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## Neuroboundaries in academic teaching

### Summary

The article addresses educational boundaries from a neurobiological perspective. Boundaries are understood not only as structural frames that regulate roles, norms and expectations, but also as triggers of novelty, surprise and cognitive conflict—that is, prediction errors that activate neuroplastic processes. The author discusses the neural mechanisms underlying novelty detection (the role of the hippocampus, amygdala, prefrontal cortex, reward system and large-scale brain networks) and shows how moderate stress can act as a catalyst for learning, whereas excessive or chronic stress leads to avoidance, consolidation of fear and decreased motivation. The text also analyses individual predispositions to crossing boundaries, resulting from the interaction of genetic, neurobiological and experiential factors, and their consequences for exploration, tolerance of uncertainty and cognitive flexibility. In conclusion, the article argues that carefully designed educational situations which combine novelty with a sense of safety and permission to err can harness boundaries as a tool for consciously fostering development, curiosity and adaptive strategies for dealing with uncertainty and unpredictability.

**Keywords:** neurodidactics; educational boundaries; prediction error; stress; neuroplasticity

In teaching, boundaries serve both a structural and neuropsychological function. They define standards of conduct and expectations, assign roles, and determine the sense of security of all participants in the educational process. However, cognitive development does not occur in conditions of complete predictability. It is situations that go beyond existing patterns that are the real catalyst for neuroplasticity, which is the basis for learning and development.

From a neurobiological perspective, crossing boundaries in teaching can be understood as an experience of novelty, surprise or cognitive conflict, which triggers a specific cascade of processes in the brain: from the generation of prediction error, through arousal or stress and the stimulation of cognitive processes, to the reorganisation of neural networks. In other words, exposure to novelty is one of the most important factors conducive to triggering processes that lead to learning – the construction of both new knowledge and skills.

The aim of this paper is to discuss these mechanisms in the context of education, to identify neurobiological predispositions that favour or hinder the crossing of educational boundaries, and to

characterise both the positive and negative changes in brain functioning that can result from crossing educational boundaries.

### **Crossing boundaries as a prediction error**

One of the basic functions of the brain is the ability to constantly make predictions about future events (Grube and Nitschke, 2013). In its basic dimension, the process of prediction occurs independently of the will as part of automated and unconscious activities carried out by cooperating cortical and subcortical structures. Of course, every teaching situation also provides a basis for the brain to make predictions – for example, students predict the course of the class, the teacher's reactions, the content and difficulty of the task, while the teacher predicts the students' reactions, their engagement and difficulties in completing the task, etc. In this context, crossing the boundary can be understood as anything that deviates from the predictions made by the brain – a scientific fact that contradicts beliefs, an unusual form of task, a question or answer that deviates from expectations, or the emotional reactions of students or teachers. When the brain detects a discrepancy, it triggers a specific reaction called a prediction error (Schultz, 2016).

In the brain, the hippocampus is primarily responsible for detecting novelty in situations, comparing incoming information with stored patterns. When the level of novelty is sufficiently high, the amygdala, which gives the situation emotional significance, and the prefrontal cortex, which decides on a course of action by modifying or creating a completely new response pattern, are stimulated (Watabe-Uchida et al., 2017). The preparation of current and future responses to prediction errors is monitored by the anterior cingulate cortex.

Dopamine neurons in the midbrain, especially those belonging to the reward system, play a key role in responding to novelty and the mismatch between expectations and reality. They encode prediction error – both its magnitude and sign (favourable or unfavourable deviation from expectations) – and also participate in assigning motivational significance to situations. This stimulation of the reward system and the dopamine released from axon terminals located in various cortical and subcortical areas opens a "window of neuroplasticity," allowing learning from both positive and negative prediction errors (Sinclair and Barense, 2019).

From the point of view of the functioning of large-scale brain networks, crossing the boundary leads to strong excitation and dynamic switching of activity between three basic systems: the default mode network, the main executive network, and the salience network. The salience network is crucial in switching the flow of information between the problem-solving and action system (main executive network) and the self-reflection and interpretation system (default mode network). By assigning appropriate weight and character to an event, the salience network also determines the strength of the stress response accompanying the crossing of the boundary (Ham et al., 2013).

### **Stress as a catalyst and regulator of responses to novelty**

Arousal or a full-blown stress response are integral components of the response to novelty. From a neurobiological point of view, stress can be adaptive or maladaptive.

A moderate level of stress arousal has a mobilising effect, increasing overall activity and motivation, intensifying attention and other cognitive processes, and supporting the integration of memory and perceptual information (Yuen et al., 2011). In the context of education, a moderate stress response can therefore be considered a factor that is extremely conducive to the construction of new knowledge or skills.

However, when stress exceeds the optimal level, executive functions may be impaired. The weakening of analytical abilities, flexibility and cognitive control over emotions and behaviour makes it inevitable to give up exploration and replace it with a defensive reaction aimed at escape (Grupe and Nitschke, 2013). In the course of the teaching process, the occurrence of such a maladaptive stress response limits or closes off the possibility of constructing new knowledge or skills related to the subject matter, and the circumstances that are encoded in the memory are mainly those that will allow the person to proactively avoid a repeat of the situation in the future, from the point of view of that person, as threatening (McEwen and Morrison, 2013).

It therefore seems that crossing boundaries in teaching can only be developmental if the intensity of stress is regulated, among other things, by appropriate support, clarity of purpose, permission to make mistakes, a task framework appropriate to the individual's abilities, and a sense of control over the situation. A key factor shaping the magnitude and duration of the stress response to novelty is inter-individual variability with biological and environmental causes (Varela et al., 2012).

### **Predisposition to cross boundaries**

Individual predispositions to explore, take risks and interact with novelty depend on both genetic factors and previous experiences.

The diverse tendency to prefer and seek novelty and the different sensitivity to potential and actual rewards associated with the experience of novelty are significantly influenced by polymorphisms of genes related to the functioning of dopamine systems (Gjedde et al., 2010). In turn, biologically determined differences in the reactivity of the amygdala and the functioning of various modulatory systems regulating emotional and stress responses are associated with a tendency to produce anxiety in response to novelty and a tendency to form anxiety responses, leading to avoidance of novelty and intolerance of uncertainty, and to adopting a defensive attitude in the face of new situations (Hur et al., 2020). Both tendencies remain under the strong control of various cortical areas, including the prefrontal cortex. Biological differences in the architecture of networks within different areas of the cortex, the pathways connecting them, as well as those connecting the prefrontal cortex with the emotional system, may account for shifts in the balance between drive-emotional and cognitive systems in shaping responses to novelty and prediction errors (Watabe-Uchida et al., 2017).

The predisposition to cross boundaries is also influenced by environmental factors, including the nature of previous educational situations, experiences of failure or success, and emotions accompanying the teaching process, which shape, among other things, the direction and strength of the emotional and stress response to prediction error. All this can be verified by the associations that the brain makes with education, the subject, and the teacher. These associations are triggered automatically upon recognition of the context and lead to the arousal of specific emotions and habitual

responses, which in turn shape the attitudes and behaviours of the participant in the teaching process. These associations shape the responses of brain structures such as the amygdala and striatum, which give the situation a specific rank and character, and also promote a specific attitude towards novelty.

As with many other traits, the predisposition to cross boundaries in an educational context depends on the interaction between biological and environmental factors. The individual combination of biological traits and experiences consolidated in the form of associations and response patterns co-determine the consequences of crossing boundaries in specific situations.

### **Positive and negative consequences of crossing boundaries**

The experience of crossing boundaries in teaching can relatively easily cause widespread and lasting changes in brain function due to the intensification of neuroplastic processes. However, the nature of these changes depends on the intensity of novelty, natural predispositions and the effects of the decision made by the brain.

Under optimal conditions, novelty can lead both to the construction of new knowledge and skills and, especially in the case of repeated positive experiences, to increased tolerance for uncertainty, increased cognitive flexibility and creativity, and an internal sense of control. Positive experiences can also lead to the creation of associations between the educational context and reward, which can result in a lasting increase in motivation to learn and curiosity about the world (Sinclair and Barense, 2019).

Conversely, in adverse conditions, a response to novelty based on fear and severe stress can lead to negative changes that adversely affect future responses. The severe stress accompanying the response to novelty can impair cognitive functions and thus reduce the likelihood of achieving the desired goal. A negative prediction error occurring in the event of failure may encode the actions taken as leading to loss and thus increase the likelihood of triggering an escape or avoidance response in the future when actively facing the challenge of novelty. The avoidance or escape response may be further reinforced if it leads to the avoidance of loss, even if the risk was objectively small. The occurrence of chronic stress can promote plastic changes within the limbic system and, at the same time, lead to the atrophy of cortical neurons' dendrites, which can perpetuate anxiety reactions and anxiety-based habits while simultaneously impairing cognitive functions, making it difficult to respond adaptively to novelty in the future (Shansky et al., 2009). In such conditions, crossing boundaries becomes a source of cognitive blocks, decreased motivation, and even negative associations with the learning process itself.

The intensity and nature of the response to novelty depends on the scale of novelty, but it is extremely difficult to determine how great the novelty value of a given teaching situation can and should be in order for the response to be optimal. Moreover, the degree of novelty at which this novelty triggers optimal responses varies greatly from person to person, depending on characteristics that determine the propensity to seek novelty, anxiety, the strength of the stress response, and the efficiency of cognitive mechanisms. Although the nature of the response greatly influences the likelihood of success or failure in an attempt undertaken in the face of novelty, the level of difficulty of the task is largely an independent parameter that co-determines the nature of the prediction error,

success or failure and, consequently, the strategy that the brain will adopt and may consolidate in response to novelty in an educational context.

In summary, a neurobiological perspective on boundary crossing in teaching seems helpful in understanding why some educational situations promote development, while others lead to withdrawal and resistance. Boundaries are experiences that generate prediction errors, which trigger complex interactions between the systems responsible for emotions and stress, reward, and cognitive control. Their effect depends both on the individual's predisposition and on the conditions in which the novel experience occurs. Appropriately designed teaching situations that combine novelty with familiar patterns and established knowledge, as well as a sense of security and openness of all participants to errors leading to development, activate neuroplastic processes that lead to the reorganisation of neural networks and condition the construction of new knowledge and skills (van Kesteren et al., 2012). Thanks to this, teaching can use boundaries not as a barrier, but as a tool for consciously shaping competences, curiosity, continuous development and building adaptive strategies for coping with novelty and unpredictability.

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