NATIONAL RESEARCH UNIVERSITY HIGHER SCHOOL OF ECONOMICS

As a manuscript

Koriakina Maria Mikhailovna

RELATIONSHIP BETWEEN COGNITIVE AND MOTOR DEVELOPMENT IN CHILDREN WITH MOTOR IMPAIRMENT

Dissertation Summary
for the purpose of obtaining academic
degree Doctor of Philosophy in
Cognitive Sciences

Academic supervisor:
Blagovechtchenski E.D., Ph.D

Moscow – 2024

The Ph.D. thesis consists of three studies that correspond to the following articles published in first-tier journals[1]:

A. Blagovechtchenski, E., Koriakina, M., Bredikhin, D., Agranovich, O., Kadieva, D., Ermolovich, E., ... & Shestakova, A. N..Similar Cognitive Skill Impairment in Children with Upper Limb Motor Disorders Due to AMC Multiplex Congenita and Obstetrical Brachial Plexus Palsy //International Journal of Environmental Research and Public Health. – 2023. – Т. 20. – №. 3. – С. 1841.

Б. Ntoumanis, I., Shestakova, A., Koriakina, M., Kadieva, D., Kopytin, G., & Jääskeläinen, I. P. (2023). Developmental differences in the perception of naturalistic human movements. Frontiers in Human Neuroscience, 16, 1046277.

В. Ntoumanis I, Agranovich O, Shestakova AN, Blagovechtchenski E, Koriakina M, Kadieva D, Kopytin G, Jääskeläinen IP. Altered Cerebral Processing of Videos in Children with Motor Dysfunction Suggests Broad Embodiment of Perceptual Cognitive Functions. J Pers Med. 2022 Nov 4;12(11):1841. doi: 10.3390/jpm12111841. PMID: 36579567; PMCID: PMC9697218.

Second-tier publications [2]

Г. Maria Koriakina, Olga Agranovich, Ekaterina Petrova, Dzerassa Kadieva, Grigory Kopytin, Evgenia Ermolovich, Olesya Moiseenko, Margarita Alekseeva, Dimitri Bredikhin, Beatriz Bermúdez-Margaretto, Ioannis Ntoumanis, Anna N Shestakova, Iiro P Jääskeläinen, Evgeny Blagovechtchenski. Aberrant auditory and visual memory

---

[1] First-tier publications include papers indexed in the Web of Science (Q1 or Q2) or Scopus (Q1 or Q2) databases, as well as peer- reviewed collections of conferences that appear in CORE rankings (ranks A and A*).

[2] Second-tier publications are papers published in journals included on HSE's list of high quality journals or indexed in the Web of Science (Q3 or Q4) or Scopus (Q3 or Q4) databases, as well as peer-reviewed collections of conferences appearing in CORE rankings (rank B).

development of children with upper limb motor disorders //Brain Sciences. – 2021. – T. 11. – №. 12. – С. 1650

The results were also presented at the following conferences:

1. Koriakina, M., Agranovich, O., Bermúdez-Margaretto, B., Ulanov, M., Shestakova, A., & Blagovechtchenski, E. (2022, September). Relationship Between Motor Impairments And Verbal Fluency In Children. In 2022 Fourth International Conference Neurotechnologies and Neurointerfaces (CNN) (pp. 78-81). IEEE.
2. Koriakina, M., Agranovich, O., Bermúdez-Margaretto, B., Ulanov, M., Shestakova, A., & Blagovechtchenski, E. (2023, September). Verbal Fluency and Semantic Association Deficits in Children with Upper Limb Motor Disorders. In 2023 Fifth International Conference Neurotechnologies and Neurointerfaces (CNN) (pp. 1-5). IEEE.

2021 Interregional Scientific and Practical Conference "Modern Methods of Rehabilitation of Motor Disorders in Children" with a presentation on the topic "EEG Dynamics as an Indicator of the Effectiveness of Rehabilitation in Children with AMC"

2022 CNN'2022, The Fourth International Conference " Neurotechnologies and Neurointerfaces", with a presentation on the topic: "Relationship Between Motor Impairments and Verbal Fluency in Children"

2022 III Joint Scientific Forum of Physiologists, Biochemists and Molecular Biologists, with a presentation on the topic: "Features of the relationship between speech development and cognitive development in children with disorders of the upper extremities (AMC)"

2022 Conference "Modern Capabilities of Neurotechnologies in the Diagnosis and Treatment of Severe Motor Disorders in Children" at the G.I. Turner National Medical

Research Center for Pediatric Traumatology and Orthopedics with a report on the topic "Cognitive Impairment in Children with Motor Disorders"

2023 CNN'2023, Fifth International Conference " Neurotechnologies and Neurointerfaces», with a presentation on the topic: «Verbal Fluency and Semantic Association Deficits in Children with Upper Limb Motor Disorders»

2023 "International Conference on Biomedical Science and Engineering", with a presentation on the topic «Impact of Upper Extremity Motor Impairments on Cognitive Processes and Perception in Children»

The work was carried out at the Centre for Cognition and Decision Making, Institute for Cognitive Neuroscience, HSE University, Russian Federation, as well as at the Turner National Medical Research Center for Children's Orthopedics and Trauma Surgery of the Ministry of Health of the Russian Federation, St. Petersburg, Russian Federation

Research problem

The relationship between cognitive and motor development has long been a subject of attention in psychology and psychophysiology, but it is still controversial because the neural mechanisms underlying this relationship are not yet fully understood (Hauert, 1986; Iverson, 2010; Van der Fels et al., 2015; Martzog et al., 2019). The aim of this work was to study the relationship between motor and cognitive functions in children with developmental disorders of the upper extremities.

Current research shows that there are relationships between certain categories of motor and cognitive functions (Stein et al., 2017; Invernizzi P. L. et al.; Hama et al., 2020), including complex motor skills and higher-order cognitive abilities, such as between motor planning and working memory (Stöckel and Hughes, 2016; Marvel et al., 2019).

For example, a recent study showed that increasing physical activity in children at primary school age improves not only motor skills but also cognitive abilities related to children's performance in school (Ferreira Vorkapic et al., 2021). Other studies have shown that the preservation of cognitive functions is important for maintaining static and dynamic balance of the body (Salman, 2016), and the development of locomotion and general body control expands the potential field of experience and contributes to the development of the child's exploratory activity (Stöckel and Hughes, 2016).

There are studies that have found that children of middle preschool age have a more pronounced relationship between motor and cognitive skills compared to children of high school age (Van der Fels et al., 2015), which means that different forms of interaction between these two functions can be manifested at different stages of a child's development, and this question is of great applied importance.

Our study involved children with impaired motor function of the upper extremities, and for this reason it is important to consider separately the effect of fine motor skills on cognitive functions. Fine motor skills are a set of coordinated actions of various body systems and are involved in the process of performing fine and precise movements of the hands and fingers and toes (Martzog et al., 2019).

Studies have shown that the fingers of the hand have extensive representation in the cerebral cortex (Shapiro, 2019; Tardelli et al., 2022). The development of finger movements precedes the appearance of syllable articulation, and the level of motor development is related to the quality of the child's articulation (Sullivan, 2018). Moreover, due to the motor development of the fingers, a projection of the "scheme of the human body" is formed in the brain, and speech reactions are directly dependent on the training of the fingers (Vinogradova, 2009; Naito et al., 2017).

That is, a significant part of a child's activity is development through movement, and new motor skills provoke a cascade of changes in areas not directly related to motor activity – perception, speech, expression and regulation of emotions, physical growth and mental health of the child. Such a relationship between the motor system and various aspects of life has been suggested in numerous studies (Baker et al., 1997, Friedman and Förster, 2002, Houwen et al., 2016, Sakreida et al., 2013).

The processes underlying these interactions are formed in the early stages of a child's development. It is important to note that the developing motor system, which allows the child to precisely control the muscles necessary for a particular movement, provides the means for effective interaction with the environment, and in the absence of such skills, the child gets used to the fact that all the functions of such interaction are performed by his parent (Houwen et al., 2016), which subsequently affects the child's recovery in the process of rehabilitation.

The evidence for a strong link between cognitive and motor development is not limited to the behavioral domain. Neurophysiological studies have also revealed the joint activation of brain structures associated with motor and cognitive functions of the brain. For example, associated activation of the cerebellum, basal ganglia, and prefrontal cortex has been shown during the performance of various motor and cognitive tasks, especially complex, novel, with changing conditions, or requiring quick reaction and concentration (Davis, 2009; Salman, 2016). The drive to move, the goal, and the plan arise in the prefrontal cortex involving many brain structures such as the limbic system, the nonspecific nuclei of the thalamus, the associative areas of the parietal cortex, and the reticular formation of the midbrain (Davis et al., 2009).

The upper limbs have a special functional role: unlike the lower limbs, they are mainly involved in the performance of precise voluntary movements. All levels of the nervous system are involved in the performance of voluntary movements, and the leading role is played by the highest one, the cerebral cortex (Hauert, 1986; Iverson, 2010; Van der Fels et al., 2015).

Cognitive skills are also associated with the involvement of high levels of control in the brain, especially the cortex (Friedman N. P., 2022). This may be one of the main factors that determine the relationship between the development of cognitive skills and motor skills (associated with precise voluntary movements). Cognitive skills and motor skills develop simultaneously and actively between the ages of 5 and 10 years (Anderson et al., 2001). Both motor and cognitive development involve important psychophysiological processes, such as sequencing planning, monitoring (Roebers et al., 2009; Kojima, 2019).

Although the described neurophysiological data to some extent confirm the relationship between motor and cognitive development in children, nevertheless, in the real clinic, there are no special approaches to patients related to the features of cognitive development in children with motor disorders (Dusing S. C. et al., 2019).

Thus, the study of clinical populations, in particular children with impaired motor development, can make a significant contribution to understanding the relationship between motor and cognitive functions during development. Moreover, establishing a clear link between the development of motor and cognitive abilities, as well as the underlying neural mechanisms, will allow the development of new and integrative rehabilitation approaches to improve both cognitive and motor skills.

From our point of view, the assessment of children with motor disorders is often limited only to their motor dysfunction, leaving their cognitive development unattended. This study was aimed at studying the features of the development of cognitive abilities in children with motor disorders.

In this study, we focused on the following issues:

1) Previous studies have demonstrated a possible role for children's motor function in cognitive development, but no studies have addressed the specifics of this relationship in children with severe motor diseases of the upper extremities, such as Arthrogryposis Multiplex Congenita (AMC) (congenital disease) and Obstetrical brachial plexus lesion ("OBPL") (acquired disease). Both diseases have extremely similar symptoms and represent a model for studying the relationship between the development of the motor and cognitive systems of the brain, since they manifest themselves immediately at birth and no longer progress (Agranovich O.E., et al., 2013).

2) The results of studies of the relationship between motor and cognitive functions are often ambiguous and contradictory, so additional methodological research is required to determine the optimal measurement parameters that allow assessing cognitive functions not only using psychological techniques, but also methods of psychophysiology, as well as correlating these methods with each other;

3) There have been no studies of the electrophysiological activity of the brain of children with severe motor diseases in order to study the difference between this group of children and a healthy group of children.

Early intervention, especially those aimed at developing cognitive functions, can prevent some of the associated learning and daily life difficulties in children with motor impairments. In this regard, the current study was aimed at concretizing the cognitive problems of these children, for the subsequent adaptation of habilitation programs.

Dissertation objectives

1) To study of the relationship between motor and cognitive functions, identification of patterns of the child's cognitive activity associated with the development of motor skills;

2) To conduct a study using psychological metrics, comparing the level of cognitive development of children with motor disorders of the upper extremities and healthy children; identification of the relationship between motor development and cognitive functions.

3) To conduct an EEG study and analyzing the neuronal correlates underlying the development of a child with motor diseases in comparison with healthy children.

Research methodology

To solve the tasks, this study evaluated the motor functions of children with motor disorders of the upper extremities, in particular, with congenital AMC and OBPL.

According to the clinical characteristics, children with these diseases have the following general pathology according to the orthopedic classification:

1) There are contractures in two or more large joints, hypoplasia or aplasia of muscles, signs of problems with motor neurons in the anterior horns of the spinal cord (Fig. 1.). At the same time, the upper extremity of the patient has a characteristic profile with the following characteristics:

- adductor contracture in the shoulder joint,

- Extensor (less often flexion) contracture in the elbow joint,

- flexion contracture in the wrist joint,

- flexion contractures of the fingers, adductor contracture of the thumb,

- hypoplasia or aplasia of the muscles of the upper extremities,

- limited or no self-service.

2) The muscles of the upper extremities are underdeveloped.

In connection with this common pathology (contractures in the joints; hypoplasia or aplasia of muscles; self-care limitations; signs of motor neuronal dysfunction), the group of children with AMC and the group of children with OBPL were combined into one clinical group. And also, not only in terms of symptoms, but also in terms of treatment and habilitation processes, since surgical interventions and therapeutic processes after them are similar in both diseases. In clinical practice, motor skills are restored by autotransplantation of muscles from various donor areas.

All patients had symptoms associated with the diagnosed disease, other disorders (for example, brain damage, hearing and vision impairment, birth injuries) were not revealed. It is also important to note that studies of pathologies in AMC show that the disease is characterized by damage to the motor neurons of the spinal cord, excluding other known systemic diseases (ICD 10: Q74. 3. ID: KR446).

During the neurological examination, the patient's gross motor skills were assessed. The history included information about the patient in infancy. Developmental delay was noted when the child did not reach certain stages within the expected period of time and his motor skills differed from those of a healthy child. Passive and active joint movements, muscle strength, muscle volume, muscle tone, tendon reflexes, and sensitivity were assessed. The level of paresis was clinically assessed according to the scheme of segmental innervation of the muscles of the upper extremities. A lower level of paresis is associated with greater motor impairment in the patient, i.e., greater involvement of the distal muscles (Agranovich et al., 2013).

Elbow performance in patients was assessed using a modified Van Heest scale (Van Heest et al. 1998). This scale includes an assessment of the child's active elbow extension, muscle strength, and the development of daily activities skills, and uses adaptive mechanisms for elbow flexion (table push, torso thrust, or cervical flexion).

Recording and analysis of EEG

Subjects/patients were fitted with a standard electrode cap according to the international 10/10 system. EEG activity was recorded using 32 electrodes at a sampling rate of 500 Hz. All signal processing was carried out in the MATLAB program. In EEG processing, EEG segments corresponding to the duration of each video block were first isolated and time-aligned between subjects and patients. The signals were then subjected to high-pass filtering (at 1 Hz) and low-pass filtering (at 50 Hz). After isolating the EEG segments corresponding to the duration of each stimulus, the electrode channels with high dispersion were manually determined and replaced with samples with a zero value, which made it possible not to take these channels into account in the subsequent calculation of covariance matrices. Artifacts related to eye movement were removed using the FastICA algorithm in the MATLAB environment.

To solve the tasks, this study evaluated the cognitive functions of children with motor disorders of the upper extremities, in particular, with AMC and OBPL, as well as a control group of healthy children. Groups of children with motor disorders were selected at the G.I. Turner National Medical Research Center for Pediatric Orthopedics and Traumatology.

Cognitive function assessment

To assess the cognitive functions of children, such as concentration, auditory memory, visual memory, visual-figurative and logical thinking and intelligence, a set of adapted diagnostic methods was used so that it is suitable for the maximum number of children in the age range we have (3-15 years).

To assess attention and auditory working memory, the Wechsler test (Wechsler Intelligence Scale for Children, WISC-IV for children from 6 years old, WPPSI for children from 3-6 years old) was used. The test consists in the fact that the child repeats a series of numbers after an adult. The amount of memory is calculated in the number of digits reproduced. The volume of attention is calculated in the number of reproduced digits in reverse order.

Short-term visual working memory, visual-figurative and logical thinking, including the processes of generalization and the ability to identify essential features, were measured using the method from the Shipitsina complex "Psychological and pedagogical diagnosis of deviations in the development of children of primary school age". Visual memory was measured in the number of pictures memorized and named by the child, shown to him. Thinking was measured by the correctness of the restoration of the plot depicted in the chaotically arranged pictures, as well as the ability to tell a story from these pictures.

Intelligence was assessed using Raven's progressive matrices (A, B, C) (CPM/CVS and SPM+/MHVZ). The child performed tasks from three sets, where he had to choose the right figure that fits into the drawing.

Scientific novelty

The results of this work contribute to the field of theoretical models of the features of the development of cognitive functions and their relationship with motor functions, namely, that motor impairment can be the cause of cognitive delay, especially in relation to visual and auditory memory. Our results also expand on previous work on the perception of human movement by introducing naturalistic stimuli into the experimental design, and conducting this study in a group of children with motor disorders.

Empirical novelty

For the first time, we have shown the features of differences between two groups of children, with motor diseases (AMC and OBPL) and healthy children. With the help of EEG, we showed the features of the perception of motor activity in a video with naturalistic stimuli in healthy adults, healthy children and children with motor disorders.

Methodological novelty

Our study makes an important contribution to the methodological discussion on the relationship between motor and cognitive functions, and on the impact of motor dysfunction of the upper extremities on the cognitive development of children. In particular, we provided data on the differences between children with delayed motor development and healthy children, thereby providing the scientific community with a direction in terms of the cause-and-effect relationship of these factors.

In addition, we examined the neuronal correlates of motion perception in healthy adults and children to show age-related features of video stimulus perception, and then made a similar comparison of groups of children with motor diseases with a control group of healthy children. It should be noted that our studies of the features of cognitive development of children with motor diseases of the upper extremities (AMC and OBPL) are among the first in the world, however, in our opinion, the results obtained by us can be extended to other motor diseases.

Theoretical and practical significance

These results should be reflected in individual approaches to teaching and habilitating children with motor disorders. While special rehabilitation programs designed for children with various developmental disabilities are now widely used (Decker et al. 2011), children with motor disabilities need programs that are specifically tailored to their needs, taking into account all the nuances of their cognitive development, as reflected in the present study. Such a program was developed by us for implementation at the Turner Institute.

Improving motor development, for example through interactive video games, could be a new avenue of experimental research, such games could be used to motivate children to slowly train their undeveloped muscles, and then it could be assessed whether this affects their cognitive development. In the future, this approach may help to understand what aspects need to be taken into account when developing rehabilitation and habilitation programs for children with motor disorders.

Key ideas to be defended

1. Regardless of the degree of motor dysfunction, children with motor diseases (AMC and OBPL) have delayed cognitive development (especially attention and memory).

2. There are significant differences in the level of cognitive development in children with the above-mentioned motor diseases of the upper extremities and healthy children, especially in the age period from 8-10 years.

3. Children with the aforementioned motor impairments and healthy children show different electrophysiologic neural correlates of the perception of video stimuli, namely, patients with AMC or OBPP demonstrate divergent neural responses to naturalistic videos.

Author contribution

The author was directly involved in the following stages of the study: review of relevant literature, planning and programming of experimental paradigms, selection of a battery of diagnostic methods, analysis of behavioral data, data collection for part of the EEG study, interpretation and description of the results.

Summary of the dissertation

Study I

In this study, we compared groups of children by the level of cognitive development. We compared groups of children with motor diseases of the upper extremities with each other, and with a group of healthy children. Children with AMC and OBPL differ in motor skills, but not in cognitive tests.

The results of the study showed the selectivity of cognitive impairment in motor diseases and revealed no differences in memory scores between patients with AMC and OBPL, despite their significant differences in motor skills. That is, cognitive skills are formed in connection with motor skills, and this relationship can be non-linear. Presumably, the presence of motor disease may be a more significant factor than its severity in explaining cognitive deficits.

Study II

In this study, we analyzed the impact of motor disorders of the upper extremities on the development of cognitive functions using psychodiagnostics methods. Our results showed a difference in cognitive ability between children with movement disorders and healthy children of the same age.

Based on the results of the study, we can talk about the impact of motor disorders on the work of auditory and visual memory, as well as on verbal and logical thinking. At the same time, indicators on tests for attention, intelligence and thinking did not differ between children with motor disorders of the upper extremities and their peers from the control group. In general, we emphasize that the level of general cognitive development was significantly lower in children with motor disorders of the upper extremities, compared to healthy children. At the same time, cognitive retardation, in comparison with the norm, is especially pronounced in children aged 8 to 10 years.

Thus, we can say that motor dysfunction of the upper extremities impairs cognitive functions, especially auditory and visual memory. These data should be taken into account when developing rehabilitation programs for persons with motor disorders.

Study III

In the present study, using ISC EEG as a marker of attention engagement, we uncovered the additional role that age can play in the perception of human movements. Our results show that scenes with limb movements, especially simultaneous arm and leg movements, cause higher attention engagement than scenes without limb movements. Moreover, this effect decreases with age.

Our results expand the list of factors affecting ISC. According to previous research, viewers' interaction with video depends on emotional content, tension, and the cognitive need to process complex dynamic information, as well as on viewers' personality traits. Here we demonstrate that the perception of video is influenced by the motor development of the child.

We demonstrated that the EEG of children with motor diseases differed from the EEG of healthy children when watching video stimuli, namely, patients with congenital AMC or Duchenne Erb paresis showed divergent neural responses to naturalistic videos. The observed effect was not associated with the severity of the patients' clinical condition, as well as with the type of movement in the video stimuli, suggesting a broad embodiment of perceptual cognitive functions.

The results of this study suggest that motor dysfunction not only affects cognition features related to movement processing, such as mirroring, but also appears to have an overall effect on the processing of naturalistic videos. This is consistent with the hypothesis that cognitive and perceptual processes depend heavily on our sensorimotor abilities and how we interact with the world (Dmochowski et al., 2012; Iotzov et al., 2017; Cohen et al., 2018).

Further research could focus on investigating whether cognitive-perceptual processes in patients with motor dysfunction are altered when their motor abilities are restored, and by examining the effects of a number of other types of motor dysfunctions on the processing of naturalistic stimuli in order to further expand the understanding of how perceptual cognitive functions are embodied.

Acknowledgements

I would like to express my sincere gratitude to my supervisor, Evgeny Dmitrievich Blagovechtchenski, for giving me the opportunity to conduct and complete my studies at HSE University.

I would like to express my sincere gratitude to Anna Shestakova, Head of the HSE Research Centre, as well as to Beatrice-Bermudez and Iiro Jäskelainen for their extremely valuable contribution.

I express special gratitude to Olga Evgenievna Agranovich and the Turner Research Institute for providing the premises, and for the opportunity to work with children with motor diseases, as well as for her help in assessing the motor development of children.

Many thanks to my co-authors Ioannis Ntumanis, Dmitry Bredikhin and others.

I would like to express my gratitude to the HSE Basic Research Program and the Russian Science Foundation (20-65-47016) for their financial support of the projects.

Conclusion

In this work, we identified differences in the cognitive development of children with motor disorders and healthy children. A theoretical analysis of existing studies of the relationship between motor and cognitive development was carried out, as well as the features of the development of children with motor disorders were analyzed. We assumed that children with motor diseases have peculiarities in the development of cognitive functions, which should be taken into account when developing habilitation programs.

The study found that regardless of the criteria for a motor disease (congenital/acquired, level of motor developmental delay, muscle strength), it affects the cognitive development of the child. Age-related features of the development of children with motor disorders were found, namely, that the greatest delay in cognitive development occurs in the age period from 8-10 years.

In addition, motor dysfunction has been shown to affect not only cognition features related to motion processing, such as mirroring, but also appear to have an overall effect on the processing of naturalistic videos. This is consistent with the hypothesis that cognitive and perceptual processes depend heavily on our sensorimotor abilities and how we interact with the world.

Thus, we see that children with motor disorders differ from healthy children in the level of cognitive development and at the level of neural mechanisms, which confirms the hypothesis of a significant impact of motor dysfunction on the child and his development.

References

Van der Fels, I.M.J.; Te Wierike, S.C.M.; Hartman, E.; Elferink-Gemser, M.T.; Smith, J.; Visscher, C. The relationship between motor skills and cognitive skills in 4–16 year old typically developing children: A systematic review. J. Sci. Med. Sport 2015, 18, 697–703.

Hauert, C.A. The relationship between motor function and cognition in the developmental perspective. Ital. J. Neurol. Sci. 1986, Apr;Suppl 5:101-7, PMID: 3759398.

Iverson, J.M. Developing language in a developing body: The relationship between motor development and language devel-opment. J. Child Lang. 2010, 37, 229–261, doi:10.1017/S0305000909990432.

Martzog, P.; Stoeger, H.; Suggate, S. Relations between Preschool Children’s Fine Motor Skills and General Cognitive Abili-ties. J. Cogn. Dev. 2019, 20, 443–465, doi:10.1080/15248372.2019.1607862.

Stein M., Auerswald M., Ebersbach M. Relationships between motor and executive functions and the effect of an acute coordinative intervention on executive functions in kindergartners //Frontiers in psychology. – 2017. – Т. 8. – С. 258076.

Invernizzi P. L. и др. Correlation between cognitive functions and motor coordination in children with different cognitive levels //Advances in Physical Education. – 2018. – Т. 8. – №. 1. – С. 98-115.

Hama S. и др. Relationships between motor and cognitive functions and subsequent post-stroke mood disorders revealed by machine learning analysis //Scientific reports. – 2020. – Т. 10. – №. 1. – С. 19571.

Stöckel, T.; Hughes, C.M.L. The relation between measures of cognitive and motor functioning in 5- to 6-year-old children. Psychol. Res. 2016, 80, 543–554, doi:10.1007/s00426-015-0662-0.

Marvel C. L., Morgan O. P., Kronemer S. I. How the motor system integrates with working memory //Neuroscience & Biobehavioral Reviews. – 2019. – Т. 102. – С. 184-194.

Ferreira Vorkapic C. и др. Does physical activity improve cognition and academic performance in children? A systematic review of randomized controlled trials //Neuropsychobiology. – 2021. – Т. 80. – №. 6. – С. 454-482.

Van der Fels I. M. J. и др. The relationship between motor skills and cognitive skills in 4–16-year-old typically developing children: A systematic review //Journal of science and medicine in sport. – 2015. – Т. 18. – №. 6. – С. 697-703.

Shapiro L., Stolz S. A. Embodied cognition and its significance for education //Theory and Research in Education. – 2019. – Т. 17. – №. 1. – С. 19-39.

Sullivan J. V. Learning and embodied cognition: A review and proposal //Psychology Learning & Teaching. – 2018. – Т. 17. – №. 2. – С. 128-143

Tardelli G. P. et al. Forearm and hand muscles exhibit high coactivation and overlapping of cortical motor representations //Brain Topography. – 2022. – Т. 35. – №. 3. – С. 322-336.

Vinogradova O. S. et al. Children's speech as a multidimensional phenomenon // Problems of ontolinguistics—2009: materials of the international conference (June 17–19, 2009, St. Petersburg).—St. Petersburg: Zlato-ust, 2009.—388 p. ISBN 978-5-86547-509-5 The conference is held with the support. – 2009. – P. 34.

Naito E., Morita T. Neural representation of human body schema and corporeal self-consciousness //Brain and nerve= Shinkei kenkyu no shinpo. – 2014. – Т. 66. – №. 4. – С. 367-380.

Abdelkarim, O.; Ammar, A.; Chtourou, H.; Wagner, M.; Knisel, E.; Hökelmann, A.; Bös, K. Relationship between motor and cognitive learning abilities among primary school-aged children. Alex. J. Med. 2019, 53, 325–331, doi:10.1016/J.AJME.2016.12.004.

Salman, M.S.; Tsai, P. The Role of the Pediatric Cerebellum in Motor Functions, Cognition, and havior: A Clinical Perspec-tive. Neuroimaging Clin. N. Am. 2016, 26, 317–329.

Davis, E.E.; Pitchford, N.J.; Jaspan, T.; McArthur, D.; Walker, D. Development of cognitive and motor function following cerebellar tumour injury sustained in early childhood. Cortex 2010, 46, 919–932, doi:10.1016/J.CORTEX.2009.10.001.

Bugalho, P.; Correa, B.; Viana-Baptista, M. Papel do cerebelo nas funções cognitivas e comportamentais: Bases científicas e modelos de estudo. Acta Med. Port. 2006, 19, 257–267.

Friedman N. P., Robbins T. W. The role of prefrontal cortex in cognitive control and executive function //Neuropsychopharmacology. – 2022. – Т. 47. – №. 1. – С. 72-89.

Anderson V. A. и др. Development of executive functions through late childhood and adolescence in an Australian sample //Developmental neuropsychology. – 2001. – Т. 20. – №. 1. – С. 385-406.

Roebers C. M., Kauer M. Motor and cognitive control in a normative sample of 7-year-olds //Developmental science. – 2009. – Т. 12. – №. 1. – С. 175-181.

Kojima, M.; Nagano, A. Assessment of physical activity and cognitive function and their potential correlation in convalescent patients of cerebrovascular disease. Sci. Rep. 2019, 9, 1–9, doi:10.1038/s41598-019-40460-6

Dusing S. C. и др. A physical therapy intervention to advance cognitive and motor skills: a single subject study of a young child with cerebral palsy //Pediatric Physical Therapy. – 2019. – Т. 31. – №. 4. – С. 347-352.

Agranovich O. E., Lakhina O. L. Clinical variants of deformities of the upper limbs in patients with AMC. – 2013. – №. 3 (69). – P. 125-129.

Van Heest A, Waters PM, Simmons BP. Surgical treatment of AMC of the elbow. J. Hand Surg. Am. (1998) 23:1063–70. doi: 10.1016/S0363-5023(98)80017-8

Baker S. C., Frith C. D., Dolan R. J. The interaction between mood and cognitive function studied with PET //Psychological medicine. – 1997. – Т. 27. – №. 3. – С. 565-578.

Friedman R. S., Förster J. The influence of approach and avoidance motor actions on creative cognition //Journal of Experimental Social Psychology. – 2002. – Т. 38. – №. 1. – С. 41-55.

Houwen S. и др. The interrelationships between motor, cognitive, and language development in children with and without intellectual and developmental disabilities //Research in developmental disabilities. – 2016. – Т. 53. – С. 19-31.

Sakreida K. и др. Are abstract action words embodied? An fMRI investigation at the interface between language and motor cognition //Frontiers in human neuroscience. – 2013. – Т. 7. – С. 125.

Cisek P., Kalaska J. F. Neural mechanisms for interacting with a world full of action choices //Annual review of neuroscience. – 2010. – Т. 33. – С. 269-298.

Smith L. B. Cognition as a dynamic system: Principles from embodiment //Developmental Review. – 2005. – Т. 25. – №. 3-4. – С. 278-298.

Hauert C. A. The relationship between motor function and cognition in the developmental perspective //Italian journal of neurological sciences. – 1986. – С. 101-107.

Iverson J. M. Developing language in a developing body: The relationship between motor development and language development //Journal of child language. – 2010. – Т. 37. – №. 2. – С. 229-261.

Higashionna T. и др. Relationship between motor coordination, cognitive abilities, and academic achievement in Japanese children with neurodevelopmental disorders //Hong Kong Journal of Occupational Therapy. – 2017. – Т. 30. – №. 1. – С. 49-55.

Thompson J., Parasuraman R. Attention, biological motion, and action recognition //Neuroimage. – 2012. – Т. 59. – №. 1. – С. 4-13.

Simion F., Regolin L., Bulf H. A predisposition for biological motion in the newborn baby //Proceedings of the National Academy of Sciences. – 2008. – Т. 105. – №. 2. – С. 809-813.

Jacobs A., Pinto J., Shiffrar M. Experience, context, and the visual perception of human movement //Journal of Experimental Psychology: Human Perception and Performance. – 2004. – Т. 30. – №. 5. – С. 822.

Lu Z. L., Sperling G. The functional architecture of human visual motion perception //Vision research. – 1995. – Т. 35. – №. 19. – С. 2697-2722.

Whitney D. Contribution of bottom-up and top-down motion processes to perceived position //Journal of Experimental Psychology: Human Perception and Performance. – 2006. – Т. 32. – №. 6. – С. 1380.

Dmochowski J. P. и др. Audience preferences are predicted by temporal reliability of neural processing //Nature communications. – 2014. – Т. 5. – №. 1. – С. 4567.

Dmochowski J. P. и др. Correlated components of ongoing EEG point to emotionally laden attention–a possible marker of engagement? //Frontiers in human neuroscience. – 2012. – Т. 6. – С. 112.

Cohen S. S., Parra L. C. Memorable audiovisual narratives synchronize sensory and supramodal neural responses //ENeuro. – 2016. – Т. 3. – №. 6.

Iotzov I. и др. Divergent neural responses to narrative speech in disorders of consciousness //Annals of clinical and translational neurology. – 2017. – Т. 4. – №. 11. – С. 784-792.

Cohen S. S. и др. Neural engagement with online educational videos predicts learning performance for individual students //Neurobiology of learning and memory. – 2018. – Т. 155. – С. 60-64.

Lankinen, K.; Saari, J.; Hari, R.; Koskinen, M. Intersubject consistency of cortical MEG signals during movie viewing //NeuroImage. – 2014. – Т. 92. – С. 217-224.

Petroni A. и др. The variability of neural responses to naturalistic videos change with age and sex //ENeuro. – 2018. – Т. 5. – №. 1.

Ki J. J., Kelly S. P., Parra L. C. Attention strongly modulates reliability of neural responses to naturalistic narrative stimuli //Journal of Neuroscience. – 2016. – Т. 36. – №. 10. – С. 3092-3101.

Pillsbury W. B. The essentials of psychology. – Macmillan Company, 1920.

Titchener E. B. A beginner's psychology. – Macmillan, 1915.

Washburn D. A., Putney R. T. Stimulus movement and the intensity of attention //The Psychological Record. – 1998. – Т. 48. – №. 4. – С. 555-570.

Campbell K. L. и др. Idiosyncratic responding during movie-watching predicted by age differences in attentional control //Neurobiology of aging. – 2015. – Т. 36. – №. 11. – С. 3045-3055.

Nastase S. A. и др. Measuring shared responses across subjects using intersubject correlation //Social Cognitive and Affective Neuroscience. – 2019. – Т. 14. – №. 6. – С. 667-685.

Irving E. L. и др. Effect of stimulus type on the eye movements of children //Investigative ophthalmology & visual science. – 2011. – Т. 52. – №. 2. – С. 658-664.

Dmochowski J.P., Sajda P., Dias J., Parra L.C. Correlated components of ongoing EEG point to emotionally laden attention—A possible marker of engagement? Front. Hum. Neurosci. 2012;6:112. doi: 10.3389/fnhum.2012.00112.

Iotzov I., Fidali B.C., Petroni A., Conte M.M., Schiff N.D., Parra L.C. Divergent neural responses to narrative speech in disorders of consciousness. Ann. Clin. Transl. Neurol. 2017;4:784–792. doi: 10.1002/acn3.470.

Cohen S.S., Madsen J., Touchan G., Robles D., Lima S.F., Henin S., Parra L.C. Neural engagement with online educational videos predicts learning performance for individual students. Neurobiol. Learn. Mem. 2018;155:60–64. doi: 10.1016/j.nlm.2018.06.011.

Cohen S.S., Parra L.C. Memorable Audiovisual Narratives Synchronize Sensory and Supramodal Neural Responses. eNeuro. 2016;3:203–216. doi: 10.1523/ENEURO.0203-16.2016.

Blagoveschenskiy E.D., Agranovich O.E., Kononova E.L., Baindurashvili A.G., Nazarova M.A., Shestokova A.N., Gabbasova E.L., Nikulin V.V. Characteristics of electrophysiological activity of the cerebral cortex in children with AMC. Neuromuscul. Dis. 2018;8:10–17. doi: 10.17650/2222-8721-2018-8-2-25-32.

Gallese V. Embodied simulation: From neurons to phenomenal experience. Phenomenol. Cogn. Sci. 2005;22:455–479. doi: 10.1007/s11097-005-4737-z.

Gallese V. Bodily selves in relation: Embodied simulation as secondperson perspective on intersubjectivity. Philos. Trans. R. Soc. B Biol. Sci. 2014;369:20130177.

Ki J.J., Kelly S.P., Parra L.C. Attention Strongly Modulates Reliability of Neural Responses to Naturalistic Narrative Stimuli. J. Neurosci. 2016;36:3092–3101. doi: 10.1523/JNEUROSCI.2942-15.2016.

Ray W.J., Cole H.W. EEG alpha activity reflects attentional demands, and beta activity reflects emotional and cognitive processes. Science. 1985;228:750–752. doi: 10.1126/science.3992243.

Khamis, H. Measures of association: How to choose? *J. Diagn. Med Sonogr.* **2008**, *24*, 155–162.

Benjamini Y., Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing //Journal of the Royal statistical society: series B (Methodological). – 1995. – Т. 57. – №. 1. – С. 289-300.

Sirotyuk A. L. Attention deficit syndrome with hyperactivity. Diagnosis, correction and practical recommendations for parents and teachers. (Moscow: TC Sphere, 2003–128 p.). – 2003.

Piek J. P. и др. The role of early fine and gross motor development on later motor and cognitive ability //Human movement science. – 2008. – Т. 27. – №. 5. – С. 668-681.

Seidler R. D., Bo J., Anguera J. A. Neurocognitive contributions to motor skill learning: the role of working memory //Journal of motor behavior. – 2012. – Т. 44. – №. 6. – С. 445-453.

Abd El-Hady S. S. и др. Correlation between cognitive function, gross motor skills and health–Related quality of life in children with Down syndrome //Egyptian Journal of Medical Human Genetics. – 2018. – Т. 19. – №. 2. – С. 97-101.

Gallese V., Cuccio V. The neural exploitation hypothesis and its implications for an embodied approach to language and cognition: insights from the study of action verbs processing and motor disorders in Parkinson's disease //Cortex. – 2018. – Т. 100. – С. 215-225.

Decker S. L. и др. Cognitive and developmental influences in visual-motor integration skills in young children //Psychological Assessment. – 2011. – Т. 23. – №. 4. – С. 1010.