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Neurobiological origins of impulsive behavior in adolescence: possibilities of physical exercise

Origens neurobiológicas do comportamento impulsivo na adolescência: possiblidades da prática de exercícios físicos

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Abstract

Objective

This article aimed to understand the neurobiological origins of adolescent behavior and how the possibility of practicing physical exercises can attenuate the maturational tendency for impulse behaviors in this age group.

Method

For this purpose, a bibliographic research of a narrative nature was carried out in the databases SciELO, Web of Science, PubMed, and in books.

Results

The data revealed that during adolescence there is a propensity as a function of neurobiological development to search for rewarding behaviors in the short term. In this sense, bodily practices, including exercise, can be an essential component in the search to increase the neural control of impulses through a neurobiological and sociological bias.

Conclusion

It is concluded that exercise can be a propelling means in the search to attenuate the immediate and even risky behaviors of the adolescent brain, increasing higher cognitive functions with this better cortical control.

Keywords: Adolescent; Impulsive behavior; Neurobiology; Physical exercise.

Resumo

Objetivo

Este artigo objetivou compreender as origens neurobiológicas do comportamento adolescente e como a possibilidade de praticar exercícios físicos (EF) pode atenuar a tendência maturacional de comportamentos impulsivos nesta faixa etária.

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Método
Foi realizada uma pesquisa bibliográfica de cunho narrativo nas bases de dados (Scielo, Web of Science e PubMed) e em livros.

Resultados
Os dados revelaram que durante a adolescência há uma propensão da busca de comportamentos recompensadores a curto prazo, em função do desenvolvimento neurobiológico. Nesse sentido, as práticas corporais, dentre elas o EF, podem ser um componente essencial na busca de aumentar o controle neural dos impulsos através de um viés neurobiológico e sociológico.

Conclusão
Conclui-se que o EF pode ser um meio propulsor na busca de atenuar os comportamentos imediatistas e até arriscados do cérebro adolescente, aumentando as funções cognitivas superiores, devido ao melhor controle cortical.

Palavras-chave*: Adolescente; Comportamento impulsivo; Neurobiologia; Exercício físico.*

Adolescence is traditionally known as a phase of emotional instability and growth spurt, characterized by physical and psychosocial changes (Meherali et al., 2021). This period is extremely important as it marks the development of lifestyle habits that can have a significant impact on immediate and long-term health (Vijayakumar et al., 2018). It is also characterized as a time of rapid physiological, sexual, neurological, and behavioral changes (Vijayakumar et al., 2018), posing a significant risk for the onset of mental disorders, with risky behaviors commonly occurring during this life stage (Meherali et al., 2021).

In this age group, the rate of deaths due to impulsive and, above all, risky behaviors, is extremely high, potentially leading to negative outcomes such as substance abuse and premature death. According to data from the World Health Organization (2015), traffic accidents are the leading cause of hospitalization in young people, often associated with driving under the influence of alcohol, with 23% of traffic accident deaths occurring between the ages of 18 and 24. This is further compounded by a high incidence of illicit drug abuse, to the extent that 11.2% of overdose deaths occur in individuals aged 15 to 24 (Britton, 2021). Additionally, suicide is a recurring issue during this period (Breslin et al., 2020).

This impulsive behavior leading to poor choices is influenced by a strong bias in neurobiological development, where the adolescent brain is more susceptible to engaging in rewarding behaviors, especially those with short-term benefits, while disregarding potential harms in the medium and long term (Kahneman, 2011). This immediate-gratification behavior, where all events in this phase seem ultimate, eternal, and maximized in their sensations, both positive and negative, is therefore one of the main drivers for risky behaviors that can jeopardize the physical and mental health of young individuals.

Nevertheless, studies indicate that adolescents with higher physical fitness tend to display fewer aggressive behaviors, as well as improvements in social interactions and behavior (Trajković et al., 2020). Regular engagement in body practices, particularly Physical Exercise (PE), is believed not only to diminish aggressive behaviors in adolescents through the acquisition of self-control skills but also contributes to a reduction in hostile thoughts and negative emotions (Shachar et al., 2016).

Engaging in regular PE has been found to enhance the development of executive functions associated with the Prefrontal Cortex (PFC), such as cognitive flexibility, working memory, and inhibitory control (de Greeff et al., 2018). Thus, recognizing that PE and body practices themselves tend to improve executive functions, and these functions appear to intervene in enhancing and/or accelerating the maturation process and proper development of cognitive abilities aligned with physical fitness, one can then posit that PE is an important construct in the relationship between the brain and behavior. This is particularly relevant as executive functions are essential for evaluating decision-making processes and, consequently, avoiding impulsive and risky behaviors (de Greeff et al., 2018).

Hence, this study is essential as it aims to comprehend, drawing upon sociological and neurobiological literature, the association between executive functions and adolescence, and the manner in which PE interacts with these factors. The aim is then to find out from the interaction of two biases (neural and social), how regular PE (greater fitness) can lead to better behavioral control (reduction of risky impulses through improved inhibitory control) in adolescents and thus propose the outline of a theoretical model. To accomplish this, a narrative literature review was conducted utilizing databases (Scientific Electronic Library Online [SciELO], Web of Science, and PubMed) and consulted relevant books in both Portuguese and English to construct the research and theoretical discussion. The inclusion criterion comprised studies, pertinent books, or articles directly associated with the theme. This study aims to enhance the comprehension of the phenomenon by proposing a model of mutual interaction. This model posits that the Autonomic Nervous System (ANS) affects neurobiology as a result of the practice of PE itself, and the social environment in which the individual is inserted influences the final behavioral outcomes.

The Adolescent Brain

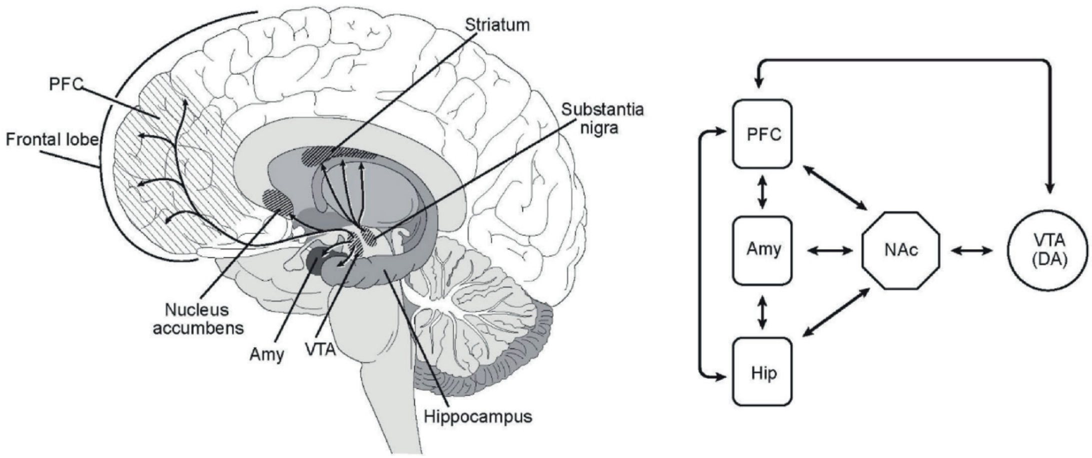
Adolescence is a period marked by various changes, both in the external environment (socialization issues, peer acceptance for inclusion, affective relationships, among others) and in the internal environment (structural and functional alterations of the brain, as well as general physiological aspects) (Meherali et al., 2021; Vijayakumar et al., 2018). Particularly, the internal changes, i.e., those occurring interoceptively to the individual, can be observed through typical behaviors of chronobiological maturational development, such as impulsive acts and a greater propensity for risky decision-making that may impact and/or fail to safeguard long-term physical, mental, or social well-being. For example, engaging in drinking and high-speed driving and displaying increased aggressive behavior (Lockhart et al., 2018). Another way to perceive these characteristic differences of this transitional period is through brain imaging studies (Structural Magnetic Resonance Imaging [MRI], Diffusion Tensor Imaging [DTI], and Functional Magnetic Resonance Imaging [fMRI]) (Casey et al., 2008).

The literature, as evidenced by MRI studies, indicates a difference in structural development between two important regions for behavior, namely the prefrontal and subcortical regions. There appears to be a chronobiological difference in the maturation of these structures, which tends to be one of the factors explaining this impulsive, uncontrolled behavior. In adolescence, the pleasure center (Nucleus Accumbens - NAcc) is already matured and at its peak activation, leading individuals to increase their pursuit of pleasurable, rewarding actions (Gogtay et al., 2004). Concurrent with the maturation of the NAcc, the Prefrontal Cortex (PFC) is also undergoing development. At this stage, the PFC is not yet fully matured, resulting in decreased impulse control. Notably, one of the primary functions of this area is Inhibitory Control (IC), a crucial aspect of executive functions (Casey et al., 2008; Gogtay et al., 2004).

The DTI studies (Liston et al., 2006; Nagy et al., 2004) support this observation, indicating that, alongside the limited control of the still-maturing PFC during this phase, the myelination of the circuit connecting the NAcc to the PFC is underdeveloped. This underdevelopment leads to a suboptimal transmission of information between these structures. In conclusion, the NAcc activates in the pursuit of immediate reward, receiving dopamine (the pleasure hormone) released by the ventral tegmental area. However, the PFC is unable to control these impulses due to its limited maturation and reduced reception of information sent by the NAcc (Casey et al., 2008; Rappaport et al., 2020) (Figure 1).

Figure 1

Reward system (A) and dopamine neurocircutry (B)



Source: Sonne and Gash (2018).

Functional Magnetic Resonance Imaging further reveals that, in childhood and during learning situations, humans heavily rely on the activation of the PFC, spreading brain activation across various distinct subareas to perform the tasks at hand. Conversely, in adulthood and situations where individuals are accustomed to a particular action or attitude, activation becomes more concentrated in a specific region, neglecting areas that are not essential for the given activity (Durston et al., 2003; Huang et al., 2019; Liuzzi et al., 2020).

The structural and functional development of brain structures and their interconnections can be considered, as the PFC cannot effectively control emotional impulses, which, in turn, are hyperactivated and represented in the NAcc region. This may lead adolescents to an unrestrained pursuit of immediate rewards, favoring short-term benefits without considering the consequences (Casey et al., 2008; Durston et al., 2003).

The pursuit of immediate rewards is more pronounced in humans, particularly in the "experiential self" (system 1), which prioritizes immediate rewards over medium and long-term ones. Throughout life, the neurobiological predominance of these immediate circuits remains evident and dominant, with older limbic regions exhibiting greater system dominance. This is further heightened in adolescence, as with the hyperactivation of the pleasure center (NAcc), there is a high demand for immediate pleasure-seeking behaviors (Kahneman, 2011). The combination of system 1's incessant pursuit of pleasure with low IC leads to impulsive and inappropriate behaviors that impact both the individual adolescent and society itself. This consideration aligns with models of individual-society interaction in human development, such as the neoecological model of human development (Navarro & Tudge, 2022).

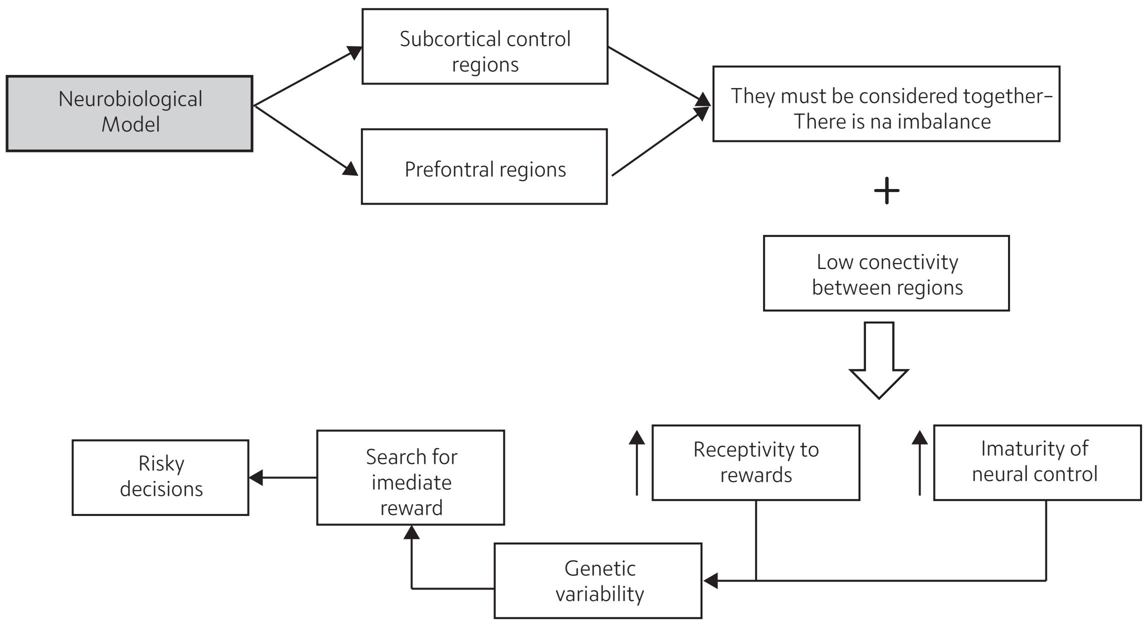
There is also a neurochemical aspect that cannot be overlooked, as there seems to be a proportional relationship between impulsive abnormalities and low levels of neurotransmitters such as dopamine, norepinephrine, and serotonin (Williams & Potenza, 2008). Particularly, serotonin (5-HT) (neurotransmitter) levels in the brain, evidenced in childhood and adolescence (Cupaioli et al., 2021), are related to impulsive and aggressive behaviors, as well as overall well-being. In other words, low levels of this neurotransmitter seem to facilitate antisocial conduct, as it regulates mood states, sleep, and pleasurable behaviors (Damásio, 2012; Williams & Potenza, 2008). Nevertheless, it is important to avoid oversimplification when attributing adaptive social behavior (good conduct) solely to serotonin or concluding that its absence directly "causes" aggressiveness. The presence or absence of specific brain systems containing specific receptors for serotonin modifies the functioning of these systems, and this modification alters the modus operandi of other systems, which ultimately express themselves in behavioral and cognitive terms. In other words, it is essential to consider how serotonin interacts – functioning in conjunction – with the structural and functional brain systems that govern social behavior. Avoid viewing serotonin in isolation as the sole controller of behavioral regulation (Damásio, 2012).

It is not about serotonin increasing or reducing aggressive and impulsive behavior; rather, it is about its involvement in a complex mechanism at the molecular synaptic level in local circuits and systems. Furthermore, serotonin is significantly influenced by the sociocultural factors to which individuals are exposed. Therefore, it is crucial to consider both social and neural factors – operating at structural, functional/connectivity, and chemical levels – in tandem when attempting to modulate behavior (Damásio, 2012).

Finally, but of great relevance in behavior, is the genetic variability of each individual. In general, adolescents exhibit more impulsive behaviors; however, within this group, there are individuals with lower IC than their peers, as well as individuals who naturally possess higher IC. This difference is sustained by many throughout life (Casey et al., 2008). We are the sum of our sociocultural experiences and our genetic load (Figure 2).

Figure 2

Neurobiological Model of the adolescent brain



Note: The maturation of subcortical regions should be considered in conjunction with the prefrontal (cortical) regions, along with the connectivity between them. These factors increase receptivity to rewards which, modulated by genetic variability, can generate short-term reward behaviors, leading to risky decisions.
Source: Adaptation of Casey et al. (2008).

In this context, interventions through body practices such as meditation, mindfulness, yoga, and general physical exercises emerge to attenuate this maturational difference and accelerate the proper development of areas controlling undesirable behaviors (Frank et al., 2020; Huang et al., 2019; Pozuelos et al., 2019; Tornberg et al., 2019; Wielgosz et al., 2019). These body practices present themselves as important allies in improving juvenile behavior through different neurobiological pathways.

Executive Functions and Juvenile Behavior: Implications of Body Practices

The literature reports that adolescents recognize and resolve their dilemmas similarly to adults. Adolescents, however, tend to exhibit higher risk behavior. What seems to occur in the adolescent brain is a greater sensitivity to rewards, indicating that they value the reward, especially in the short term, above possible negative consequences. Furthermore, in the presence of their peers, this effect is amplified, causing adolescents to expose themselves more to risky situations (Ferreira-Vorkapic et al., 2015).

The ability to control actions depends on the integrity of the executive functioning system, related to how we manipulate our actions, thoughts, and emotions daily. Executive Functions (EF) constitute the set of skills responsible for top-down control of behavior, operating in the control and regulation of behavioral processes, including cognition and emotion (Diamond, 2020).

Good executive functioning enables individuals to reflect before acting, mentally work through different ideas, solve unexpected challenges, think from various perspectives, reconsider opinions, and avoid distractions. These skills are fundamental for decision-making, living and thinking autonomously (Diamond, 2020).

Executive functions come into play whenever an individual engages in new tasks or situations, as well as in problem-solving and goal-setting, being crucial for adaptive functioning in daily life. According to Diamond (2020), three fundamental dimensions constitute Executive Functions: (1) Working Memory, defined as the storage and updating of information while the individual engages in activities related to them; (2) Cognitive Flexibility, defined as the ability to shift the focus of attention and cognition between different but related dimensions or aspects of a particular task, and (3) Inhibitory Control, defined as the inhibition of prepotent or automated responses when the individual is engaged in task execution (Diamond, 2020).

Inhibition or inhibitory control is the ability that allows individuals to control inappropriate behaviors, referred to as response inhibition or self-control, enabling control over cognitive, emotional, and behavioral processes (Diamond, 2020), providing mastery over behavior despite the presence of impulses and emotions, encouraging specific conduct. Having self-control means having the ability to act differently from inner desires, such as having the discipline to complete unenjoyable but necessary tasks to achieve the desired goal. Moreover, having self-control involves avoiding mistakes due to impulsivity, such as drawing premature conclusions, speaking without prior thought, or not calculating the consequences of an action or decision (Diamond, 2020; Giordano et al., 2021).

Considering that the prefrontal cortex is the area correlated with executive functions (Diamond, 2020), a cross-sectional study demonstrated that the higher the level of cardiorespiratory fitness, the greater the gray matter volume in the dorsolateral region of the prefrontal cortex (Castells-Sánchez et al., 2021). According to de Greeff et al. (2018), regular physical exercise by adolescents constitute an excellent form of executive training and is highly suitable for stress management.

The body is an essential part of the integral development of the individual, and knowing how to use it is paramount. Evidence points to the benefits of different types of programs that can favor the development of self-regulation. Moreover, they suggest that martial arts, contemplative practices such as meditation, and interventions conducted in the school context can impact the development of executive functions and be used to promote promising outcomes (Giordano et al., 2021).

Mindfulness interventions have been reported as beneficial for assisting in executive development and functioning, including working memory, sustained attention, and attention shifting (Pozuelos et al., 2019). Additionally, mindfulness-based cognitive therapy has been documented in the literature as an effective treatment for improving well-being, particularly related to mood and cognition, in various populations (Azevedo & Menezes, 2020).

Studies investigating the benefits of body practices, analyzing aspects related to the psychological domain such as tension, anxiety, self-esteem, and other mood indicators, as well as cognitive functions, have consistently shown positive and beneficial results for the individual (Ferreira-Vorkapic et al., 2015; Trajković et al., 2020). In this regard, studies on contemplative practices have identified positive results mainly in relation to factors such as emotional stability, attention control, cognitive efficiency, anxiety, negative thought patterns, and emotional and physiological excitability (Estevao, 2022; Hagen et al., 2021; Khalsa & Butzer, 2016).

In a randomized clinical trial conducted by Telles et al. (2013), comparing a yoga intervention group with another engaged in physical exercise, it was concluded that both groups showed significant improvements in cognition, particularly in emotional and behavioral factors, exhibiting higher rates of behavioral improvement in terms of obedience, attention, and interpersonal relationships with teachers and peers. Trajković et al. (2020) contribute by describing that high levels of physical fitness can help reduce aggressive behavior in children and adolescents, improving their social interaction and behavior.

Nagendra et al. (2015) investigated the effects of yoga on cognitive capacity, the Autonomic Nervous System (ANS), and Heart Rate Variability (HRV) − measured through electroencephalography (EEG) and echocardiography (ECG) recordings − in engineering students. The results indicate significant improvements in various cognitive functions, including memory, neuronal activity, alertness, and changes in HRV tending towards parasympathetic dominance (Nagendra et al., 2015). HRV involves an analysis through an objective and non-invasive tool that describes the influence of the ANS on heart activity. It reflects the degree of physiological, endocrine, and emotional balance in the body (Forte et al., 2019). Chronic stress leads to a dominance of the sympathetic nervous system and decreased vagal activity, as expressed by lower HRV. This is reflected by a decrease in energy spectral density in the High-Frequency (HF) range (Kim et al., 2018).

The ability to adapt to stress is a central facet of human development. Successful adaptation includes how individuals manage their emotions, think constructively, regulate and direct their behavior, control their autonomic stimulation, and act in social and non-social environments to alter or reduce sources of stress (Frank et al., 2020; Kim et al., 2018). Key elements, such as attention regulation, body awareness, emotion regulation, acceptance, self-transcendence, and cognitive flexibility, are effectively developed through mindfulness training (Frank et al., 2020). It is believed that promoting the ability to be focused on the present moment and on distant observers of our internal cognition or emotions adopted during mindfulness training enhances cognitive function and improves objective and adaptive stress response strategies.

de Greeff et al. (2018) propose that physical activities characterized by a higher cognitive demand, such as those requiring memorization of sequences of movement patterns and sustained attention for intentional changes in movements, may attenuate healthy brain development. These activities not only benefit the musculoskeletal and cardiovascular systems but also impact the cognitive system through engagement in executive control processes. They also assist in adaptive control and stress response (de Greeff et al., 2018).

Thus, it appears that body practices, especially physical activity, through increased physical fitness, promote improvement in juvenile behavioral parameters by reducing improper impulses and risky and socially inappropriate decision-making.

The Brain-Physical Exercise Interaction

Throughout childhood and, particularly, adolescence until early adulthood, the brain undergoes continuous development, encompassing both structural changes and the establishment of connections, such as synapses, neurogenesis, synaptic pruning, and others. According to the literature, regions like the PFC, for example, are known to develop until approximately 25 years of age (Arain et al., 2013).

Understanding this information about the delayed maturation of the PFC and the knowledge of EF (working memory, cognitive flexibility, and inhibitory control), primarily controlled by this region, can provide insights into the mechanism of low control of these functions in this age group. From this understanding, potential pathways to mitigate disruptive behaviors caused by this neural immaturity can be proposed.

As we can see, the adolescent brain is prone to impulsive and risky decision-making due to a neurobiological developmental tendency toward such behavior in the pursuit of optimizing short-term rewards, ignoring potential long-term drawbacks. As previously described, decision-making is influenced by two main systems: a rapid, emotional system (system 1), governed by subcortical areas; and a slower, rational system (system 2), involving neocortical areas (Kahneman, 2011). However, recognizing that impulsive behavior is associated with poor performance of executive functions managed by the prefrontal brain region, possibilities can be formulated to increase this higher cortical control (PFC) and diminish the eminent dominance of the limbic system (NAcc) in the pursuit of immediate rewards (Casey et al., 2008).

As previously mentioned, body practices, especially PE, and activities aimed at regulating the ANS such as meditation, mindfulness, and yoga, can assist in the realignment of the mechanism, resulting in behavioral improvements, particularly by reducing impulsive and aggressive behaviors (Frank et al., 2020; Huang et al., 2019; Pozuelos et al., 2019; Tornberg et al., 2019; Wielgosz et al., 2019). Regular physical exercise, in general, can attenuate impulsive behaviors through various means, all somehow linked to increased physical fitness. These effects manifest through two primary avenues − sociological and neurobiological − each exerting influence on the other.

Regarding the sociological origin of behavior influencing the neurobiological aspects of decisions, the literature indicates that social factors are crucial for behavioral conduct, especially in childhood and adolescence. In social relationships, especially with peers (individuals of the same age group), social contracts are formed, a moment when humans develop and learn to coexist in society. This social relationship undoubtedly affects the neural development of the individual in formation, as humans are social beings, and effective neural control involves learning social norms (Ammar et al., 2020; Vasilopoulos & Ellefson, 2021).

It is also worth noting that social relationships are essential for motivating behaviors, given that they fulfill a primary psychological need, with peers appearing to directly influence human behavior, especially in adolescents (Deci & Ryan, 1985; Vasilopoulos & Ellefson, 2021). Therefore, PE, especially when conducted in a group setting, is a powerful ally in learning social rules and behavioral control, in addition to benefiting physical and mental health (Mikkelsen et al., 2017; Seino et al., 2019).

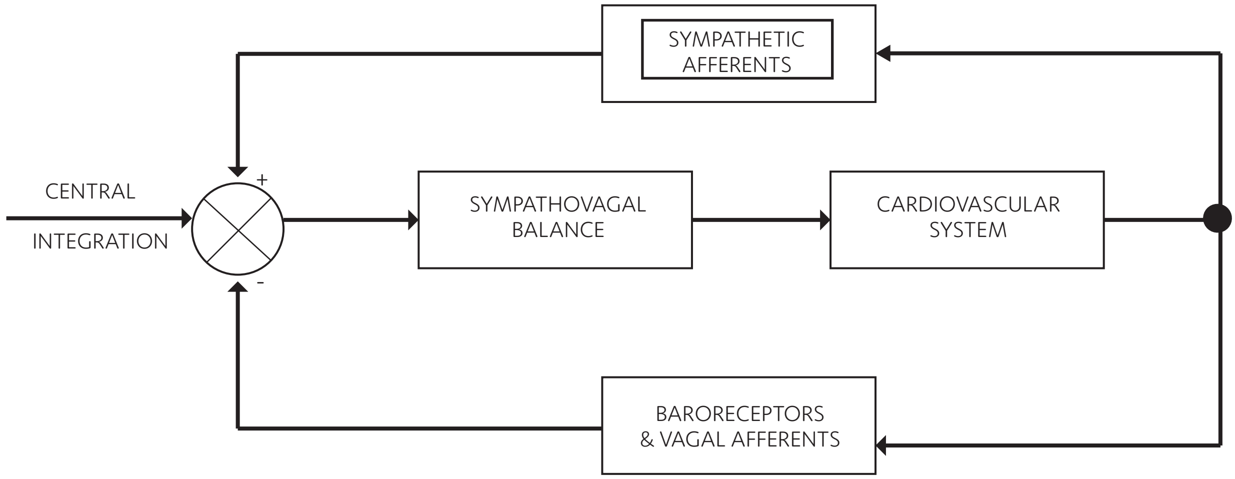
From the neurobiological perspective influencing social behavior, the psychophysiology of emotional aspects, especially stress mechanisms, comes into play. Specifically, when psychological stress (emotion) occurs, it affects physiological processes (in response to the stressor) in order to prepare our system to face the potential adverse event, seeking to safeguard physical, social, and mental well-being. This mechanism is guided through the ANS, which is divided into two pathways, the Sympathetic Nervous System (SNS), and the Parasympathetic Nervous System (PNS). The SNS is responsible for stressful situations, preparing the body for "fight or flight" scenarios, increasing Heart Rate (HR), for example. The PNS, in turn, is activated during periods of homeostasis or when the physiological mechanism has already recognized the end of the stressor event and seeks to restore the basal state, decreasing HR and other reactions that had been activated during the SNS increase (Ziemssen & Siepmann, 2019).

That said, in the face of a stressful situation, there is an increased physiological response in the SNS, activating the Sympathetic-Adrenal Medullary (SAM) system, responsible for the action of primary stress hormones. It stimulates the adrenal medulla to produce catecholamines, primarily adrenaline, triggering the primary stress response chain (positive feedback) upon perceiving a stressor. Simultaneously, the Hypothalamic-Pituitary-Adrenal (HPA) axis is also activated. After the action of catecholamines, the hypothalamus, one of the main stress-reactive regulators, secretes the Corticotropin-Releasing Hormone (CRH) to the pituitary gland, which signals the Adrenocorticotropic Hormone (ACTH) to the adrenal gland. This, in turn, releases adrenaline and cortisol (mainly responsible for negative feedback) into the bloodstream. The release of cortisol into the bloodstream results in preparatory changes for the body to face real action. Therefore, there is a cascade increase in heart rate, respiratory rate, sweating, release of energy stored in the liver (glucose), muscle contraction strength, mental activation, pupil dilation, among other alterations. Conversely, its activation still inhibits visceral mechanisms, such as the digestive and urinary systems (Guyton & Hall, 1998; Ziemssen & Siepmann, 2019).

It is important to emphasize that, following the cessation of the SNS activation process in response to a stressor stimulus, i.e., when this stimulus ends, in a normal individual, there is a return to baseline levels, promoting homeostasis (consequently activating the PNS more). This process involves negative feedback, primarily modulated by cortisol. This return to homeostasis is known as allostasis, signifying the human capacity to navigate adverse situations while sustaining internal conditions in a healthy state. It involves the ability to modify the system in response to a stressor stimulus, enabling a return to the baseline state. However, the return through allostasis occurs in different ways, contingent on the individual's prior personal experiences and genetics (McEwen, 2000; McEwen & McEwen, 2017; Miller & O'Callaghan, 2003) (Figure 3).

The ANS can be non-invasively assessed through HRV - the interval between one heartbeat and another (a direct measure of the PNS). This interval corresponds to the "R" waves, indicating the closure of the inlet valves and the end of diastole. In essence, it involves a more microscopic analysis of the HR itself, represented as an average over time (beats per minute) (Gasior et al., 2018; Malik et al., 1996). This HRV, inversely proportional to HR (indicating a negative correlation), when at low levels (corresponding to high HR), suggests a greater dominance of the SNS, a factor identified in the literature as a risk for various diseases, including cognitive impairment in functions such as executive functions (Alves Donato et al., 2021; Gasior et al., 2018).

Figure 3
Schematic representation of opposing feedback mechanisms



Note: Schematic representation of opposing feedback mechanisms that, in addition to central integration, serve the neural control of the cardiovascular system. Baroreceptor and vagal afferent fibers from the cardiopulmonary region mediate negative feedback mechanisms (exciting vagal flow and inhibiting sympathetic flow), while positive feedback mechanisms are mediated by sympathetic afferent fibers (exciting sympathetic flow and inhibiting vagal flow).
Source: Malliani et al. (1991).

In this context, given that PE itself is a stressor event and consequently employs the same stress mechanism as psychological stress or cognitive challenges, the mechanism can be conditioned through PE (increasing physical fitness) to restore homeostasis more rapidly, thereby enhancing control of the PNS (as evidenced by low HRV). This, in turn, minimizes potential harm to the system due to the relatively short duration of the stressor. This is because the system is being adapted, accustomed to face healthy stressor stimuli, facilitating management and homeostatic return (Oliveira et al., 2017; Sharma et al., 2017; Tornberg et al., 2019). That is, the mechanism recovers more easily from stimuli that stress it because it is adapted to these stimuli.

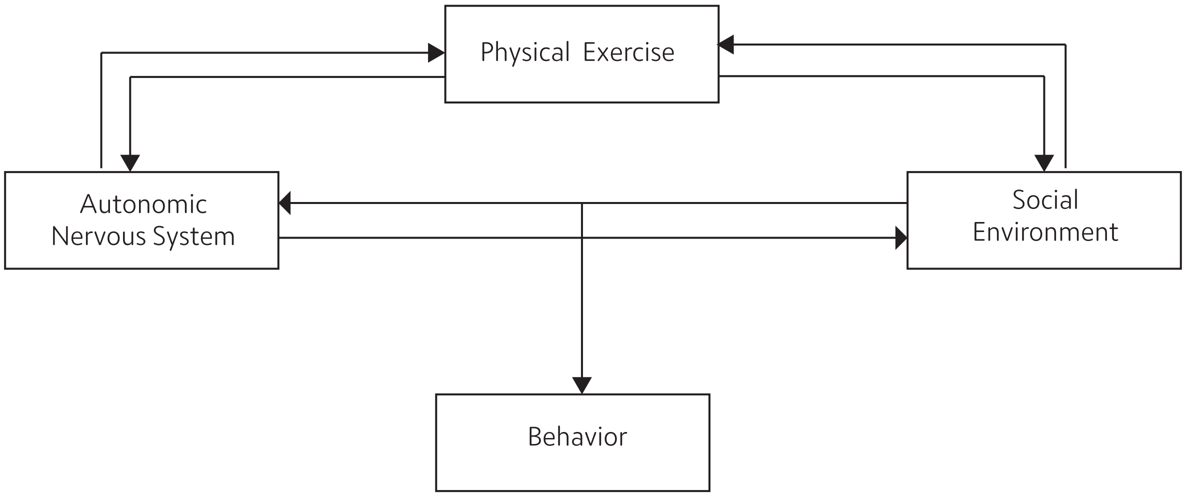
However, an important observation needs to be made; there is an optimal plateau of PNS activation through PE that enhances cognitive performance (Murray & Russoniello, 2012). The issue is that individuals with low physical fitness easily surpass this "optimal" activation of the SNS (requiring greater physiological effort to meet the same demand), resulting in a reduction in executive functions, leading to low cognitive performance and physiological problems derived from the hyperactivation of the stress mechanism (Murray & Russoniello, 2012).

It is evident, then, that HRV is a crucial variable to analyze, as elevated HRV levels (within an ideal zone) serve as an indicator of an individual's health. HRV during rest, mediated by the vagus nerve (a PNS activity mediator), is associated with enhanced performance in executive functions (such as attention and emotional processing) in the frontal cortex. As such, it can modulate and impact these higher neural activities, improving social and cognitive processing (Lane et al., 2009; Lehrer, 2013; McCraty & Childre, 2010; Thayer & Lane, 2009). A low HRV, however, is inversely proportional and indicates increased risks for various types of diseases, such as stress, chronic pain, depression, cancer, and low emotional flexibility (Alves Donato et al., 2021; Gasior et al., 2018).

Thus, it can be understood that PE affects neuropsychophysiological variables, serving as potential mediators of human behavior. In essence, there is a belief that engaging in physical exercise has the capacity to modify behavioral phenotypes, consequently shaping individuals' interactions within society (Sinclair et al., 2014). Based on this, it can be inferred that the relationship between PE and behavioral changes stems from socioenvironmental changes, subsequently influencing the psychophysiological responses of individuals (social environment − behavior − neurobiology) (Sando & Sandseter, 2020). Alternatively, these psychophysiological changes, affected by physical exercise, function as regulators of behavior (psychophysiology of PE − behavior − social context) (Oliveira et al., 2017), creating a triple relationship of interdependence: PE − psychophysiological changes − social environment − behavior.

Thus, PE interferes with adolescent behavior through the social regulation obtained in social contracts established with peers during daily encounters promoted by PE. Furthermore, PE influences behavior by inducing physiological and neurobiological changes through habituation to PE as a stressor of the system, ultimately impacting the individual's social component (Figure 4).

Figure 4
Model of mutual interaction ANS – PE - social environment – behavior



Final Considerations

The brain undergoes various structural and functional changes throughout its maturational development. It is observed that there are periods, especially during adolescence, where due to the non-linear maturation between subcortical and cortical regions, there is a greater propensity for behaviors that seek immediate reward, disregarding potential harm that this short-term benefit to the limbic system may bring.

These impulsive and sometimes risky behaviors in the pursuit of rewards appear to be mitigated by body practices, including physical exercise. Such practices contribute to the development of the sociological mechanism by regulating social contracts with peers and the existing social structure in sports and group activities. Simultaneously, they affect the neurobiological mechanism through the regulation of the ANS. Concerning the sociological control mechanism of behavior, exercise proves to be an important ally in promoting group interaction with individuals of the same age group, generating a long-term purpose in life, and possibly reducing impulsivity in system 1 (impulsive).

From a neurobiological perspective, an alternative is to improve control of the ANS, especially that of homeostatic return (PNS), in the pursuit of controlling psychological stress. This better control of stress mechanisms can be achieved through good physical fitness, conditioning the system to better cope with adverse stress stimuli.

In conclusion, there seems to be an interdependent relationship between the social environment, psychophysiological (neurobiological) responses, and physical exercise, resulting in greater upper-level neural control, especially regarding executive functions. Thus, creating a Model of mutual interaction between ANS – PE – social environment - behavior.

However, there are limitations to this study, the main one being the fact that it is a narrative literature review, which leaves some methodological gaps. Nevertheless, this article points towards future directions for new empirical studies to advance the understanding of the phenomenon, as well as the proposal for an a posteriori systematic review, aiming to make these findings more robust in the literature.

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