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Neuroplasticity and the zone of proximal development: A neurobiological reflection on a key psychological construct

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Executive summary

- Two well-established approaches that have significantly influenced the study of the development of the human mind are presented.
- Vygotsky's cultural-historical approach addresses the impact of culture in the shaping of mind and behaviour. Key to this approach is the concept of the *zone of proximal development* (ZPD): the distance between the actual development level, as determined by independent problem-solving and the level of potential development, as determined through problem-solving under adult guidance or in collaboration with more capable peers.
- The neuroscientific approach undertakes the experimental study of the brain and addresses how the brain supports mental activities and representations. Key to this approach is the concept of neuroplasticity: the biological set of mechanisms that allows the brain to receive, encode, store, and retrieve information and enables developing and adult brains to undergo structural and functional modifications and react and adapt at different coexisting levels—from molecules to neurons, circuits, networks, persons, and societies.
- To combine or integrate these approaches remains a challenge. However, they seem compatible and continuous, as the concept of neuroplasticity appears an acceptable neurobiological mechanism to explain the ZPD, at the core of socially mediated learning processes.
- Understanding the interplay between social interaction and neuroplasticity is relevant to the design of ways to structure and support learning and academic achievement in educational settings.

Introduction

Two scientific approaches have significantly influenced the study of the development of the human mind. One, from psychology, points to the importance of culture in shaping mind and behaviour. This "apprenticeship model" is fundamentally associated with Lev S. Vygotsky. In the Vygotskian view, socialization by parents, peers, and general society strongly influences children's thinking and behaviour[1].

On the other hand, the neuroscientific approach involves the experimental study of the brain and addresses how the brain supports mental activities and representations. The major idea of this approach, heavily dependent on the work of Donald O. Hebb, is that brains consist of cells and that, in the course of development, assemblies of cells (brain networks) are formed with repeated stimulation[1]. This approach prompted studies of the concept of neuroplasticity: the biological set of mechanisms, and its developmental expression, that allows the brains to receive, encode, store, and retrieve information and enables developing and adult brains to undergo structural and functional modifications and react and adapt at different coexisting levels—from molecules to neurons, circuits, networks, persons, and societies[2].

Both approaches recognize that nature and nurture interact at all levels, and hence that development is simultaneously both biological and social in its nature. However, these two approaches are so academically insulated from one another that to combine or integrate the two remains a challenge[1]. Nevertheless, they have been proposed to represent rather complementary biological and cultural lines of explanation of development that, when reconciled, would significantly add to the development of the science of learning. Moreover, here, we present a neurobiological view on the notion of zone of proximal development (ZPD), defined by the cultural-historical approach, in order to bridge this gap by revealing that the mechanisms of neuroplasticity lie at the core of the limitless nature of development as defined by the cultural-historical approach to learning.

Learning and development according to Vygotsky

According to Vygotsky, at the time when he started his career in psychology, the discipline was going through a crisis because it was torn into two irreconcilable halves: a "natural science" branch able to satisfactorily explain elementary sensory and reflex processes, and a "mental science" branch that fundamentally addressed higher psychological processes and their emergent properties[3].

In contrast, Vygotsky argued for the development of a comprehensive approach allowing both the description and explanation of higher psychological functions in terms acceptable to natural science[3]. In this approach, explanation included the specification of the brain mechanisms underlying a particular function; which in turn required a detailed explication of the developmental history of the function to be described in order to establish the relation between simple and complex forms of what was considered to be the same behaviour. Additionally, it also required the specification of the "societal context in which the behaviour developed" or, in other words, the understanding of complex mental functions required for developmental analysis.

Consequently, Vygotsky acknowledged two forms of behavior: elementary or natural, which emerges from a direct relation to the environment, and mediated or cultural, which involves an additional psychological link between stimulus and response, and originates when people create new, indirect relationships to the external world by using tools and interacting in society.

The approach developed by Vygotsky is called the cultural-historical approach. He is best known for the "general genetic law of cultural development"[4], which conveys the spirit of his comprehension of the cultural determination of the mind: "Every function in the child's cultural development appears twice: first, on the social level, and later, on the individual level; first, between people (interpsychological), and then inside the child (intrapsychological)"[3, p.57]. Hence, according to Vygotsky, "All the higher functions originate as actual relations between human individuals"[3, p.57].

This view presented mental processes, generally conceived as fixed and immutable, as complex and mobile functional systems that change during development and learning[1] through "mediation." *Mediation*, another valuable concept introduced by Vygotsky, refers to the processes intervening between the stimuli received by the individuals and the responses elicited by them. He specified the role of both physical tools and psychological tools as mediational devices. Both types of mediational resources are social in nature; however, material tools are aimed at the control of processes in nature (for instance, a hammer or a computer), whereas psychological tools are used to master the natural forms of individual behaviour and cognition (for instance, language or executive functions).

Regarding psychological tools, Vygotsky focused particularly on language[4] since he considered it allowed humans not only to communicate but provided a powerful tool to regulate their own mental processes[1]. According to Vygotsky, psychological tools have a fundamentally semantic nature and higher psychological functions rely on the mediation of natural forms of cognition and behaviour by socially created systems of signs and symbols, the most important of which is speech[1]. Signs are, for Vygotsky, special types of stimuli that become psychological tools by contributing additional relevant information about the environment to the human processing system (the brain/the cognitive system)—in addition to the physical/sensory information already received. Vygotskian developmental psychology fundamentally focuses on the explanation and formulation of this relationship, in which the elementary forms of behaviour come to support the development of higher mental functions through mediation[1]. Hence, according to Vygotsky, since speech and sign systems in general originate in a social context and conform to social rules and determinants, the development of higher mental activities is social in nature.

In sum, Vygotsky's cultural-historical theory of mind addresses the processes through which learning and development take place. Cognitive development is conceived as the result of interactions within a cultural and historical context, and not as the unfolding of functions following a biologically driven sequence. In this approach, learning is seen as leading, or fostering, cognitive development. Development cannot be alienated from its social and cultural context and social interaction with cultural artifacts contributes the most to the learner's psychological development. Another Vygotskian seminal notion, the *zone of proximal development*, was specially developed to account for the learning potential of children.

The zone of proximal development

This concept constitutes one of the fundamental notions of the cultural-historical approach. Vygotsky defined the ZPD as "the distance between the actual development level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peers"[3, p.86]. That is, the ZPD was used by Vygotsky to extend the description of the current or actual level of development of the learner by defining the next developmental level attainable, under the influence of mediating semantic and environmental tools, in the context of interaction with a capable adult or peer facilitation.

In general, the take-home message universally extracted from this concept by educators and teachers is the idea that individuals learn best when working with others and that, through collaborative interactions with more skilled persons, learners acquire and internalize new concepts, psychological tools, and skills[4].

However, a more theoretical analysis of the concept shows, in Vygotsky's own words, that "the zone of proximal development defines those functions that have not yet matured but are in the process of maturation, functions that will mature tomorrow but are currently in an embryonic state. These functions could be termed the 'buds' or 'flowers' of development rather than the 'fruits' of development. The actual developmental level characterizes mental development retrospectively, while the zone of proximal development characterizes mental development prospectively"[3, p.86-87].

According to Vygotsky, by focusing on the ZPD, it is possible to account for "not only the cycles and maturation processes that have already been completed but also those processes that are currently in a state of formation, that are just beginning to mature and develop. Thus, the zone of proximal development permits us to delineate the child's immediate future and his dynamic developmental state, allowing not only for what already has been achieved developmentally but also for what is in the course of maturing"[3, p.87].

Hence, from a pedagogical standpoint, it has been suggested that, according to Vygotsky, the main goal of education is to keep learners in their own ZPDs as often as possible by presenting them with interesting and culturally meaningful learning and problem-solving assignments slightly more difficult than what they are capable of doing on their own, such that they will need to work with a more competent peer, a teacher, or an adult to successfully complete the task. Through that process, the learner's ZPD for that particular task will become the new actual developmental level, and new potential development levels will unfold. Then, this process should be systematically repeated at the higher level of task difficulty that the learner's new ZPD requires, providing a foundation for the continuous and limitless nature of learning and development. Therefore, this concept acknowledges the existence of processes and mechanisms underlying change and maturation of cognitive processes: allowing the zone of proximal development of today to become the actual developmental level of tomorrow. In neuroscientific terms, the ZPD concept refers to the (neuro)plasticity of the human (neuro)cognitive system.

Neuroplasticity: The neurobiological mechanism underlying the ZPD?

Neuroplasticity is one of the most powerful concepts for neuroscience and developmental psychology. It refers to a characteristic property of the brain: its high susceptibility to environmental influence. It allows the brain to undergo temporary or permanent changes underlying learning (understood as the process of acquiring and encoding relevant information from the environment) and memory (including the previously mentioned learning stages and the process of storing and retrieving information that will eventually be used to orient behaviour)[2].

Neuroplasticity is defined as the biological set of mechanisms that allows the brain to receive, encode, store, and retrieve information and enables developing and adult brains to undergo structural and functional modifications in order to react and adapt at different coexisting levels—from molecules to neurons, circuits, networks, persons, and societies[2].

Structural neuroplasticity refers to the modification of the structure of brain cells, including sprouting of axons (wire-like parts of neurons connecting the body of the cell with its junctions to neighbouring neurons), the expression of proteins that act as channels for electric currents, governing the communications between neurons in the junctions between them (synapses), or even the presence of new neurons, called neurogenesis, to cite some examples at the "molecules to neurons" level of analysis. Also, modifications in the volume, longitude, thickness, surface area, or integrity of brain tissues/areas, are examples of structural neuroplasticity at the level of circuits and brain networks. Functional neuroplasticity, in contrast, refers to changes in the electrical and biochemical responsiveness of the brain to stimuli received from the internal organs (including the brain itself) and the environment.

Neuroplasticity allows individual neurons to learn. How is this possible? During the communication between neurons, electrochemical impulses travel from one neuron to the next through the synapses. Concurrently, slower biochemical signals are sent to the nucleus of the cells and activate genetic mechanisms influencing the synthesis of proteins that stabilize and strengthen the communication between neurons, modulating the corresponding synaptic transmission[5]. Two fundamental mechanisms of this kind of (synaptic) neuroplasticity have been described: long-term potentiation (LTP) and long-term depression (LTD)[2]. LTP is a form of plasticity dependent on the repetitive activity of neurons that results in a persistent enhancement of the transmission of signals between them[6]. LTP is long-lasting and input-specific, hence it can occur in a set of synapses in a single neuron without affecting other synapses of the same neural cell. In contrast, LTD causes the efficacy of synaptic transmission to be reduced. Both processes are thought to contribute to the processing and storage of information in the brain. Although the electrophysiological changes that occur in the synapse itself dissipate in relatively short time, the genetic machinery activated simultaneously in the nucleus of the cell generates genetic messengers and proteins that are sent back to the originally activated synapse. These proteins increase the bond between the neurons that were tagged by the previous information transmission and this, in turn, increases the number of synapses between these cells and, hence, establishes the original information in the brain[2]. This way, relatively transitory electrochemical phenomena become stable memory traces, available for future retrieval.

Additionally, a high number of individual neurons are connected forming circuits, and these circuits connect to other neurons and the allegedly "support" cells in the brain (glial cells). These complex circuits and the resulting activity patterns become the basic repository of "memory traces" in the brain (called engrams). Groups of cells and entire columns of the brain cortex have been shown to perform similar computations during development[2].

Also, studies in animals and humans have described the differentiation and proliferation of new neurons from neighbouring stem cells in the hippocampus, a brain structure implicated in memory processes, demonstrating a structural neuroplasticity phenomenon called neurogenesis, both during development and in adults. Additionally, learning itself seems to boost neurogenesis, creating a self-reinforcing (virtuous) cycle for the phenomenon and providing an explanation for learning at the cellular level[2].

Yet, how do these neurobiological mechanisms relate with the ZPD concept? The mechanisms described here may seem hard to relate with the explanation of complex behaviours. However, it has been proposed that learning during communication or educational activities operates precisely through neuroplasticity[2]. In fact, several brain networks have been described to specialize for culturally complex tasks, including reading, writing, and arithmetic. The previously mentioned brain networks are considered to specialize during postnatal development, since they cannot be explained by evolutionary mechanisms, because these tasks are very recent cultural acquisitions for humans[2].

One might think then, that by means of plasticity the human brain would be capable of representing any form of culture. Should this be the case, a significant variability in the brain architecture supporting cognition should be expected. In contrast, highly reproducible brain networks have been reported to support cognitive processes across cultures. Hence, some researchers have pointed out that the representation of novel cultural products such as writing and arithmetic is harnessed by the brain's prior evolution and organization. They have put forward the "*neuronal recycling hypothesis*" (NRH), to account for how new cultural objects are represented in the brain[7]. This theory poses that new knowledge will be mapped onto brain structures that are highly reproducible across cultures to produce so-called "cultural maps." The biological reproducibility of these cultural maps is accounted for by the fact that they result from "minimal transformation of cortical precursor maps present in other nonhuman primates" and early on in infancy[7]. A set of circuits sufficiently plastic and close to the novel cultural acquisitions (e.g., reading or arithmetic) would reorient a significant part of the available neural resources to its novel use, making learning possible.

This idea bears a close resemblance to that of Vygotsky on how mediation of elementary forms of behaviour come to support the development of higher mental functions. Note also that, following this logic, it is by social interaction that the previously mentioned circuits would be targeted to invest neuroplasticity and remap their prior computations to represent relevant novel cultural objects.

The NRH also predicts the speed and ease of cultural acquisition in children should depend upon the complexity of the cortical remapping required[7]. Researchers suggest "the systematic difficulty that children exhibit in discriminating mirror-image letters such as p and q may ultimately be traced back to the native propensity of our visual object recognition system for mirror-image generalization, due to its evolution in a world where the left-right distinction is largely irrelevant"[7, p. 385]. This, again, highlights both the existence of basic behaviours/neural resources to build upon and the influence of cultural mediational tools of different complexity levels, in terms of the computational complexity of the cultural system to be represented (e.g., a specific arithmetic procedure). Nevertheless, according to the NRH, cortical constraints should ultimately explain the difficulty in acquiring cultural tools. Although this might seem not entirely in line with the Vygotskian view, it could actually refer to the material foundation and neural machinery that supports the development of higher mental functions.

Examples from reading and numerical processing

Research shows that reading repurposes brain networks implicated in object recognition and spoken language[7]. In illiterate subjects, it has been reported that face recognition tasks activate some areas of this network[8]which means plasticity is determinant in this case since the same cortical regions can be recruited both by face recognition or by grapheme recognition tasks when learning to read. Additionally, a longitudinal study conducted in 5-year-old prereaders has shown that it is possible to predict the location of the *word form area* at age 8, from the way the brain areas were anatomically connected with other areas in the brain, before learning to read[9]. The word form area is a brain region that responds preferentially to visually presented letter strings or words compared to similar stimuli, including digit strings, faces, or words written in unfamiliar orthography[9] systematically reported in readers across cultures. The researchers suggest this may reflect a general mechanism in cortical development: early connectivity instructs the functional development of specific brain areas.

Similarly, in the case of numerical processing, experiments in adults have shown the expression of neuroplasticity within hours when training adults with new arithmetical operations. This is seen in the modification of the brain areas recruited when solving exercises learned by training vs. untrained exercises[10]. Also, in children with moderate-to-severe learning disabilities who underwent one-in-one cognitive tutoring during eight weeks, the manifestation of neuroplasticity has been reported in the normalization of performance at both the behavioural and the neural level, as reflected by the absence of aberrant functional responses in brain networks showing significant differences when compared to control children, prior to the intervention[11].

Implications for education

It is advisable to disseminate to educators and policy makers the neural network approach alongside the perspective of early learning as an apprentice to culture provided by Vygotsky. Understanding the specific but connected levels of interactions between the brain and social environment and its impact in the quality of the resulting learning processes should better prepare educators to design students' learning experience towards reaching the self-actualizing potential level of the ZPD. Also, it would allow decision makers to search for and identify relevant theoretical principles and scientific knowledge in the rationale of educational processes and methodologies and, when successful, to scale them.

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