Adverse environments for (disadvantaged) development and learning: Which brain systems are most impacted?

Adverse environmental factors can significantly and pervasively impair learning and development, jeopardizing the future of an alarming proportion of children, even in developed nations.

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Executive summary

- Even in developed countries, an alarming proportion of children grow up in environments that are disadvantageous for appropriate physical, psychological, and cognitive development. These include children from households of low socioeconomic status (SES).
- Relative to higher SES peers, children of low SES are more likely to have deficits in learning, lower academic achievement, and increased behavioral problems, with negative long-term consequences for their professional success and overall quality of life.
- Adverse environmental factors that often characterize low SES households include lack of cognitive and emotional stimulation, inadequate nutrition, as well as higher levels of stress, preoccupations, and unstable routines (e.g., fragmented sleep schedules).
- These factors—either together or alone—represent a huge hazard for the growing brain as they can alter the adequate development of brain systems that are foundational to learning.
- Brain systems that are susceptible to adverse environmental factors include those important for memory, attention, and planning, as well as those in charge of regulating our emotions.
- Knowledge of the brain systems that are the most impacted by environmental adversities can help identify targeted pedagogical approaches and, concomitantly, develop dedicated educational policies aimed at reversing the negative effects these environments can have on healthy brain development and successful learning in children from low SES.

Introduction

Adverse environmental factors can significantly and pervasively impair learning and development, jeopardizing the future of an alarming proportion of children, even in developed nations[1]. Adverse living environments refer to those which prevent an individual from fulfilling their physical, psychological, intellectual, and cultural needs. They are often associated with poverty or, more generally, disparity of resources, which is commonly identified under the umbrella term "*socioconomic status (SES).*"

SES is the by-product of several parameters including: (1) family income, (2) occupational status, and (3) educational level of the parent(s)/guardian(s). Often, these parameters go hand-in-hand, yet their correlation is far from perfect. Research studies often have to assess them simultaneously when establishing criteria for different levels of SES (e.g., low *versus* high), or when evaluating their independent (or joint) contribution to indices of life success.

Family income below the appropriate self-sufficiency standard is considered a marker of low SES. The *self-sufficiency standard* refers to the amount of income necessary to meet basic needs without any public or private subsidies (e.g., public housing, food stamps, food provided by churches). This index is customized to each family's circumstances (i.e., taking into account where the family lives and the number and age of their children). Yet, income can vary over time, hence the need for additional criteria to characterize the complex construct of SES. One is occupational status: Parental occupation is one of the most frequently used indicators of early life adversity[2,3], including low SES[4,5]. Occupational status can reflect the long-term outcome of a person's educational background and tends to be fairly stable over time. Similarly, parental education has been identified as a reliable predictor of academic success[6]. Conventionally, educational attainment for low SES refers to both parents/guardians having a high school diploma or less; while parental occupation is normally calculated on an *8-point-scale* where low SES reflects routine, manual, and lower supervisory jobs, and higher SES includes higher managerial and professional occupations (see, for example, Table 3 in SOC2010 Volume 3).

Through the use of these types of indices, research studies have converged towards a worrisome scenario: Children growing up in low SES households present with increased behavioural and emotional problems; poorer mental and physical health[4]; lower academic achievement[1]; and, overall, face fewer opportunities for educational, professional, and social success. Can neuroscience help us shed light on the mechanisms leading to such disparities between high and low SES?

Low SES and learning

Relative to children from higher SES, low SES children are likely to perform significantly worse on cognitive tests. Children from low SES are also more likely to have deficits in learning, particularly in key academic subjects such as reading and mathematics[1,7–9]. This is often referred to as the "*achievement gap*," or the "*opportunity gap*." It has been reported that children from disadvantaged backgrounds fall behind their higher SES peers by larger margins than between any other two groups of students[1]: a less advantaged student scores 39 points lower in mathematics—the equivalent of nearly one year of schooling—compared with a more advantaged student. Critically, SES-related differences in learning and academic achievement exist from early elementary school and tend to grow over time. As a result, teens from low SES backgrounds are more likely to fail school courses and drop out of high school. Moreover, as adults, children from low SES are expected to earn less than half as much as their peers coming from higher SES families, creating a significant societal and economic challenge. Why do low SES learners fall behind? Has their brain been compromised to be able to achieve adequate learning standards? And if so, how?

Nurturing or damaging the "plastic" brain

The developing brain is a tremendously *plastic* organ: It is shaped both in its structure and function by everything we do, but also by everything we do not do or that we do wrong[10]. *Experience-dependent brain plasticity* is a key aspect of any type of learning; it can be greatly affected by the social environments that formally and steadily accompany the child's development—namely the school, and earlier, the home. Within these settings, the brain is constantly being "sculpted" from birth and throughout childhood, late adolescence, and early adulthood—for better or worse. Some environments can be highly enriching and hence foster advantageous brain changes that lead to healthy development and successful learning. In the case of low SES, the environment experienced by the child is instead often impoverished: It lacks adequate cognitive stimulation and/or emotional nurturing, both in terms of quality and quantity. Often, low SES environments are also depleted of (other) basic health needs (e.g., appropriate nutrition). Low SES households can also be physiologically and psychologically "toxic": they are often charged with higher levels of stress, preoccupations, and unstable routines (e.g., poor sleep schedules).

These factors—either together or alone—represent a huge hazard for the growing brain, altering brain systems that are foundational to any type of learning. Neuroscientific findings have now started to shed light on which systems are the most affected.

Deprivation: Lack of cognitive/emotional stimulation and malnutrition

Certain environmental factors are known to support favourable brain development and learning by promoting *plasticity,* mechanisms of dedicated brain systems important for memory, attention, and planning. These systems reside within regions of the brain called the hippocampus and prefrontal cortex[11] (see Figure 1).

For example, enhanced parental stimulation has been shown to foster better academic achievement. A recent study with ~600 participants reports that children whose parents/guardians engaged in math-story time with them showed significantly better math achievement scores than those whose parents did not[12].

By contrast, poor stimulation has been reported as one of the top risk factors jeopardizing favourable development[13]. Critically, for low SES children, opportunities for cognitive stimulation are not only lacking at home, but also in school. Overcrowded classrooms, diminished 1:1 interactions, and reduced opportunities to participate in classroom discussions are very common for low SES pupils, contributing to their suboptimal development and learning. Quality observations have revealed that, as early as in preschool, toddlers from low SES are less likely to engage in verbal exchanges in the classroom, compared to their peers of higher SES (i.e., they are less likely to share their opinions or experiences)[14].

Highly nurturing environments do not only provide cognitive but also emotional support, which represents another foundational factor to successful learning. Emotional neglect—a form of deprivation—can cause severe social and emotional issues. It can negatively impact learning by acting on a set of very primordial brain regions (i.e., we share them with reptiles and even early fishes!) that are responsible for regulating our emotions[15]. Regulating our emotions by modulating the level of (positive or negative) valance we attribute to a certain behaviour (or action) is at the core of any type of learning and decision-making we do. This (very useful) system for emotion regulation originally evolved to detect and respond to threats (e.g., prompting an animal to run away or freeze in the event of a predator) or to seek survival-type rewards (e.g., when foraging, mating). As such, this system is anchored in the inner (and most ancient) layers of our brain—in a region called the amygdala, and in a series of related structures characterized by very tiny, interconnected sets of brain nuclei, called the basal ganglia (see Figure 1). We, as humans, have fine-tuned this system in such a way that is not only useful for adaptive behaviours, such as running away or seeking survival-type rewards. For us, it can act as our initial compass to guide our complex actions, thoughts, and choices. This is made possible by the fact that, in our brains, these inner structures are highly and preferentially interconnected with the outer (and much more "modern"—i.e., evolutionary more recent) layers of our brain. This is the cerebral cortex and, in this case, connections are preferentially made to one of its mostly evolved regions: the prefrontal cortex. This region, that humans have developed more than any other species on this planet, is responsible for planning, attention, and information updating. Together, these older and newer brain structures work together to help us integrate the emotional and cognitive aspects of our behaviour, and optimally calibrate our decisions to ultimately learn better in our environment. A classic example is motivation: When we are motivated to learn, when there are rewards in our learning context, when we like what we are learning, or when we see the benefits of it, our learning seems less effortful, easier—we attach a positive valence to our learning.

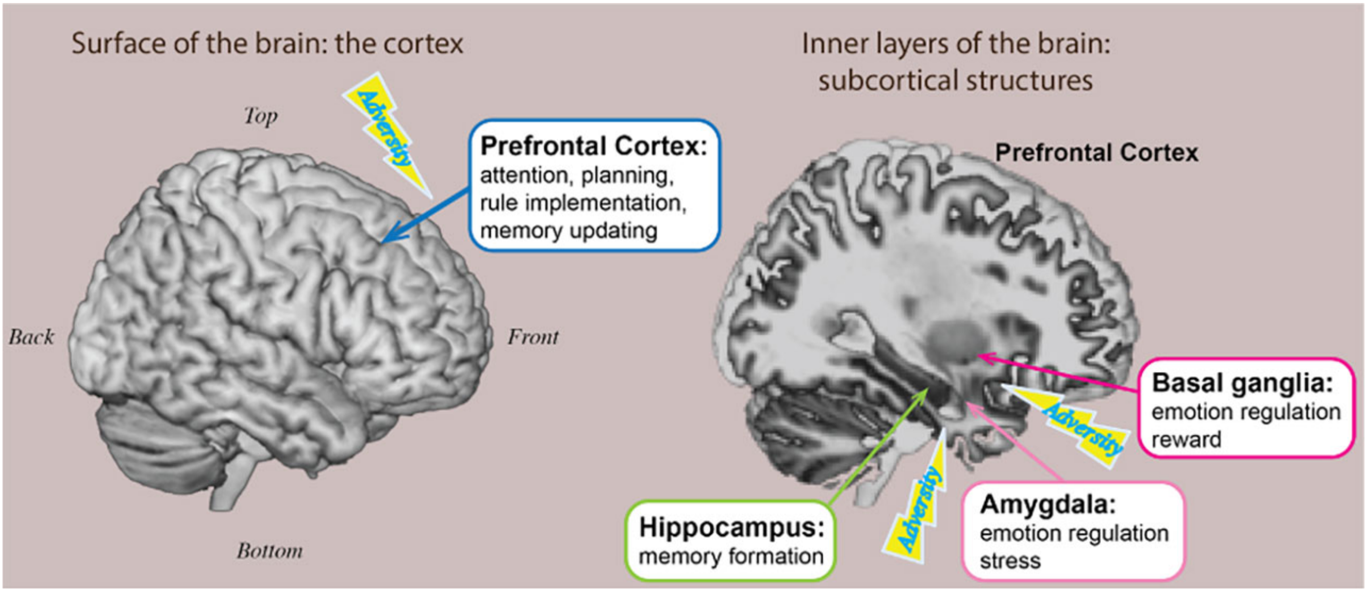

Figure 1. Schematic illustration of the location and key function of the brain systems supporting successful learning, whose age-appropriate development can be highly impacted by adversity.

The brain mechanisms underlying motivation and reward are modulated by dopamine (DA), a chemical in our brain that significantly increases in dose when we are anticipating a reward or a prize. Once this chemical is released, it is detected by specialized structures within our brain cells called receptors. For the detection of DA, receptors most abundantly reside within the inner layers of our brain: in the basal ganglia and in the amygdala. Interestingly, preliminary evidence suggests that SES is positively correlated with the presence of DA-specific receptors in the brain: the higher the SES, the greater the amount of DA in the basal ganglia[16]. Moreover, it has also been shown that adolescents from low SES have smaller amygdala volumes (i.e., the result of fewer number of cells)[17]. Critically, smaller amygdala volumes in these teens were associated with higher symptoms of depression, suggesting that appropriate emotion regulation skills may be lacking in this group, possibly affecting their learning skills[18]. However, another study found intact reward processing in a group of children from low SES compared to a group of middle SES[19]. It is, therefore, possible that emotion regulation skills are still salvageable at earlier stages of development. More research is needed in this area but, if this were to be confirmed, it could open up promising avenues for interventions focused on sparing "at-risk" children from potential emotion regulation issues (or reward processing issues) which could, in turn, jeopardize their learning and overall chances of life success. Another possibility to be explored in this context is identifying resilience-type mechanisms which could characterize certain vulnerable groups. In this sense, it is possible that certain individuals are more prone to developing compensatory mechanisms to overcome their (cognitive or emotional) issues/deprivations.

Nurturing does not only occur cognitively and emotionally. Notably, lack of an appropriate diet can also negatively impact brain development and learning. Indeed, consistent and prolonged deprivation of key nutrients—which can be common in low SES environments—has been related to atypical functioning of prefrontal, hippocampal, and amygdala systems important for learning. For example, children with high levels of iron deficiency, one of the most common nutrient deficiencies worldwide[20], have been shown to perform worse on tasks that are under the responsibility of the prefrontal cortex[21], such as planning, task-switching, and information-updating. Iron deficiency has also been linked with deficits in memory[22], and change in the hippocampus[23]. Moreover, iron deficiency is also known to cause alterations within the dopamine system affecting reward[24].

All in all, the additive effects of impoverished environments characterized by protracted *lack of nurturing* in multiple domains (i.e., cognitive, emotional, dietary) can be dramatic. Intervention strategies aimed at rescuing academic outcomes and developmental trajectories in low SES children should thus be focused on fostering environmental "enrichments"—both at home and in the school.

Toxic factors: Stress and fragmented sleep

Within disadvantaged environments—such as impoverished households—children are greatly exposed, and perceive high levels of stress and preoccupations on a daily basis[25]. Critically, high levels of stress, particularly during development, have been systematically linked to structural and functional alterations of several brain systems important for learning including the hippocampus, the prefrontal cortex, and the amygdala[26–28](see Figure 1).

As discussed, the amygdala—part of our emotion regulation system—is linked to the positive aspects of learning (i.e., reward, motivation). Yet, it is also very much involved in the negative ones (i.e., stress, anxiety).

As a consequence of their stressful environments, low SES children can develop an early sensitivity to threats, leading to dysregulated emotional control, which can negatively affect learning. Indeed, it has been shown that the amygdala is overly active in response to threatening/fearful stimuli in groups of low SES[29]. Atypical activation of the amygdala can have cascading effects on other brain systems important for learning, such as the hippocampus and the prefrontal cortex (see Figure 1). For example, greater engagement of both the amygdala and the prefrontal cortex has been reported in children with high levels of anxiety towards certain school subjects, typically math[30]. Critically, this type of anxiety is often associated with poorer performance and lower academic achievement[31,][32,][33], highlighting the key role of all these brain systems in achieving successful learning.

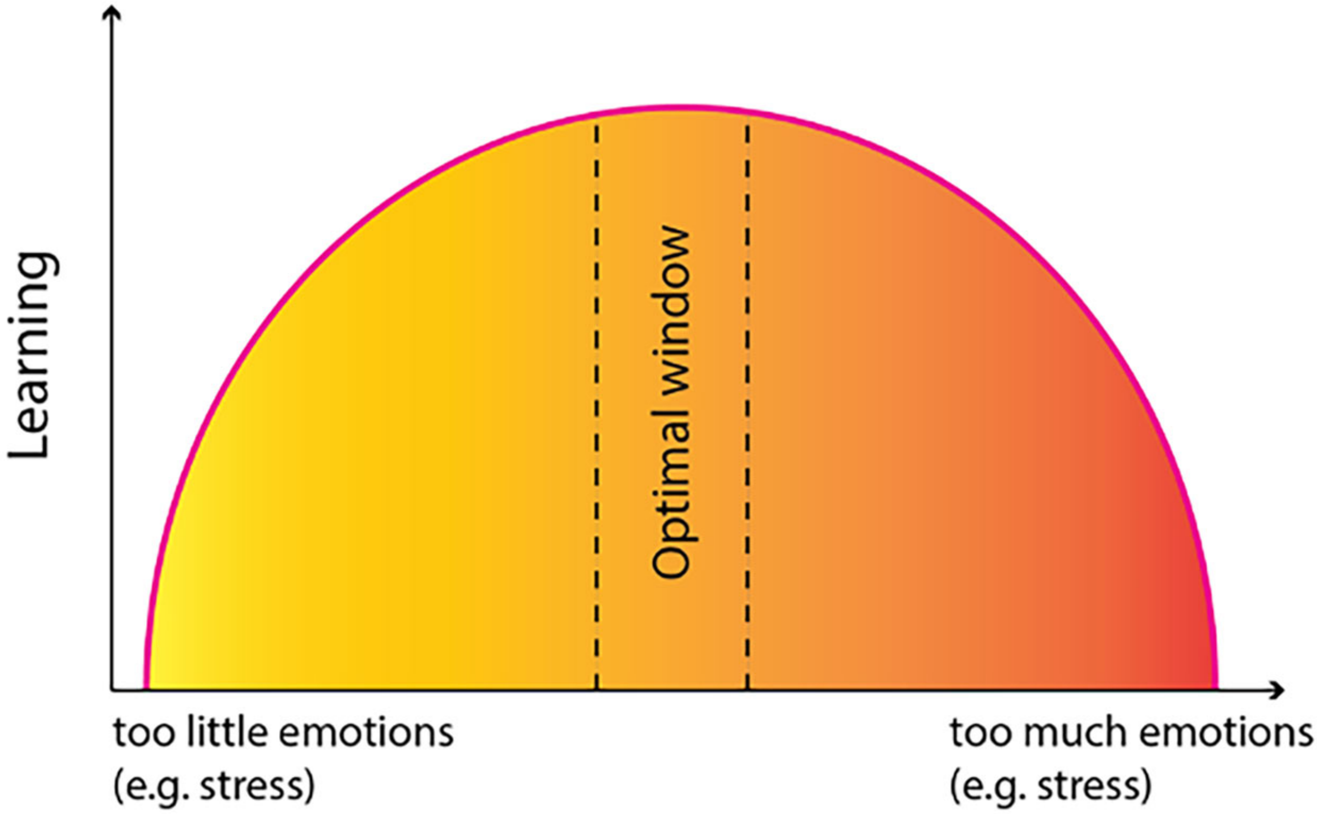

Figure 2. Schematic illustration of the "inverted U-shaped" curve.

Structural and functional brain alterations elicited by stress are likely mediated by elevated levels of what is commonly referred to as "*the stress hormone*" (i.e., cortisol), whose receptors are the most abundant in the amygdala, the hippocampus, and the prefrontal cortex[34,35]. As discussed earlier, experiencing an appropriate level of certain emotions can be very beneficial for learning. For example, a moderate level of cortisol can help us be adequately alert to our performance and well-focused on the task at hand. Yet, too much (or too little) cortisol can differentially impair our abilities to concentrate and focus: We are either too stressed, or too disengaged and distracted. This notion has been illustrated well by what is referred to as the "inverted U-shaped" curve[36] (see Figure 2). By being highly susceptible to emotional imbalances—and less able to properly regulate their emotions—children from low SES face additional barriers to learning, compared to their higher SES peers. That is, in terms of Figure 2, they are more vulnerable to experiencing the extremes of either side of the curve.

Apart from being able to maintain an appropriate "e*motional balance*," safeguarding our sleep-wake cycle is also crucial for learning, particularly for consolidating newly acquired knowledge into stable memories/known facts[37,38]. Studies have shown that children from low SES are more likely to have disrupted sleep cycles. This is likely due to their parents' hectic work schedules (which often includes night shifts), overcrowded households, and/or chronic stressors associated with scarcity of resources (i.e., preoccupations/anxiety)[39,40].

How does (good) sleep affect learning? Recent studies suggest that, especially during development, the consolidation of memories into stable knowledge is greater over sleep than wakefulness[41,42]. During sleep, memory consolidation is achieved by the interplay of two critical sleep-phases: *slow-wave sleep* (SWS) (i.e., nondreaming sleep) and *rapid eye movement sleep* (REM) (i.e., dreaming sleep). Together, these two sleep-phases help to promote the "transfer" of memories from their "entry point" (i.e., the hippocampus, where memories are formed) to their final "storage destination" (i.e., within cortical networks on the surface of the brain) where they can be easily retrieved. As such, a good night's sleep promotes optimal cross talk between the hippocampus and regions of the cortex, improving learning through the creation of stable memories. If this process gets disrupted by poorer sleep, learning will be highly affected. Critically, poorer sleep architecture has also been associated with greater cortisol responses and stress levels[39,40,43]. It is therefore possible that disruption of sleep patterns is one of the mechanisms through which stress impacts learning and brain plasticity in low SES children. On the other hand, it is possible that poor sleep is also related to diminished levels of alertness the next day, thereby impacting learning via mechanisms that are a prerogative of the other side of the "inverted U-shape" curve (see Figure 2). Yet, both these hypotheses remain to be directly tested.

Improving home and school environments

Families of low socioeconomic status (SES) can represent a highly disadvantageous environment for the appropriate development of brain systems important for learning (see Figure 1). Fortunately, for better or worse, our brains are highly plastic, and some of these environmental influences can be reversed with appropriate, highly targeted interventions as well as dedicated educational policies that can ultimately foster healthier brain development and better learning trajectories for low SES children. Below is a brief list of recommendations aimed at promoting cognitive, emotional, and physical nurturing, while concomitantly containing "toxic" factors—both at home and in the school.

- *Encourage parent-child interactions at home.* We discussed how cognitively and emotionally enriched environments—where parent-child interactions are more frequent—can foster better development and learning[12]. To encourage greater cognitive and emotional stimulation in the home environment, particularly in low SES families, teachers and policy makers could guide and promote the implementation of parent-child activities (e.g., read a book to your child, engage in educational activities with them, have a story time session) as part of the home routine. It is important that these approaches/activities are implemented as early as possible during development. In this way, a series of negative, cascading effects that are otherwise increasingly difficult to remediate could be halted.

- *Invest in adequate and balanced school meals, including provision of breakfast.* Providing one (or even two) balanced school meals can have significant benefits for children's nutritional status and their academic achievement. It could also help improve other aspects of academic life. For example, a study looking at the implementation of a "breakfast club" at school has reported a significant increase in school attendance, with the highest increments in low SES students[44]. From school attendance to improvements in academic achievement may hopefully be a short step.

- *Promote relaxation periods or mindfulness sessions as part of the curriculum.* Mindfulness training is increasingly being introduced in schools and recent preliminary data show that it may improve emotion regulation skills by acting on brain systems in the amygdala and prefrontal cortex [45]. Relaxation-type trainings before class have also been shown to be fruitful in reducing math anxiety and aiding math performance[46].

- *Reduce stress.* Expressive writing exercises have been shown to improve test performance in a group of college students with high levels of math anxiety[47]. Expressive writing exercises capitalize on the idea that writing down fears and worries towards something (e.g., towards math, a test, or a preoccupation at home) can help put these feelings "in perspective," reducing their negative valence. Another possible approach to release anxiety consists of exposure-based therapy. The underlying principle of this type of intervention is that repeated exposure to distressing stimuli and fearful situations in a positive environment can result in perceiving them in a less negative way[48]. A recent study has shown that, for example, mere exposure to math stimuli in a positive and rewarding setting decreased math anxiety and remediated amygdala functioning in a group of elementary school children[30].

- *Foster healthy sleep habits.* This could be achieved by adopting flexible school start times—yet only to a certain extent and notwithstanding the risk of disrupting healthy routine. It may also be appropriate to implement short naps, which have been shown to restore cognitive fatigue. For certain tasks, naps have been reported to increase performance, with gains comparable to those observed after a full night's sleep[49]. Additionally, in certain cases, it could be worthwhile to have students complete sleep diaries to help them monitor their sleep habits. The implementation of these diaries may increase students' awareness of their wake-sleep cycle and encourage them to adopt effective coping strategies to overcome disruptive habits.

- *Improve classroom communication by encouraging equal opportunities.* Collective verbal exchanges in the classroom—such as expressing opinions or sharing experiences—can be highly *biased* towards higher SES students[14]. They are the ones that tend to speak more often in collective verbal exchanges, and this bias is already evident at the preschool level. Critically, teachers may not be aware of such bias and, as a consequence, they might inadvertently hinder low SES students from improving their linguistic and communication skills, further enlarging the "*achievement/opportunity gap.*" Helping teachers to recognize and be aware of such bias could encourage them to implement systematic strategies to motivate equal participation of low SES students, ultimately increasing their chances of success.

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