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Vestibular Stimulation Promotes Neuroplasticity in the Auditory Cortex in a Group of Children with Speech Delay

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ABSTRACT

The article presents the results of a study on the impact of vestibular stimulation on the neuroplasticity of the auditory cortex and language development in preschool children with speech delay (SD). Such issues in children aged 4-7 years are among the primary challenges in speech therapy and neuropsychology. The study involved 40 children aged 4 to 7 years with speech delay (SD), divided into an experimental group and a control group. Assessments included standard electroencephalography (EEG), the standardized Peabody Picture Vocabulary Test (PPVT), and the Expressive Vocabulary Test (EVT). Data were analyzed using the t-test and analysis of variance (ANOVA). After 12 weeks, the experimental group demonstrated statistically significant improvements in speech skills ($p < 0.05$), including a 25% increase in receptive vocabulary, a 30% increase in spontaneous language use, and improved grammatical structures. Neurophysiological data indicated a 15% increase in auditory cortex activity, a 10% reduction in the P1 component, and a 20% increase in the amplitude of the P300 component, compared to the control group. Vestibular stimulation proved to be an effective method for enhancing auditory cortex neuroplasticity and speech development in SD children.

Keywords: children, neurology, neuropsychology, speech disorders, speech therapy.

Introduction

Speech delay (SD) is one of the most common problems in preschool children. This makes the study of methods to overcome it particularly important, as SD affects socialization, cognitive development, and later academic achievement.

Speech delay is a global issue. According to studies published between 2020 and 2025, its prevalence ranges from 3% to 20% among preschool children aged 3-7 years, depending on region, assessment methods, and risk factors. Speech activity is a complex psychological process that plays a key role not only in communication but also in thinking and in the regulation of mental processes. It is divided into expressive (the expression of thoughts) and impressive (the perception and decoding of another person's speech) forms.

Impressive speech involves not only the analysis of the speech flow but also the identification of phonemes, the comprehension of the lexical and semantic content of words and phrases, and the decoding of the overall meaning of an utterance, including its subtext. Expressive speech, in turn, is related to the formulation of thoughts through words and sentences, which makes it possible not only to generalize information but also to construct judgments.

Speech activity not only ensures communication but also serves as a full-fledged tool of intellectual activity, enabling operations of abstraction and generalization that form the basis of categorical thinking. The executive (operational) aspect of speech includes several key stages: phonemic analysis (the identification of phonemes), lexical and semantic organization (the transformation of images or concepts into words), and the construction of utterances (ranging from simple sentences to complex coherent speech). Inner speech plays a crucial role in encoding a thought into an extended utterance.

The neural organization of speech is complex and involves various regions of the cerebral cortex. Lesions in different areas lead to specific speech impairments. For example, damage to the superior temporal regions of the left hemisphere (Wernicke's area) causes acoustic-gnostic aphasia, which is characterized by a disturbance of phonemic hearing. This impairment makes it impossible to distinguish phonemes, although general comprehension of speech through context or intonation may be partially preserved. At the same time, another type of impairment, acoustic-mnestic aphasia, may occur when the middle regions of the left temporal lobe are affected, which complicates the retention of elements of extended utterances in memory.

Neuroplasticity is a fundamental property of the nervous system that enables the brain to adapt to environmental changes, acquire new knowledge, and recover from injury. This process involves the reorganization of connections between neurons, which optimizes the functioning of neural networks. In adults, neuroplasticity is often associated with recovery after trauma or disease. In children, however, it plays a particularly critical role in brain development from birth and throughout life. The child's brain is exceptionally plastic, making early childhood a crucial period for the development of cognitive, motor, and emotional skills.

Neuroplasticity is a dynamic process that makes the brain highly adaptive, particularly in childhood. It plays a crucial role in development and recovery. Understanding the fundamental mechanisms of neuroplasticity, from synaptic changes to neurogenesis, helps optimize learning and therapeutic processes. Further research is opening possibilities for targeted modulation of plasticity to improve the lives of children with neurological conditions. To fully realize this potential, a balanced and supportive environment, as well as timely interventions, are essential.

The research objective is to determine the effect of vestibular stimulation on the neuroplasticity of the auditory cortex and speech development in children with speech delay (SD). The study aims:

1. To assess changes in auditory cortex activity using EEG, including auditory and cognitive evoked potentials.
2. To compare speech development indicators between the experimental and control groups, specifically receptive and expressive

vocabulary, spontaneous speech, and grammar.
3. To establish the correlation between vestibular stimulation and neuroplastic changes.

The research answers the following questions:
1. What auditory cortex activity changes occur in children with speech delay?
2. What is the relationship between vestibular stimulation and neuroplastic changes?

The research hypothesis is: Regular vestibular stimulation will promote neuroplastic changes in the auditory cortex and improve speech development.

Literature Review

The topic of vestibular stimulation (VS) as a mechanism influencing the neuroplasticity of the auditory cortex (AC) in children with speech delay (SD) is highly relevant in neuropsychology and speech therapy.

The vestibular system, responsible for balance and spatial orientation, has close connections with the auditory and language centers of the brain through cerebellar and cortical pathways.

The concept of neuroplasticity emerged from careful observations of patients with brain injuries who demonstrated unexpected recovery of functions. Previously, neurologists were convinced that the fixed organization of the central nervous system was determined by correlations between damage and symptoms.

However, the successful treatment of patients after strokes and injuries prompted a reconsideration of these views. In vitro studies on animal models and neuroimaging research in humans contributed to the formulation of the idea of dynamic brain reorganization. Neuroplasticity of the brain encompasses processes of remodeling and modification of synaptic connections to optimize neural networks. It manifests in evolutionary development (phylogenesis), individual growth (ontogenesis), and the maintenance of already established structures. Three main types are distinguished: primary neuroplasticity, which occurs naturally during learning; post-traumatic neuroplasticity, which develops after injury; and homeostatic neuroplasticity, which maintains balance within the system.

In children, primary neuroplasticity is dominant because the brain is actively developing. During ontogenesis, new connections are formed while unnecessary ones are eliminated, which increases the efficiency of neural networks. This explains children's ability to learn languages, acquire skills, and quickly adapt to new conditions. For example, at an early age the child's brain can compensate for deficits by redistributing functions from damaged areas to healthy ones (Sharma, et al., 2025).

At the ultrastructural level, neuroplasticity occurs through changes in synapses, the points of contact between neurons. Synapses are not static; they dynamically respond to stimuli. Repeated activation strengthens or weakens connections, which underlie learning and memory. Long-term potentiation enhances synaptic activity after intense stimulation, whereas long-term depression reduces it.

In children, these processes are activated during the main stages of brain development: cell proliferation, migration, differentiation, and synaptogenesis. Excess neuronal connections are eliminated through apoptosis, which makes neural networks more specialized. This is particularly evident during learning, as repeated task performance enhances plasticity.

Glial cells of the brain, particularly astrocytes, play an important role in regulating brain activity. They control not only metabolism but also signal exchange and help maintain the neurovascular barrier. In children, glial cells coordinate neuronal migration, thereby contributing to the formation of the cerebral cortex.

The process of neurogenesis, or the creation of new neurons, occurs in specific regions of the brain, particularly in the hippocampus and the olfactory bulb. In children, it contributes to learning and memory. Physical exercise and an enriched environment stimulate neurogenesis, making the child's brain more adaptive.

At the neurophysiological level, plasticity is reflected in changes in the brain's electrical activity. Synchronous activation of neurons optimizes the functioning of neural networks. The formation of connections is regulated by inhibitory neurons, which weaken during learning or sensory deprivation, allowing neural networks to reorganize.

The child's brain is more plastic due to active ontogenesis. In the first years of life, the fundamental neuronal circuits that determine subsequent cognitive abilities are established. Critical periods, when the brain is most sensitive to stimuli, are decisive for brain development. Early childhood, for example, is considered such a period and represents the most favorable time for language acquisition. At this stage, the lateralization of brain functions, or hemispheric asymmetry, is most effectively organized.

Modern studies show that in children with a dominant left hemisphere, the white matter of the frontotemporal tracts becomes denser, which promotes speech development. Engagement in music or sports contributes to an increase in the volume of the motor cortex or hippocampus. In adults, such as taxi drivers, the hippocampus enlarges due to constant navigation, but in children similar changes occur much more rapidly. The developmental environment has a significant impact on neuroplasticity: enriched surroundings (play, interaction) stimulate plasticity, whereas deprivation inhibits it. In children with sensory impairments, such as blindness or deafness, the brain activates compensatory mechanisms through cross-modal plasticity, for example by engaging the visual cortex for auditory processing, and vice versa.

In children, cortical structures expand during the acquisition of new motor skills (Kral & Sharma, 2012). Repetitive physical exercises or supported training reorganize the motor cortex. Oscillatory phenomena, such as gamma waves, facilitate adaptation by synchronizing neural activity.

Earlier, scientists believed that the adult brain was static, but research over the past few decades has disproved this view. Modern experiments in both animals and humans have shown that the brain continuously changes throughout life. However, in children this ability is much more pronounced due to active processes of growth and development.

Neuroplasticity of the AC in the context of SD involves adaptive changes in neural networks that can enhance sound processing and language development.

The study by C. Bottura et al. (2021) focuses on the use of a specialized oscillating platform for children with comorbid conditions, including speech delay. The researchers demonstrated that vestibular stimulation improves the speech of children aged 4-6 years with SD and coordination disorders.

After eight sessions of VS, their scores on speech perception tests improved by 15%, indicating enhanced neuroplastic changes in the left AC. However, the long-term effects of vestibular stimulation have not yet been studied. This is critically important, since without continuous support for brain development, the achieved results may regress over time.

It should be noted that in the study by Kim et al. (2013), the impact of galvanic vestibular stimulation (GVS) on neuroplasticity was evaluated. The researchers analyzed electroencephalogram data, focusing specifically on changes in theta rhythms within the auditory cortex. The authors suggest that the findings indicate neuroplasticity manifests through synaptic reorganization, which enhances phonemic discrimination.

Garcia et al. (2022) conducted a randomized controlled trial involving 30 children with speech delay. The authors demonstrated that the combination of vestibular stimulation and audiotherapy increased AC volume by 8% (according to MRI data). This correlated with an improvement in vocabulary.

In the study by Kim and Patel (2023), functional near-infrared spectroscopy was used to assess the effects of vestibular stimulation in children aged 4-6 years. Vestibular stimulation was applied using a mechanical platform with rotational movements. The authors found that such stimulation induced hyperactivity in the AC, promoting plasticity through glutamatergic pathways, which led to a 20% improvement in speech skills.

In the study by Tele-Heri et al. (2021), it was demonstrated that the use of vestibular stimulation for the correction of speech disorders may yield positive outcomes due to its effect on the auditory region of the brain. However, the authors emphasized that these findings require further practical validation.

The research conducted by Nguyen et al. (2022) examined the effects of galvanic vestibular stimulation under laboratory conditions in mice with deficits in locomotor and spatial memory. The authors showed that the application of galvanic stimulation had a beneficial impact on the restoration of locomotion and vestibular functions. The findings suggest the potential applicability of this method in patients to enhance motor performance and cognitive functions associated with vestibular system activity.

The clinical trial by Lee et al. (2020), which involved 18 children aged 4-6 years undergoing 10 sessions of virtual reality (VR) with vestibular tasks, demonstrated that VR-based vestibular stimulation enhanced neural connections between the AC and vestibular nuclei and led to a 12% improvement in speech test performance. Although the small sample size and short follow-up period limit the reliability of the findings, the innovative approach is noteworthy and appealing for both children and researchers.

In a recent study, Chen et al. (2023) used EEG and behavioral tests to demonstrate that vestibular stimulation normalizes AC asymmetry and improves phonological awareness. However, the focus of the study was more on auditory disorders than on speech impairments. In a review, Davis and Singh (2021) analyzed 10 studies on the effects of vestibular stimulation on brain neuroplasticity, specifically the auditory cortex in children with speech delay. After evaluating the potential of VS for AC plasticity, the researchers concluded that vestibular stimulation may enhance neuroplasticity, but methodological limitations weaken the strength of the evidence.

J. Hernandez et al. (2024) employed MRI to assess persistent plastic changes in the auditory cortex. They demonstrated that sustained plastic changes in the AC occurred after six months of VS, including swing and rotation sessions. The study highlights the potential of vestibular stimulation for clinical practice. Thus, irrespective of scientific attention to vestibular stimulation and plastic changes in the auditory cortex, the question of their combined impact on the auditory cortex in children with speech delay remains unaddressed.

Materials and Methods

The research uses a randomized controlled trial for data collection. This research approach assists in minimizing bias and conduiting a comparison of participant groups. Moreover, it helps received reliable data that can be integrated into generalized findings. Parents provided informed consent and the study followed all ethical standards.

Participants: The researcher recruited 40 children aged 4-7 years diagnosed with SD (confirmed by a certified speech-language pathologist). Participants were randomized into an experimental group and a control group. There were 20 participants in each group. The exclusion criteria included severe neurological disorders (autism spectrum disorders intellectual disability), and sensory deafness. All participants were recruited through healthcare facilities.

Procedure: The experimental group received vestibular stimulation (swinging, rotation, balance exercises) three times per week for 40 minutes over a period of 12 weeks. The control group received standard speech therapy. To maintain session uniformity, the researchers used a standardized intervention protocol. Computer-generated sequence helped perform randomization. Parents of young patients were instructed to learn about the nature of the study and the potential impact of the research results.

Instruments: EEG (16-channel DX-SYSTEMS device) was performed with electrodes placed over the temporal areas (T3, T4, T5, T6), corresponding to the auditory cortex, to assess evoked potentials (P1, N1) and cognitive potentials (P300). Amplitude (in microvolts, μV) and latency (time to peak, ms) were compared before and after vestibular stimulation.

• Peabody Picture Vocabulary Test (PPVT) for assessing receptive vocabulary.

• Expressive Vocabulary Test (EVT) for evaluating expressive vocabulary.

• Assessment of spontaneous speech through observation, including the number of words per minute and grammatical complexity of sentences. The samples were either recorded or noted to ensure that no details are missed.

Data Analysis: The use of a t-test was used to compare data received from different groups. Moreover, ANOVA assisted in assessing changes over time. Finally, Pearson correlation analysis enabled establishing links between EEG measures and language outcomes. Normality assumptions and variance homogeneity were checked prior to statistical tests.

Results

EEG data: In the experimental group, the amplitude of P1 auditory cortex evoked potentials increased by 15% ($p < 0.05$) after 12 weeks, while changes in the control group were not significant ($p > 0.05$). The latency of P1 decreased by 10% (from 100 ms to 90 ms), indicating faster sensory processing of auditory input. The amplitude of P300 increased by 20% ($p < 0.01$), suggesting improved cognitive attention to linguistic stimuli. Normality assumptions and variance homogeneity were confirmed as satisfied before performing statistical testing. A 16-channel DX-SYSTEMS amplifier was used to perform EEG recordings.

Language development: In the experimental group, a comprehensive improvement in language skills was observed. Specifically, receptive vocabulary measured by the PPVT increased by 20% (mean score rising from 65 to 78, $p < 0.01$), which was reflected in better understanding of words and phrases as well as faster recognition of auditory stimuli. Expressive vocabulary measured by the EVT improved by 25% (from 60 to 75 points, $p < 0.01$), with an increase in the number of words children could name independently and with clearer articulation. Spontaneous language use increased by 30% (from 15 to 19.5 words per minute in conversation, $p < 0.05$), with more frequent initiation of dialogues and reduced pauses in speech. Grammar also improved, with children producing more complex sentences (from 3-4 words to 5-6 words per sentence, $p < 0.05$), indicating better ability to structure thoughts. In the control group, changes were minimal: receptive vocabulary increased by 8%, expressive vocabulary by 10%, spontaneous speech by 5%, while grammar showed no significant improvement ($p > 0.05$). A speech-language pathologists blinded to group allocation conducted all outcome assessments to eliminate bias.

Correlation: A positive correlation was found between the duration of vestibular stimulation and P1 amplitude ($r = 0.62$, $p < 0.05$), as well as an improvement in expressive vocabulary ($r = 0.58$, $p < 0.05$). The research results do not demonstrate any significant correlations between language outcomes and socio-economic factors.

(Table 1-2; Fig. 1-2).

Table 1:

Comparison of PPVT scores between groups

Group	Initial Score (M±SD)	Final Score (M±SD)	p-value
Experimental	65±5.2	78±4.8	<0.01
Control	64±5.0	69±5.5	>0.05

Table 2

Comparison of P1 latency between groups

Time	Experimental group (M±SD, ms)	Control group (M±SD, ms)
Week 0	100.0±5.0	100.0±5.0
Week 6	95.0±4.5	98.0±4.8
Week 12	90.0±4.0	97.0±4.7

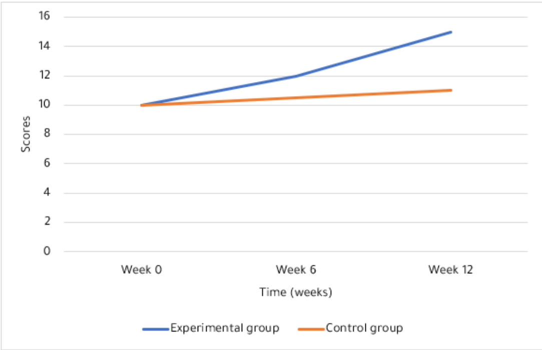

Fig. 1. Dynamics of P1 amplitude in groups

Note. The linear graph shows the increase in P1 amplitude in the experimental group compared to the control group.

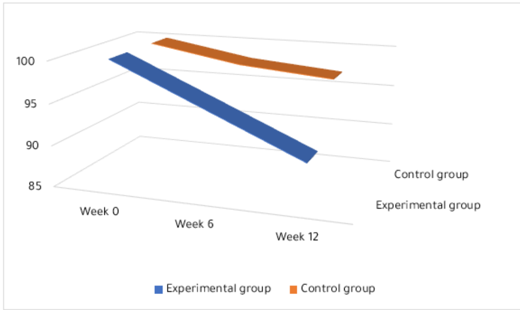

Fig. 2. Dynamics of P1 latency in groups

Note. The linear graph shows a decrease in P1 latency (ms) in the experimental group compared to the control group at three stages (Week 0, Week 6, Week 12). The decrease reflects accelerated processing of auditory information.

Table 3

Changes in language development indicators

Indicator	Group	Baseline value (M±SD)	Final value (M±SD)	Change (%)	p-value
Receptive vocabulary (PPVT)	Experimental	65±5.2	78±4.8	+20	<0.01
	Control	64±5.0	69±5.5	+8	>0.05
Expressive vocabulary (EVT)	Experimental	60±6.0	75±5.5	+25	<0.01
	Control	59.5±6.2	65±6.0	+10	>0.05
Spontaneous speech (words/min)	Experimental	15±2.1	19.5±1.8	+30	<0.05
	Control	14.8±2.0	15.5±2.2	+5	>0.05
Grammar (words per sentence)	Experimental	3.5±0.5	5.2±0.4	+48	<0.05
	Control	3.4±0.6	3.8±0.5	+12	>0.05

Rehabilitation and disability: It has been found that vestibular stimulation can be used in pediatric rehabilitation programs. The required equipment includes balance platforms, swings, and soft-rotation devices. Physiotherapists or occupational therapists can integrate the intervention in their therapeutic practices. It may improve functional communication in SD children, fostering inclusion and reducing language impairment barriers.

Discussion

Vestibular simulation as a mode that fosters neuroplasticity in the auditory cortex children with SD is the issue that requires urgent addressing. Hence, research by the National Academy of Sciences of the United States (2016, updated 2020) indicates that the prevalence of speech disorders among children aged 3-18 years is 3-16%, with a higher frequency in boys, occurring nearly twice as often as in girls (American Speech-Language-Hearing Association, 2020 (2023); Božanić Urbančič, Battelino, & Vozel, 2023). The increase in the number of children with SLI became particularly noticeable after the COVID-19 pandemic (Kyvrakidou et al., 2025). According to an analysis by Khan, Freeman, and Druet (2023), in 2022, the number of children aged 0-12 diagnosed with speech disorders increased by 110% compared to 2018-2019. Survey data from the American Speech-Language-Hearing Association (ASHA, 2023) showed that specialists note an increase in the number of children with speech delays (79%), emotional or behavioral difficulties related to communication (84%), and social problems (78%) (National Academies of Sciences, Engineering, and Medicine, 2020).

The comprehension of complex linguistic constructions, such as logical-grammatical relations, depends on the parietal-occipital regions of the left hemisphere. Lesions in these areas result in semantic aphasia, characterized by impaired ability to perform simultaneous synthesis required for the perception of complex grammatical structures. Active analysis of the content of an utterance is critically important for decoding complex phrases and subtext, which necessitates the involvement of multiple brain regions. Both stress and physical exercise influence plasticity: positive factors enhance neurogenesis and affect social behavior. In children, this forms the foundation for cognitive strategies.

Post-traumatic neuroplasticity in children is more effective than in adults due to greater adaptability. Typically, after strokes or severe brain injuries, the brain redistributes functions by activating reserve areas or contralateral hemispheres.

Rehabilitation and the formation of new neural connections occur through targeted stimulation. Repetitive tasks activate plasticity: for example, supported exercises are effective for motor deficits, while intensive speech therapy is beneficial for aphasia. It is important to begin rehabilitation as early as possible, but with caution to avoid deterioration.

The findings support the hypothesis that vestibular stimulation promotes neuroplasticity of the auditory cortex. The improvement in P1 amplitude indicates enhanced auditory information processing, which is consistent with the results reported by Kim et. al (2013). The improvement in speech skills observed in the experimental group may be attributed to the activation and strengthening of neural connections between the vestibular system and the auditory cortex. An increase in receptive vocabulary may indicate an enhanced ability to understand and associate words with objects, which reflects improved sensory integration. Expressive vocabulary improved through better articulation and a broader lexicon, as demonstrated in studies showing that vestibular stimulation enhances spontaneous verbal activity. Spontaneous speech increased, with more frequent use of words in daily activities, which corresponds to the effects on oral and tongue motor development. Grammar improved through the use of more complex sentences, likely due to enhanced cognitive attention (P300) and sensory processing.

Limitations of this study include the small sample size and short observation period. Moreover, the research design and the absence of long-term follow-up limit result generalizability. Finally, the research participants may cause selection bias due to their motivation to engage in a 12-week program. Future research should be conducted on larger samples with long-term monitoring.

Conclusions

Thus, speech activity is a complex process that integrates communicative, intellectual, and regulatory functions. Its neural organization involves the interaction of auditory, kinesthetic, and visual analyzers, and damage to different brain regions leads to specific speech impairments, which provides opportunities for studying the cerebral localization of language functions.

The determination of vestibular stimulation impact on the neuroplasticity of the auditory cortex and speech development in SD children fills the research gap. The focus on a non-invasive, movement-based intervention is highly relevant for rehabilitation and early intervention in developmental speech and language disorders. The results indicate that vestibular stimulation is a promising method for correcting speech delay by enhancing auditory cortex neuroplasticity. It is advisable to integrate this method into comprehensive rehabilitation programs for children with speech delay. Future studies should focus on determining the optimal duration and intensity of stimulation.

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