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A.M. Khafizova, T.K. Davydova

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THE NEUROPROTECTIVE POTENTIAL OF BILINGUALISM IN THE PREVENTION OF COGNITIVE IMPAIRMENT

This literature review analyses current scientific research that focuses on the impact of bilingualism and multilingualism on human cognitive functions. The focus is on the impact of two or more language experiences on executive functions such as inhibitory control, cognitive flexibility and working memory. The article examines the concept of «bilingual advantage» and the factors that modulate its manifestation, as well as the role of bilingualism in the formation of cognitive reserve.

Keywords: bilingualism, multilingualism, cognitive functions, neuroplasticity, cognitive reserve, neuropsychology.

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The phenomenon of bilingualism has stimulated scientific interest in studying how the experience of managing multiple language systems affects cognitive processes and brain structure.

In the context of globalization and growing cross-cultural communication, the phenomenon of bilingualism and multilingualism is attracting increasing attention from researchers in psychology, neuropsychology and neurology.

A central focus in research on the cognitive effects of bilingualism is the study

of its influence on executive functions – a set of higher-order cognitive processes responsible for planning, attention control, ignoring distractions, and multitasking.

The key components of executive functions are inhibitory control, cognitive flexibility, and working memory. The "bilingual advantage" hypothesis suggests that the constant need for bilinguals to control and manage two simultaneously activated language systems, by inhibiting the irrelevant language, acts as continuous training for executive functions [32].

Numerous studies confirm the existence of this advantage. For example, the work of A.N. Veraksa and co-authors (2020) demonstrated that bilingual children exhibit higher performance in tasks requiring attentional switching and the suppression of impulsive responses compared to their monolingual peers [18].

The constant practice of switching between languages seems to develop a general ability for cognitive flexibility, that is the ability to switch between different tasks or mental settings.

Studies using non-verbal tests, such as the Stroop task or the task-switching paradigm, often show that bilinguals perform better on them, with faster reaction times and fewer errors [16]. All of the above is related to the fact that the mechanism used to inhibit one language and activate another is domain-general and extends its influence to other cognitive tasks requiring control.

However, simply being bilingual or multilingual is not enough to protect against cognitive decline. It is important to note that only certain types of so-called "active" bilingualism have the greatest impact on brain health, namely those where individuals are sufficiently exposed to their languages, use them regularly, and are actively engaged in situations that require switching between languages [14].

Bilinguals constantly face an additional cognitive load: unlike monolinguals, they have to control their languages. Research shows that all languages of bilinguals/multilinguals are constantly activated, regardless of contextual necessity or conscious intention. Lan-

KHAFIZOVA Anastasiya Marselievna – associate researcher at the laboratory of neurodegenerative diseases, Epidemiology of Chronic Non-Communicable Diseases Department, Yakut Scientific Centre of Complex Medical Problems, Yakutsk, ahafizovado2010@gmail.com, ORCID 0000-0003-1719-8271;
DAVYDOVA Tatyana Kimovna – PhD in Medical Sciences, leading researcher, head of laboratory of neurodegenerative diseases, head of the Center of neurodegenerative diseases clinic, Yakut Scientific Centre of Complex Medical Problems, tanya.davydova.56@inbox.ru, ORCID 0000-0001-9525-1512.

languages need to be managed to switch the choice to the one that matches the given communicative context [15], thereby avoiding unwanted interference from a contextually irrelevant language. For bilinguals, the necessity of switching between languages in the real world is dynamic, complex, and not always predictable. One might use language X or switch between languages X and Y (because the interlocutor's context allows and requires it) when someone exclusively associated with language Y enters the room or calls. However unexpected this may be, an instantaneous switch to (another) monolingual mode is required. It is argued that this constant suppression of contextually irrelevant language through substantial and continuous engagement of executive control processes "trains" the relevant cognitive skills and brain networks, making them more efficient. Indeed, this "training" has been shown to alter general processes and the underlying neural architecture directly and fundamentally [10].

However, it is worth noting that the hypothesis of the "bilingual advantage" is not universally accepted and has been subjected to active criticism in recent years. A number of studies have failed to replicate previously obtained results or have shown that the advantage only manifests under strictly defined conditions and depends on a multitude of factors, such as the age of second language acquisition, proficiency level, and sociolinguistic context [17].

Reas E.'s research revealed the "dose effect": each additional decade of active second language use reduces the risk of cognitive impairment by 20%, and proficiency in 3+ languages quadruples the likelihood of maintaining cognitive health in old age [26]. The key is not formal knowledge, but regular communicative use of languages throughout life [14].

Unlike formal education or professional complexity, bilingual experience creates a daily cognitive load comparable to continuous training. Ellen Bialystok emphasizes that it is precisely the constant switching between languages that trains the prefrontal areas, compensating for changes in the hippocampus. This explains why bilingualism affects not memory itself, but the compensatory capabilities of the frontal lobes [23].

Some authors argue that the observed differences may be attributable not to bilingualism itself, but to other confounding variables, such as socioeconomic status or cultural specificities. Thus, the contemporary discussion is shifting from the question "Does an advantage exist?"

to the question "Under what conditions does it arise and through what mechanisms is it mediated?"

Advances in neuroimaging have enabled a shift from observation to the study of the neural underpinnings of bilingualism's influence. Research indicates that the experience of multilingualism leads to significant structural and functional changes in the brain, demonstrating its high neuroplasticity [2; 3].

Most studies demonstrate changes in the brains of bilinguals that topographically coincide with areas closely associated with language processing and control, memory, and executive functions [13]. MRI studies show increased efficiency of neural engagement during task performance in bilinguals, even in the absence of measurable behavioral differences [14]. More recently, neuroimaging work has demonstrated how greater bilingualism is associated with individual neuroanatomical variations and more efficient neural engagement during behavioral tasks [28].

Bilinguals exhibit increased gray matter density in regions associated with language control and executive functions, specifically the inferior parietal lobule and the dorsolateral prefrontal cortex [5; 6]. These brain areas play a crucial role in attention, task switching, and interference suppression.

Functional MRI studies suggest that bilinguals often exhibit more efficient neural network activation during cognitive tasks, implying that their brains may utilize fewer resources compared to monolinguals to achieve the same outcome [13].

The idea that bilingualism creates "cognitive noise" has long given way to the concept of structured neurocognitive training. The essence of the phenomenon lies not in the parallel storage of two linguistic systems, but in the formation of a dynamic system for suppressing interference, where the prefrontal cortex acts as an arbiter of competing signals [31]. MRI studies demonstrate that even during silent speech production, bilinguals maintain a background level of activation in the dorsolateral prefrontal cortex (DLPFC) and anterior cingulate cortex (ACC) – areas responsible for conflict resolution and the selection of relevant stimuli [20; 21]. This explains the phenomenon of neural economy: when performing non-verbal executive control tasks, bilinguals show reduced activation of control networks compared to monolinguals, indicating a more efficient allocation of resources [15].

Neurophysiological differences are also evident in information processing

strategies. While monolinguals engage the right middle frontal gyrus to compensate for age-related changes, bilinguals activate the left inferior parietal lobule (IPL) [30]. The left IPL is involved in phonological and semantic processing and plays a key role in second language acquisition and vocabulary knowledge [24]. This alternative activation pattern allows for the maintenance of cognitive performance even in the presence of early degenerative processes.

Enhanced neural efficiency is a result of constant training of cognitive control networks [25]. Furthermore, studies using diffusion tensor imaging (DTI) have revealed higher white matter integrity in the corpus callosum and other tracts connecting different brain regions in bilinguals. The foregoing, thus, indicates a more sophisticated and rapid transfer of information between and within hemispheres, which is a prerequisite for the effective management of two language systems [10; 11; 12].

Diffusion Tensor Imaging (DTI) in the study by Reyhaneh Bakhtiari, Carol Bolik, and Jacqueline Cammin [7] revealed structural differences underlying functional advantages. Individuals with extensive bilingual experience exhibit:

- Increased fractional anisotropy in the inferior fronto-occipital fasciculus and superior longitudinal fasciculus, indicating enhanced myelination and axonal tract organization.
- Increased functional connectivity between nodes of the Default Mode Network (DMN) and the executive control network, with the strength of the correlation directly depending on the frequency of foreign language use.

These changes create a neuroanatomical substrate for cognitive reserve. The epidemiological study by Alladi and colleagues (2013), which included 648 patients with dementia in India, showed that the clinical manifestation of Alzheimer's disease began 4.5 years later in bilinguals than in monolinguals, regardless of education level and socioeconomic status [1]. Paradoxically, however, bilinguals with dementia showed a greater degree of atrophy in medial temporal structures compared to monolingual patients with the same symptom severity.

Neuroanatomical and neurofunctional changes underlie the observed advantages in bilinguals and serve as a clear example of how life experience can shape the structure and functioning of the human brain throughout life.

One of the most significant and practically important areas of research is the

role of bilingualism in the formation of cognitive reserve. Cognitive reserve is the brain's ability to withstand pathological changes (e.g., age-related or neurodegenerative diseases) and maintain normal cognitive functioning [8].

The concept is that life experiences, including education, professional activities, and multilingualism, create a "reserve capacity" in the brain that allows for compensation of emerging impairments [22].

A series of large epidemiological studies has shown that older adults who are bilingual or multilingual experience the onset of dementia symptoms, particularly Alzheimer's disease, on average 4–5 years later than monolinguals [19].

It is important to note that bilingualism does not prevent the disease itself – pathological changes in the brain (e.g., amyloid plaque accumulation) occur just as they do in monolinguals. Nevertheless, thanks to the developed cognitive reserve, the bilingual brain is capable of compensating for these changes for longer, maintaining functionality at an adequate level [9; 27].

The mechanism of this protective effect is linked to the same brain changes discussed above: more developed executive functions and increased efficiency of neural networks [28].

When some neural pathways are damaged as a result of illness, the bilingual brain is better able to find alternative routes to solve cognitive tasks, utilizing more flexible and efficient networks trained by years of language management experience [1; 29].

This effect is seen even when a second language is learned as an adult, suggesting potential for language learning as a preventative measure for cognitive health in old age.

Analysis of contemporary scientific literature shows that the experience of bilingualism and multilingualism has a profound and multifaceted impact on cognitive functions and the neural organization of the brain. The constant need to manage multiple language systems leads to significant changes, manifesting both at the behavioral level in the form of improvements in certain aspects of cognitive control, and at the neurobiological level in the form of structural and functional reorganization of the brain.

Therefore, bilingualism can be considered a contributing factor to cognitive plasticity and the development of a lifelong neurocognitive reserve.

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