glutamatergic and dopaminergic systems), undergoes extensive restructuring during adolescence [67]. While the two key cannabinoid receptors CB1 and CB2 are already present in the rodent embryo (gestational day 11–14 [68]), neuroanatomical distribution and number of receptors changes during development. CB1 receptor expression in several brain regions was found to peak with the onset of puberty in female and male rodents [69]. Any disturbance caused by cannabis exposure during the adolescent period may have lasting effects on the endocannabinoid system, which affects neurodevelopmental processes including neuronal genesis, neural specification, neuronal migration, axonal elongation, and glia formation [70–72]. For instance, exposure to D9-tetrahydrocannabinol (THC), the main psychoactive ingredient in cannabis, during puberty in female rats (PND 35–45) resulted in a decrease in CB1 receptor density and functionality in several brain regions [73]. However, comparative data from other age groups are lacking.

Strong evidence for an adolescent sensitive period for drug use comes from a set of studies investigating chronic cannabinoid exposure in male rodents. Cannabinoid exposure in adolescence (PND 40–65) predicted long-term cognitive deficits in adulthood (object recognition memory), whereas similar exposure in prepubescent (PND 15–40) and young adult rodents (>PND 70) was not linked to such persistent deficits [74,75]. It is not clear, however, if this evidence directly translates to humans. It should also be noted that only a subset of human adolescents experiment with drugs such as cannabis. Future studies are needed to investigate individual differences, particularly in relation to peer influence and risk-taking behaviour, to understand when and for whom adolescence may be a vulnerable period for drug use.

Concluding Remarks

Evidence for plasticity in memory and the effects of social stress and drug use is consistent with the proposal that adolescence is a sensitive period for certain areas of development. The strongest evidence for sensitive periods to date comes from rodent studies showing a heightened vulnerability to the disruptive effects of social isolation and cannabis use, as well as reduced fear extinction learning. There is little conclusive evidence for human adolescence, however. Studies are needed on the effects of training or stress across human childhood, adolescence, and adulthood (see Outstanding Questions).

Outstanding Questions

Is there greater plasticity in adolescence than in other periods of development or do we see a continuous decline of plasticity from childhood to adulthood?

How do environmental influences such as cognitive training, social stress, or drug use impact brain development in humans?

What are the molecular mechanisms of plasticity in adolescence? Are they the same as in early childhood? What is the role of puberty in the onset of sensitive periods in adolescence?

Is there variation in the timing and duration of sensitive periods within adolescence? What is the role of individual differences in moderating the presence and onset of sensitive periods during this time of life?

What are the effects of enrichment and training in adolescence as compared with other age groups? Conversely, what are the consequences of stress in humans across the lifespan?

Can we harness adolescent brain plasticity for educational interventions? Do training effects transfer to real-life measures such as academic performance? If so, what are the side effects of such interventions? What are the ethical implications of cognitive enhancement through training?

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