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The principles of plasticity in Lurian neuropsychology

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Abstract

This paper demonstrates the ways in which the problem of plasticity was formulated in Luria's theory of the systemic dynamic localization of higher mental functions. Luria's neuropsychological theory is based on the principle of the cultural and historical conditionality of mental functions and the principle of the systemic functional organization of mental functions in the brain. As early as the mid-20th century, this theory set up a series of regularities that govern plasticity. In the neuropsychological context, one needs to consider plasticity from two interconnected perspectives. The first perspective builds on the plasticity of the brain and its capacity for reorganization (i.e., structural changes). The second perspective builds on the plasticity of cognitive processes (i.e., changes in the structure of mental functions). Notably, this interconnectedness appears during ontogenesis (i.e., during the development of mental functions) or in cases of brain lesion. According to Luria's theory, the development of mental functions occurs during postnatal ontogenesis, and the particularities of structures associated with these functions are influenced by cultural and historical conditions. Environmental conditions define structural changes in the functioning of the brain while the brain adjusts to these conditions. In cases of brain lesions, the destruction of an established system of interrelations among different brain areas occurs. Emerging structural changes in the brain are factors that need to be considered when compensating for mental function defects. This suggests the necessity to artificially condition to the environment where compensation procedures take place (i.e., adjusting for the capacities of the brain). **Keywords**: Alexander Luria, Lurian neuropsychology, higher mental functions, cognitive functions, functional systems, inter-system and intra-system rebuilding, rehabilitation, brain plasticity, plasticity of cognitive functions.

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Definition of plasticity: neuropsychological aspects

In neurosciences, brain plasticity is understood as the ability of the brain to change or reorganize the functioning of its structures and neural mechanisms. Changes in the functioning of the brain are both related to its high susceptibility to new experiences and emerge in response to significant changes in external and internal factors (Farber & Dubrovinskaya, 2005). Neuropsychology, which studies correlations between mental processes and the functioning of various brain structures, allows analyses of brain plasticity while considering interrelations between mental and physical aspects. Mental or cognitive plasticity is related to changes in the structure and content of mental functions (i.e., mental activity). Structural and functional plasticity of the brain's functional systems is related to changes in both the specialization of brain areas and relationships between them. Modifications in the structure of higher mental functions (HMFs; also known as higher psychological functions) and functional brain systems are determined by external (environmental) and internal (biological, related to the body) conditions.

Basic principles that characterize the neuropsychological approach to the problem of plasticity were formulated in the works of Alexander R. Luria and his school. In the theory of the systemic dynamic localization of HMFs, Luria rejected the consideration of mental functions as depending on either unique brain "centers" or the homogeneous, undifferentiated working of the entire brain. The representation of a specific contribution of each part of the brain to mental functions is the fundamental aspect of his theory. This means that each mental function relies on the collaborative work of different brain areas that are united into functional brain systems (Luria, 1969, 1973, 1980).

Luria highlighted Vygotsky's focus on the dynamic change in the ratio of brain center recruitment in the process of development and disintegration, according to which Luria formulated the idea that "at different stages of development the same functions can be realized by different areas of the cerebral cortex, and at different stages of development the relationship of individual

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cortical areas may not be the same" (Luria, 1970a, p. 59); heretofore, the translations of all quotations were provided by the author of this paper). According to the principle of both the systemic nature and dynamic organization of HMFs, changes in the structure of HMFs should lead to changes in both the composition of brain centers and connections between them. Interrelations among changes in the structure of mental functions and change-over in the work of the brain are observed more prominently in ontogenesis (development) and in cases of brain damage.

Plasticity during development, in a psychological context, is defined by the gradual formation of a hierarchical structure of HMFs. In the morpho-functional context, it is defined by heterochrony of the maturation of brain zones and communication among them. The relationship between these two aspects is manifested in the form of qualitative changes in mental processes and the variability of functional brain systems (i.e., the ability of the brain to adapt to a variety of environmental conditions in which mental development is realized). In pathology, neuroplasticity implies the restoration of functions that have been lost or broken as a result of various changes in the central nervous system (CNS; Beaumont & Kenealy, 1996). The ability to compensate for functional deficits caused by damage to the CNS (i.e., restructuring HMFs and functional cerebral systems) is made possible by a large number of brain centers that are involved in the provision of certain mental functions and the variety of relations among different areas of the brain (Luria, 1969).

Mental functions and their changes can be influenced by the external environment, including cultural, historical, and language-specific features of the social environment, and define the specifics of education practices, both at home and at school. The formation and reorganization of a particular functional system are influenced by internal conditions (i.e., properties of brain centers) such as their (1) functional specialization, (2) functional ambiguity, and (3) sensitivity. The first is related to the genetically specific propensity of brain areas to receive certain types of information (Kinsbourne, 1975). The second is related to the ability of brain areas to assume, under certain conditions, other functions that are not specific to them (Filimonov, 1949). The third is related to an increase in the heterochronic sensitivity of brain areas to certain influences from the surrounding environment (Vygotsky, 1982-1984).

Plasticity in development

In regular ontogenesis, plasticity manifests itself as a change in both the structure and content of behavior during a child's socialization and any voluntary and conscious activity at different stages of life. In his article first published in 1934, Luria noted that a psychological function at different stages of development "doesn't remain equal to itself...it significantly changes its structure in carrying out the same task with completely different operations" (Luria, 2002, p. 17). This thesis, which indicates the continuous and dynamic nature of the formation of HMFs in ontogenesis, is based on a number of principles that were introduced in Soviet psychology by Vygotsky. These principles (i.e., systemic approach, social genesis, mediated structure, and voluntary regulation) are reflected in Luria's argument that HMFs are "complex self-regulated processes, social in origin, mediated in structure and conscious and voluntary in their mode of functioning" (Luria, 1969, p. 31). This definition presents HMFs' main properties that cause the plasticity of mental functioning and associated brain tissues. The social genesis of HMFs and mental activity implies the formation of mental functions in the social environment, in collaboration with adult activities, resulting in the gradual mastery of increasingly complex forms of adaptation to the environment (Vygotsky, 1982-1984).

In ontogenesis, in accordance with the law of heterochrony (Anokhin, 1980), we can observe both the uneven development of centers that belong to different brain systems and links among these centers. The hypersensitivity of certain brain centers as the main (internal) condition of morpho-functional maturation works in conjunction with environmental conditions and creates the background for changes in the structure of functional brain systems. Even in early stages, the gradual development of sensory and then associative brain fields provides a transition from temporary functional independence of individual components of the brain systems to their coordination and hierarchical interaction. Joint child-adult activities in the surrounding environment and the use of language lead to an increase in the functional specialization of brain centers. At a certain stage of development, a brain center reaches a level of maturity that is sufficient for the performance of a leading role in a functional system in the brain, which, in turn, provides some form of social behavior, cognitive skills, and abilities. This new quality of a brain center leads to a change in the hierarchy of the associated functional system that restructures the functional system and provides it with new modes of work (Bernstein, 1990; Luria, 1963; Lebedinsky, 1985; Mikadze, 2008).

For example, the development of writing skills is associated with numerous changes in the structure of writing skills. At the initial stage of mastering writing, each letter poses a challenge that is related to the process of sound analysis, the selection of phonemes from sound complexes, and the preservation of the visual and motor images of letters. As soon as one masters the skill of writing, these difficulties (i.e., reliance on acoustic and kinesthetic characteristics) are no longer present, and kinetic and visual-spatial signs gain higher importance that is related not so much to writing individual letters as to writing complexes of letters. Developed grapho-motor coordination (i.e., smooth and fluent writing) includes voluntary regulation and control, in which letter writing becomes automated. The number of afferents that are involved in the first stage is sharply reduced to principal ones. The remaining afferents move into a reserve fund and can be amended again if necessary (e.g., in the case of a forced change in the dominant writing hand). Luria noted that "the complex constellation of zones that are involved in the act of writing may vary at different stages of the development of the skill and, moreover, turns out to be different for the writing in different languages" (Luria, 1969, p. 75). Changes in the structure of writing are reflected in changes in the component structure of the functional system that is responsible for the writing function.

The quality of the mediated structure of higher mental functions is determined by the influence of the cultural and historical content of a particular social environment on the structure of HMFs and functional systems. In this case, the leading factors are (1) the surrounding material culture (environment) and (2) the language environment that surrounds a child. The leading role in the mediation of HMFs' structures belongs to speech, which influences the highest levels of HMFs' organization and coordination. Cultural differences in an environment where the child develops manifest in different compositions of brain functional systems for similar HMFs and different types of inter- and cross-system interactions. In the following example of a disorder, Luria considered the possibility of different mental organizations of speech.

Distinguishing components that are included in the psychological structure of writing, Luria wrote that we could trace how writing is disturbed by damage in different brain areas. In short, one must first select a phoneme that corresponds to an individual letter. This requires the involvement of the left temporal region of the cerebral cortex. Luria noted:

> " … damage to these brain areas inevitably leads to the inability to differentiate speech sounds and choose appropriate letters ... which causes severe writing disorders. This happens in Indo-European languages. However, for the Chinese, whose symbol-based hieroglyphic writing system depicts not the sounds of speech but concepts, temporal-auditory parts of the brain are not involved in writing" (Luria, 1969, p. 23).

For example, according to our data (Mikadze, 1999, 2003), at the age of 8, the structure of memory is changing. There is a change in the hierarchy of processes that perform a leading role in information processing while memorization occurs. Error analysis (literal and verbal paraphasias) of the memorization of a series of words demonstrated that up to 8 years of age, children make errors of acoustic and perceptual similarity with the original stimuli (literal paraphasias). After 8 years of age, the number of literal paraphasias decreases, and the number of errors of semantic similarity-verbal paraphasias increases. Perception, which initially plays the dominant role (i.e., reliance on phonological, perceptual image of words), is replaced by thinking (i.e., reliance on meanings of words as "objectively established … systems of links that stand behind the word" (Luria, 1979, p. 53). This indicates changes in the structure of the process of memorization and brain organization. The transformation of interactions among different brain areas occurs along with a transition from a leading role played by perceptual components (right-brain centers) to speech-thinking components (left-brain centers). Therefore, the change in the hierarchy of interconnections in brain areas in 8-year-old children leads to the reorganization of functional memory systems (Mikadze, 1999, 2003).

Features of the historically developed cultural environment in which the formation of the structure of mental activity is realized affect the sequence of active integration of the relevant brain zones in a functional system and determine the logic of the neuropsychological scheme of ontogenesis. Brain plasticity is manifested in the variability of its ability to adapt to the specifics of external influences. The leading and mediating role of environmental conditions (cultural and educational) in patterns of the functional specialization of different brain areas was shown in a comparative neuropsychological study of mental development between Russian and Arab children (Mikadze, 1997; Korsakova, Mikadze, & Balachova, 2003; Badarni, 2003). The study's data allowed for the analysis of the specifics of the development of different parts of the brain and mental development and an analysis of the logic of a "neuropsychological scheme" of ontogenesis in different sociocultural contexts. A comparative qualitative analysis of the efficiency of task execution by younger school children, 6 to 10 years of age (for each year of age), was performed.

Errors that were seen in this neuropsychological examination were described as "symptoms" that characterized the condition of various links of mental functions and related brain areas. Positive changes (i.e., a reduction of the number of errors) that were associated with these elements of mental functions were evaluated. Errors that were seen in the assessment were associated with the functioning of anterior and posterior regions of the left and right hemispheres. At the same time, the dynamics of error reduction in the transition from one age to another were different for each cerebral region. The maximum speed of the reduction of the number of errors was observed for errors that were associated with the functioning of posterior parts of the left hemisphere and then the functioning of anterior parts of the left hemisphere, followed by posterior and anterior parts of the right hemisphere. These results can be considered an indirect indicator of the fact that the aforementioned areas of the brain undergo maximum maturation in Russian children in the 6-10 year age range. The order in which they are located indicates which of them develop most intensively (Mikadze, 1997; Korsakova, Mikadze, & Balachova, 2003).

A similar study was performed with younger Arab students (7-9 years of age; Badarni, 2003). The dynamics of the reduction of the number of errors from one age to another in Arab children was different from Russian children. The maximum reduction of the number of errors was observed for errors that were associated with the work of the posterior left regions of the brain, followed by the anterior right, anterior left, and posterior right regions of the brain. This means that at 7-9 years of age, the maximum speed of maturation in Arab children is found in other brain areas.

Overall, these results demonstrate the role of cultural conditions in determining the type of environmental impacts on the maturation of specific (corresponding) brain areas. For example, when entering school, Russian and Arab children begin to learn writing and reading. Russian children generate cognitive strategies associated with left-to-right vector scanning and the processing of information. Arab children, who learn the Arabic language, exhibit the converse, with a right-to-left vector. Such strategies begin to develop at school age. This was confirmed in another experiment with Russian and Arab children (Chursina & Badarni, 2002). Children aged 3, 5, and 8 years were given a card with a picture of five different animals and were asked to show and name what they saw. Russian and Arab children of 3 and 5 years of age named the pictures from left to right in 50% of the cases and from right to left in 50% of the cases. All of the 8-year-olds named pictures in only one direction: Russian (from left to right) and Arab (from right to left; Chursina et al., 2002). Therefore, in preschool years, there is no difference in the perception of visual stimuli. Yet, the development of a child in one of the two different culture-specific training programs leads to a change in cognitive strategies.

During further development, the cognitive strategy of visual scanning in Russian children does not change. Arab children, beginning at 8 years of age, start learning foreign languages, which requires a change in the strategy of visual scanning from right-to-left to left-to-right. A resulting perceptual conflict requires greater activation of perceptual processes associated with the right hemisphere. This is probably among the factors that lead to more active maturation of these processes, reflected by the specifics of "neuropsychological schemes" associated with greater active maturation of certain areas of the brain (Badarni, 2003; Mikadze, 2008).

The conscious and voluntary characteristic means the possibility of both planning mental activities and controlling their implementation. In this case, the behavior of an individual acquires purpose in which the activities that are performed correspond to the needs and circumstances of the material and social reality that surrounds an individual (Gordeeva & Zinchenko, 1982). In this case, in response to changing internal and external conditions, it becomes possible to consciously and voluntarily modify mental activity and the central regulation of brain activity. Luria noted that this condition provides structures that are "directly related to the retention of stable motives" (Luria, 1948, p. 74). Therefore, motivation for encouraging the voluntary and conscious management of one's own behavior is one more condition that determines changes in the structure of mental activity and functional brain systems in ontogenesis. The parameter of voluntary regulation is associated with functional specialization in the frontal parts of the brain and their interactions with other brain areas.

Consequently, many conditions must be taken into account in the assessment of the plasticity of neuropsychological development. Conditions of mental or cognitive plasticity are formed by the social environment, interactions with a native representative of a culture (mediated structure), or the activity (i.e., consciousness and voluntary control) of an individual him- or herself. Conditions of structural and functional plasticity of the brain (i.e., the plasticity of brain areas and the links between them) are formed by heterochrony in the development and sensitivity of brain structures, the availability of social influences that are adequate for this sensitivity, and shifts in the hierarchy of these influences. Overall, patterns of reorganization of the brain and psychological structure of HMFs in ontogenesis can be useful for understanding their recovery in cases of brain lesions. Therefore, these patterns need to be considered in the assessment of neuropsychological development plasticity.

Plasticity in brain damage

In the monograph *Restoring Function after Military Trauma*, Luria (1948) writes about two components that characterize traumatic disorders of the brain. The major one is associated with destruction of the medulla and is irreversible. The second one is related to dynamic changes in the preserved areas of the brain caused by injury that may be reversible. Luria noted, "Along with persistent and irreversible disintegration of functions the inhibition of functions as a result of temporary brain dysfunction caused by injury should be distinguished" (Luria, 1948, p. 12).

The spontaneous recovery of temporarily inhibited functions leads to recovery of the function in its original form. In contrast, the recovery of a function after destruction of brain areas is not a simple process of involution. It is instead associated with "specific restructuring of options that results in the fact that the initial function is radically changing its psycho-physiological structure and is being performed by the new, i.e., intact brain systems" (Luria, 1948, p. 35). Luria argued that the restructuring of functional systems in patients with brain pathology requires that the patient's own activity and connections between brain centers are preserved. The compensation of mental functions is possible in the case of brain damage that "both does not affect the apparatuses of the brain that are directly related to the preservation of stable motives and does not lead to the fact that the emergence of new functional relationships between different regions of the brain becomes anatomically impossible" (Luria, 1948,

p. 74). Luria believed that the solution to the task of "directional development and active restructuring of the functions of the cerebral cortex" (Luria, 1948, p. 35) will both reveal the nature of the functional "plasticity" of the brain cortex and provide tools to restore brain function.

Luria considered three main forms of possible brain readjustment. The first form is associated with partial damage at the elementary level (primary fields); in this case, fast spontaneous (automatic) restructuring is possible. The second form—"intra-system semantic (psychological) rebuildings" (Luria, 1948, p.65)"—is required in cases of disintegration of the functional system (when dysfunction in the work of specific components leads to a pathological mode of functioning of the entire system) that occurs because of the loss of components that are associated with the secondary areas of the brain that are formed during the learning process. In this case, restructuring can occur through components that are included in the same functional system by giving them new meanings. Luria suggested that human speech both facilitates this transfer and allows a new form of plasticity of functional systems, which has great potential. This implies a transfer of the function to a higher organizational level. In this case, when a certain element of a functional system is disturbed, restructuring can occur quickly and relatively easily at the expense of mutual afferentational shifts within a single functional system. Each functional system has many afferents, a small number of which retain a leading capacity over the course of ontogeny, while the others become a "reserve fund" (Luria, 1948, p. 58; see also Anokhin, 1980). Therefore, the introduction of a new functional system in the afferent field is a necessary condition for recruiting a new organ into action. Thus, compensation for a defective function can occur either through changing a system or changing a level within a system. Such cases can be considered when the broken link is on the periphery of a functional system, whereas central components secure and perform the key role in the rebuilding process.

The third form—cross-system rebuilding—is needed during the deterioration of the functional system (when complete deterioration of specific components of a functional system occurs) and requires the involvement of links that were not previously used in this system that begins to assume a new role. For example, if primary visual fields are affected (e.g., blindness), using tactile sensations is necessary. When secondary fields are affected (e.g., kinesthetic synthesis disturbances), a transition to visual control becomes essential. This rebuilding requires special training (Luria, 1947, 1948).

Therefore, the restoration of higher mental functions may be associated with two main ways of restructuring their brain basis. The first is the passing of functions of the affected area to related brain areas, the functions of which are based on a similar neurophysiological principle but focus on different kinds of information processing. The prognosis of compensation in this case will be favorable if in cases of damage of the most important brain center in a given area, related brain areas can be activated by the same type of stimuli and remain intact.

The possibility of transferring a function to related fields is demonstrated in the case of blindness. The functional restructuring of neurons in the visual cortex takes place, and neurons are involved in the functioning of the neighboring auditory cortex. For example, data show that for people who were born blind, the visual cortex can participate in the processes associated with speech function. The visual cortex can change its functions (in relation to processing visual information) to participate in speech. The left visual cortex was shown to more actively participate in the speech of blind individuals (Bedny, Pascual-Leone, Dodell-Feder, Fedorenko, & Saxe, 2011). Data also show that blind individuals rapidly develop cross-modal plasticity. The occipital cortex, combined with the posterior parietal region, is a part of the functional neural network for tactile discrimination. Experiments with electrical stimulation of the tongue have shown that it may act as a portal for the transfer of somatosensory information to the visual cortex (Ptito, Moesgaard, Gjedde, & Kupers, 2005).

One can find theoretical explorations of the possibility of restructuring individual components of functional brain systems in the works of Edelmen and Mayntkasl (1981) on the modular organization of cortex, Zavarzin (1941) on clusters of similar structural organization of neurons (nuclear facilities), and Filimonov (1949) on the concept of the functional multivalence of brain structures. These findings were further developed in the works of Shklovsky and Wisel (1997), Wisel (2002), and Vinarskaya (1971), which showed individual variability of neuropsychological syndromes of speech disturbances, and the work of Goldberg (2001), who considered the principle of graduality in brain functioning.

The second way is to transfer the functions of the damaged area to symmetrical parts of the opposite brain hemisphere. For example, the interhemispheric disconnection of motor and sensory components of speech (located in different hemispheres) was described in patients with long-term localized epilepsy (Kurthen, Helmstaedter, Linke, Solymosi, Elger, & Shramm, 1992; Helmstaedter, Kurthen, Linke, & Elger, 1997; Hamberger & Cole, 2011). The prognosis for compensation in this case will be favorable if the affected brain center is not the one that acquired the main functional role in a particular system. Such restructuring, with a change in the leading element of a functional system, may occur up to age 7-10 years.

The transfer of a leading element of a functional system to another less specialized area not only reduces the functionality of the affected system but consequently reorganizes the functions of other brain areas. This is manifested in the phenomenon of "stealing," in which other systems cannot fully rely on the brain area that becomes "appropriated" as a result of the restructuring. Symptoms that are related to unaffected brain areas and distant from the affected area were described by Konovalov (1960) as frontal cortex dysfunction that results from damage of posterior areas of the brain and by Mikadze and Chursina (1996) as a reduction of visual-perceptual functions in children with speech disorders.

The plasticity of the brain and HMFs that determine the dynamic localization of HMFs at different stages of ontogenesis and the possibility of their recovery can be associated with two main determinants: internal and external. The redirection of functions of a damaged area to other intact brain areas is based on self-regulation. The internal resources of functional systems are actualized in the form of large variability of the components that are dynamically linked to each other. This redirection is possible when the brain areas that are adjacent to the damaged area restore their functional activity or when the stored afferents that were utilized during the initial stages of habit training are actualized again. For example, one can speak of the inclusion of pronunciation in reading activities that typically occurs in the formation of various types of actions in the child. This type of restoration is realized by internal neurophysiologic plasticity mechanisms.

The restoration of HMFs may undergo training that presumes purposeful and externally initiated reorganization of the structure of a functional system. This kind of reorganization is contingent on the inclusion of new elements of a functional system, namely, those that were not part of the affected functional system. For example, the proprioceptive link (body scheme) and kinetic link (spatially oriented locomotion) are engaged in the functional speech system to restore the understanding of logical-grammatical constructions.

In understanding restoration processes in HMFs, one can speak of yet another form of correspondence between mental and brain plasticity. If over the course of its development the brain adapts to environmental impacts, then in the case of deterioration, one needs to consider the ways in which influences from the environment can be taken into account with regard to the limited capacities of the brain as well. Rehabilitation education techniques (i.e., interactions between a specialist and a patient) in this case become "different in relation both to different localization of a lesion and in different forms of mental functioning deficiencies" (Luria & Tsvetkova, 1966, p. 7). This type of recovery largely depends on the conscious activity of an individual that continues through the orientation of an individual toward the reconstruction of cerebral bases of mental activity by changing its nature (Vygotsky, 1982-1984).

Conclusion

This article examined the neuropsychological approach to plasticity based on the principles of the theory of the systemic dynamic localization of mental functions that was introduced by Alexander R. Luria. Formulated in the mid-20th century, these ideas served as a theoretical and methodological basis for the formation of Russian neuropsychology. They have also been successfully implemented in diagnosis and rehabilitation practices related to HMFs in humans.

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