Культурно-историческая психология
2022. Т. 18. № 3. С. 81—91
DOI: https://doi.org/10.17759/chp.2022180311
ISSN: 1816-5435 (печатный)
ISSN: 2224-8935 (online)

Cultural-Historical Psychology
2022. Vol. 18, no. 3, pp. 81—91
DOI: https://doi.org/10.17759/chp.2022180311
ISSN: 1816-5435 (print)
ISSN: 2224-8935 (online)

Brain Executive Functions and Learning Readiness in Senior Preschool Age

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It is known that the formation of executive functions (EF), which exert control over cognitive processes and behavior is crucial for children's cognitive development and social adaptation. It has been shown that the efficiency of EF during the preschool period is a predictor of academic performance in primary and secondary school. However, it is still unknown to what extent the age and individual characteristics of EF during the preschool period determine children's potential school readiness and success in mastering preschool educational programs. To address this issue, we conducted a comparative study using qualitative and quantitative neuropsychological tests. Children aged 5—6 (n=132, M=5.67±0.46 years) and 6—7 years (n=163, M=6.67±0.37 years) participated in the study. According to teachers' estimates, both groups were subdivided into three subgroups of participants with low, medium and high school readiness. The statistical analysis showed that such cognitive functions as programming, selective regulation and control of behavior, working memory, inhibitory control, cognitive flexibility and sustained attention were developed significantly (ps<0.05-0.001) better in children with a high level of school readiness (compared to children with low and medium levels of school readiness).

Keywords: brain executive functions, working memory, inhibitory control, cognitive flexibility, preschool age, neuropsychology, leaning readiness.

For citation: Zakharova M.N., Machinskaya R.I., Agris A.R. Brain Executive Functions and Learning Readiness in Senior Preschool Age. *Kul'turno-istoricheskaya psikhologiya = Cultural-Historical Psychology*, 2022. Vol. 18, no. 3, pp. 81—91. DOI: https://doi.org/10.17759/chp.2022180311

Управляющие функции мозга и готовность к систематическому обучению у старших дошкольников

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Известно, что формирование управляющих функций мозга (УФ), осуществляющих контроль когнитивных процессов и поведения, является критичным для познавательного развития и социальной адаптации детей. Показано, что эффективность УФ в дошкольном возрасте является предиктором академических успехов в начальной и средней школе. Открытым остается вопрос о влиянии возрастных и индивидуальных особенностей УФ дошкольников на освоение дошкольных образовательных программ и потенциальную готовность к обучению в школе. С целью исследования этого вопроса проведено сравнительное нейропсихологическое обследование детей 5—6 (n=132, средний возраст — 5,67±0,46 лет) и 6—7 лет (n=163, средний возраст — 6,67±0,37 лет) с низкой, средней и высокой степенью готовности к систематическому обучению по экспертной оценке воспитателей детского сада. Использовались качественные, основанные на концепции А.Р. Лурии, и количественные методы тестирования. У детей с высокой степенью готовности к обучению выявлен значимо (ps<0,05—0,001) более высокий уровень развития функций программирования, избирательной регуляции и контроля деятельности, рабочей памяти, тормозного контроля, когнитивной гибкости и длительного удержания внимания.

Ключевые слова: управляющие функции мозга, рабочая память, тормозный контроль, когнитивная гибкость, дошкольный возраст, нейропсихология, готовность к систематическому обучению.

Для цитаты: *Захарова М.Н., Агрис А.Р., Мачинская Р.И.* Управляющие функции мозга и готовность к систематическому обучению у старших дошкольников // Культурно-историческая психология. 2022. Том 18. № 3. С. 81—91. DOI: https://doi.org/10.17759/chp.2022180311

Introduction

Brain executive functions (EF) is a term that combines various aspects of the control of goal-directed behavior. In cognitive neuroscience [26; 31], they distinguish three core components of EF: information updating and monitoring in *working memory* (WM), *inhibition* of prepotent and impulsive response and mental set shifting — *cognitive flexibility*. In Luria's neuropsychology EF are interpreted more broadly and are associated with frontal lobes and its functions — programming, selective regulation and control of behavior and mental activity [10].

EF develop within a long period of time. However, many researchers emphasize their important significant changes during preschool years [14; 28]. These EF changes are expressed in better organization of their mental processes and self-control, developing of inhibition of impulsive reactions, increasing *cognitive flexibility and capacity to* follow instructions.

EF development is determined both by the maturation of the *brain regulatory systems*, which are the neurophysiological basis of this process [12], and by child *social experience*, which should provide opportunities for mastering various ways of self-regulation and these skills automation. During development, the brain maturation, primarily the long-term maturation of the frontal cortex, and social experience including learning, constantly interact with each other. This reciprocal interaction must be taken into account during EF assessment and treatment [3]

Various components of EF show distinctive developmental trajectories and significant individual variability in the child population. Thus, 5-year-old children are already able to execute sequential action programs [11]. At 6—7 years the efficiency of performing tasks according to verbal and visual instructions becomes equal [7]. The ability to *understand instructions and algorithms of the activity* demonstrate significant positive age-related changes from 5—6 to 6—7 years [8; 18], which could be related with an increase in the efficiency and volume of WM observed between the ages of 5—6 and 9—10 years [19]. It is important to note the intense formation of the *planning function* at the age of 5 to 8 years, which determines the ability to organize one's actions consistently to achieve the goal [34]. The development of planning becomes possible due to the formation of the hierarchy of motives [17]. The hierarchical structure of motives and their relations with inner objects' images (rather than directly perceived objects) are formed in the process of development and execution of role-playing games, constructive activity and other activities in which preschoolers begin to implement their intentions [6; 17].

At preschool age, there is a significant increase in the effectiveness of *voluntary regulation of movements*, including graphic movements, underlying the writing skills development [4]. In 6-7-year-old children, progress in voluntary regulation of movements is expressed also in the possibility of gaze fixing on the significant features of objects. That suggests the development of categorization and generalization processes, underlying the creation of an internal model of the object [14]. At this age, a child is able to use the sign as a means of external mediation [5], which also affects the regulation of *mnestic activity*, allowing the development of semantic memory [9].

The development of EF, which controls cognitive processes, social behavior and affective reactions, is critical for cognitive development, school success and general life achievements [26]. The effectiveness of EF turns out to be a predictive sign of school success in a number of disciplines [19; 22; 24] and even predicts the development of social intelligence and moral forms of behavior [32]. A longitudinal study [24] found that scores of visual WM measured in 4-year-old children predict the success of these children in learning mathematics at 7 years. In children aged 3 years, the statistical relationship is already found between the abstract thinking ability and cognitive flexibility [29].

Thus, the preschool age is characterized by the intense development of EF, which makes it extremely interesting and relevant for a thorough study and analysis of their influence both on cognition and behavior, and on the readiness of children for systematic learning and their future academic success at school. ***The goal*** of this study is to analyze the relationships between the level of maturity of various components of EF in preschoolers on the one hand and the readiness for systematic learning and the success of mastering the education program in the preschool organization on the other hand.

Method

295 children aged 6—7 years who attended the school preparatory group of the kindergarten, and children aged 5—6 years who attended the senior group of the kindergarten participated in the study. Based on the expert opinion of teachers, the children in each group were divided into 3 subgroups depending on the success (high, average, low) of mastering the school preparation program and participation in the educational process (see Table 1).

To assess the formation of EF, group and individual studies were used. The group study included the following tests:

- *Reciprocal Motor programmer Tes*t is aimed to analyze the possibilities of following the speech instruction, suppressing immediate habitual reactions, switching;
- *Graphomotor Sequences Task* is aimed to study the possibilities of mastering a motor program when copying a visual sample, switching from one element of the program to another, and automatization of motor series;
- *Spot the Difference Task* is aimed to assess selective visual attention, its distribution and switching from one image to another;
- *Cancellation Test* allows to evaluate the ability to keep attention on a monotonous task and switch from one rule to another;
- *"The Zoo Task"* allows to evaluate visual-spatial WM;
- *The Trail Making Test* is aimed at analyzing the possibilities of holding the program, planning the next action, suppressing immediate reactions.
- *The Maze-tracing Task* is aimed at analyzing the possibilities of forming an activity strategy and suppressing direct reactions;
- *Digit Symbol Coding Task* allows to evaluate the effectiveness of voluntary attention, including its selectivity, the possibility of switching and long-term retention on the task;
- *Three-dimensional Drawing Task*: allows to evaluate the possibilities of planning and creating a copy strategy based on analytical and holistic components of perception.

Some of the tests were taken from the methods of traditional neuropsychological examination of children [13], some are used in group neuropsychological diagnostics [1], and some were modified specifically for this study. Frontal diagnostics was carried out by one teacher in a group of no more than 12 people with the participation of 2-3 assistants who helped children with difficulties in understanding instructions and recorded

Table 1

Subgroups of children participating in the study

Group	Subgroup 1 (high success)	Subgroup 2 (average success)	Subgroup 3 (low success)	Total
6—7 years old (6.67±0.37 yrs.)	n =75 34 boys	n =67 33 boys	n =21 14 boys	n =163 81 boys
5—6 years (5.67±0.46 yrs.)	n =61 21 boys	n =54 31 boys	n =17 13 boys	n =132 65 boys
TOTAL participants				295 children 146 boys

various behavioral manifestations in the form of impulsivity or emotional reactions that were inadequate to the examination situation.

An individual study included 4 computerized methods from the "Praktika-MSU" battery of tests [2] presented on the touch screen of a tablet:

- *Cancellation test* is aimed at assessing the ability to keep attention on a monotonous task (series 1) and switch from one instruction to another (series 2). In each series, the child is presented with a 16x12 table, the elements of which are six different geometric shapes. In series 1, the child is asked to find and mark all the figures of one type — circles, in series 2 — figures of two types — circles and stars.
- *Hands-Legs-Head (HLH)*: a 1-back task procedure adapted for children, used to assess the development of WM and concentration.
- *Corsi Block-tapping Test*: the technique is aimed at assessing the visuospatial WM. In different places of the screen, images of cubes (from 2 to 9) are highlighted in turn in a certain sequence. The task of the child is to remember and then reproduce this sequence (if the answer is correct, the length of the reference sequence in the next sample increases).
- *Hearts and Flowers Test* is a modified method of *The Dots Task* [25; 26], consisting of three subtests, each of which presented 20 stimuli. Subtest 1 (task to press the response button on the same side where the image appears) assesses the ability to follow the instructions and reaction speed, subtest 2 (task to press the button on the opposite side from the image) — the ability to suppress direct response. In subtest 3, the participant needs to switch between two competing programs (combining the first two subtests).

Based on the results of performing neuropsychological tests according to the scheme proposed by Semenova O.A. [16], the individual characteristics (presence/absence of implementation difficulties) of separate components of EF were evaluated. The assessments of these components were combined into four integral indicators:

— deficit of programming functions (average indicators of difficulties in understanding instructions or algorithms and creating a strategy of an activity),

— deficit of selective regulation (average of scores that depicts difficulties in overcoming immediate (impulsive) reactions, switching from one action to another, switching between programs, difficulties in difficulties of sustained program execution),

— deficit of voluntary control of one's own activities, as well as

— general index of EF deficit (average of the deficits of programming, selective regulation and control).

All task evaluation parameters included in the integral indicators of the immatureness of certain components represent a system of penalty points: the minimum score corresponds to the best performance, and the maximum score corresponds to the worst performance. The statistical software package SPSS 28.0 was applied for data processing. Non-parametric Kruskal-Wallis (H) and Mann-Whitney (U) criteria were used for assessing the significance of group and subgroup differences in the analyzed neuropsychological parameters.

Results

Functions of programming, selective regulation and control

Comparison of children aged 5—6 and 6—7 years revealed significant **age differences** between the groups in terms of the level of EF development, assessed according to neuropsychological examination results, both in terms of the overall EF deficiency index (U=3216, p=0.042), and separately for three indices:

— deficit of programming (U=5638.5, p<0.001), including deficit of internalization of ready-made programs (U=6949, p<0.001) and creation of activity strategies (U=6510.5, p<0.001);

— deficit of selective regulation (U=5128, p<0.001), including the number of perseverations of program elements (U=4800.5, p<0.001), repeating of whole programs (U=6267.5, p<0.001), difficulties of sustained program execution (U=5479.5, p<0.001) and impulsivity (U=6135.5, p=0.03);

— deficit of control (U=6117, p<0.001).

In accordance with the study goal, **neuropsychological indices were compared in subgroups of children with different success rates in learning** (Fig. 1, 2) for each age group. An intergroup comparison in terms of the overall EF state index revealed significant differences in all three subgroups both in the older (6-7-year-old) (H=19.735, p<0.001) and in the younger (5-6-year-old) (H=15.735, p<0.001) groups. In children aged 6-7 years, the compared subgroups showed significant differences in almost all neuropsychological indices: *programming deficit* (H=12.228, p=0.02), primarily in terms of strategy formation difficulties (H=9.968, p=0.007); *selective regulation deficit* (H=20.437, p<0.001), including the severity of impulsivity (H=12.357, p=0.02) and difficulties in task switching (H=17.168, p<0.001), sustained program execution (H=14.516, p< 0.001), as well as by the number of perseverations of program elements (H=12.283, p=0.002); and by *control deficit* (H=8.929, p=0.012). At the same time, pairwise comparisons of subgroups 1 and 2 did not reveal any differences in relation to the programming deficit index (and its components) and control; thus, subgroup 2 turned out to be closer to subgroup 1 than to subgroup 3 in terms of neuropsychological parameters of EF.

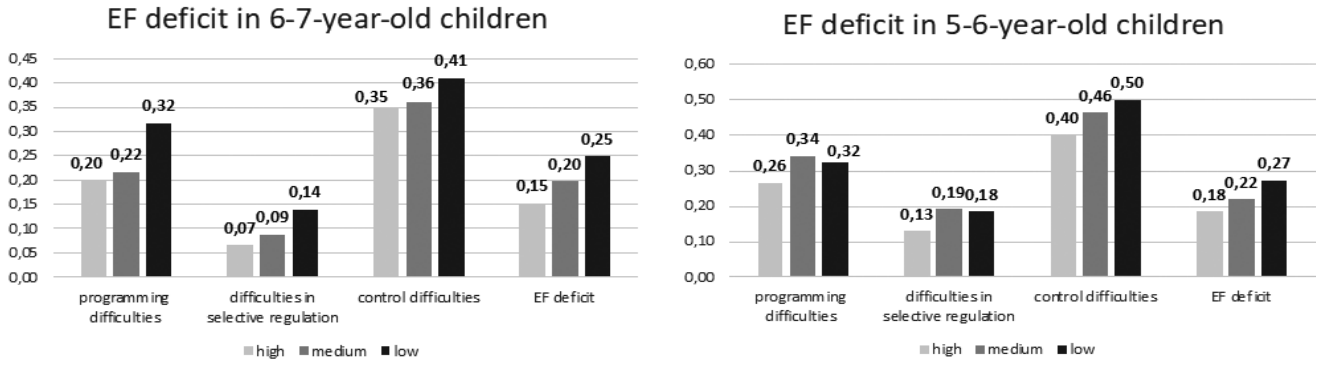

Fig. 1. Integral neuropsychological indices characterizing the state of various components of EF in preschoolers with different degrees of success in learning

At 5—6 years, intergroup differences were found for all EF deficit indices:

— *programming* difficulties (H=8.159, p=0.017), including difficulties in understanding instructions (H=12.095, p=0.002);

— difficulties in *selective regulation* (H=11.244, p=0.004), including impulsivity (H=9.335, p=0.009), perseveration at the action level (H=9.413, p=0.009), difficulties in task switching (H=9.631, p =0.008), difficulties in sustained program execution (H=14.187, p<0.001);

— *control* difficulties (H=11.773, p=0.003).

Differences were not found only for the parameter reflecting the difficulties of creating activity algorithms, which showed high rates in all subgroups, which indicates the immaturity of this EF component. For almost all analyzed neuropsychological indices, pairwise comparisons of subgroup 1 with the other two were significant (ps<0.05), and there were no differences between subgroups 2 and 3.

Working memory

The effectiveness of WM was assessed using three tasks — *the Zoo, Corsi Block-tapping Test and Hands-Legs-Head*. The main indicators of the effectiveness of WM were accuracy (the number of correct answers), the number of errors of various types, the pace of execution and productivity (the product of accuracy and pace). WM indicators showed significant age differences between children aged 5—6 and 6—7 years: older children made fewer mistakes in *the Zoo Task* (U=8747.5, p=0.012), completed the *Hands-Legs-Head Test* more accurately (U=1473.5, p=0.019), productively (U =1115.5, p<0.001) and quickly (U=3128.5, p=0.012), and more often correctly reproduced long sequences of 4 elements in the *Corsi Block-tapping Test* (U=940.5, p<0.001). They also showed a higher response rate within the trial (U=1150, p<0.001) with shorter pauses between them (U=1148, p<0.001).

In children aged 6-7 years, the comparison of subgroups with different level of learning readiness allowed to find significant differences in terms of productivity parameters (H=29.030, p<0.001) and the number of correctly shown sequences of 4 (H=30.433, p<0.001) and 5 (H= 29.030, p<0.001) elements in the *Corsi Block-tapping Test*, and in the *HLH* test — in terms of accuracy (H=12.085, p=0.002) and productivity (H=7.776, p=0.020). In terms of WM productivity, children with the average learning readiness were close to the subgroup with the low learning readiness: pairwise comparisons revealed differences (ps<0.05) only between subgroups 1 and 3 according to the parameters of *HLH* described above, and According to the *Corsi Block-tapping* Test, differences were noted only between subgroups 2 and 3

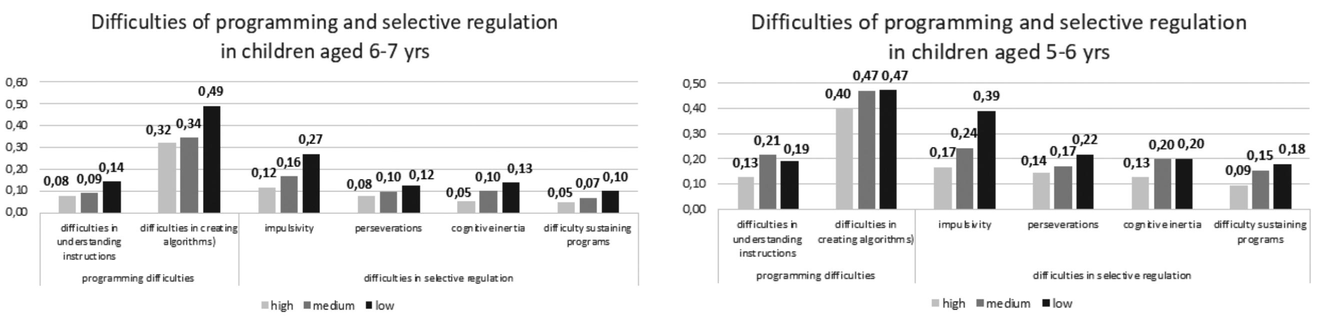

Fig. 2. Neuropsychological indices characterizing the state of various components of programming and selective regulation in preschool children with different degrees of success in learning (designations of subgroups with different success in learning — as in Fig. 1)

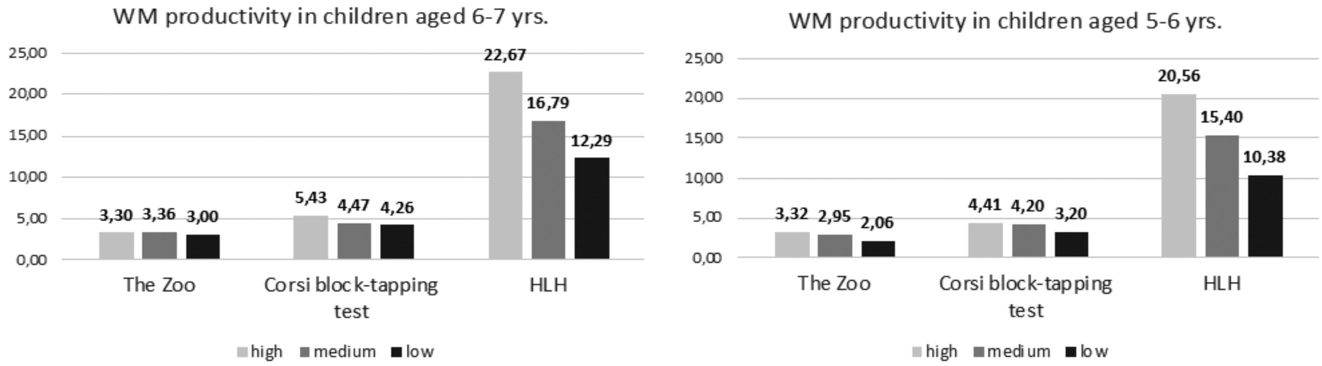

Fig. 3. The productivity of WM in preschoolers with different degrees of success in learning (designations of subgroups with different success in learning — as in Fig. 1)

in terms of the number of repeated answers — perseverations (U=462, p=0.035). Speed indicators depending on success in training did not differ.

In the younger group, children with different learning readiness significantly differed in productivity (H=13.066, p=0.001) and accuracy (H=18.315, p<0.001) in *the Zoo Task*, as well as in the number of repeated choices (H=8.683, p= 0.013) in the *Corsi Block-tapping Test*. Pairwise comparisons showed that children with the high level of learning readiness more often corrected errors in *the Zoo Task* (ps<0.05), less often made errors by the repeated stimulus selections (ps<0.05) in the *Corsi Block-tapping Test*.

Inhibitory control and cognitive flexibility

Consider the results of the *Hearts and Flowers* (The Dots task) *Test*, which evaluates, along with the ability to understand and retain programs of varying complexity, the ability to suppress habitual actions (inhibitory control) and switch from one action to another (cognitive flexibility). Productivity significantly increased in children aged 6-7 years compared with children aged 5-6 years in the first, the most simple series of this test (U=2503, p<0.001), and in the second, more complex series (U=2621, p<0.001) where it was necessary to push the button from the side of the stimuli. The number of errors decreased with the age (in series 1: U=2965.5, p=0.001; in series 2: U=2936, p=0.002), including omissions (in series 1: U=2636, p<0.001; in series 2: U=2891, p<0.001). Children aged 6-7 years made fewer errors and omissions in the entire test (errors: U=3214, p=0.022, omissions: U=2440, p<0.001). In series 1 and 2, the reaction time decreased (in series 1: U=2926.5, p=0.003; in series 2: U=2772.5, p<0.001), which also decreased throughout the test as a whole (U=2986.5, p=0.004). In the third, most difficult series, requiring the retention of two programs at once, no age differences were found.

In children aged 6-7 years, a number of differences in the performance of the test by children with different learning readiness (Fig. 4) were found for productivity (H=8.595, p=0.014) and errors (H=11.115, p=0.004) in series 2. Pairwise comparisons also revealed differences between children with high and average learning readiness in terms of the number of errors in the third series (U=1108, p=0.04), and children with average learning readiness did not differ from the low-ready ones.

In children aged 5-6 years, subgroup differences were obtained for productivity in the second series (H=8.734, p=0.013) and the number of errors in it (H=11.611, p=0.003), as well as for productivity in the first series (H=6.019, p=0.049) and the number of omissions in it (H=6.998, p=0.030). Pairwise comparison of subgroups

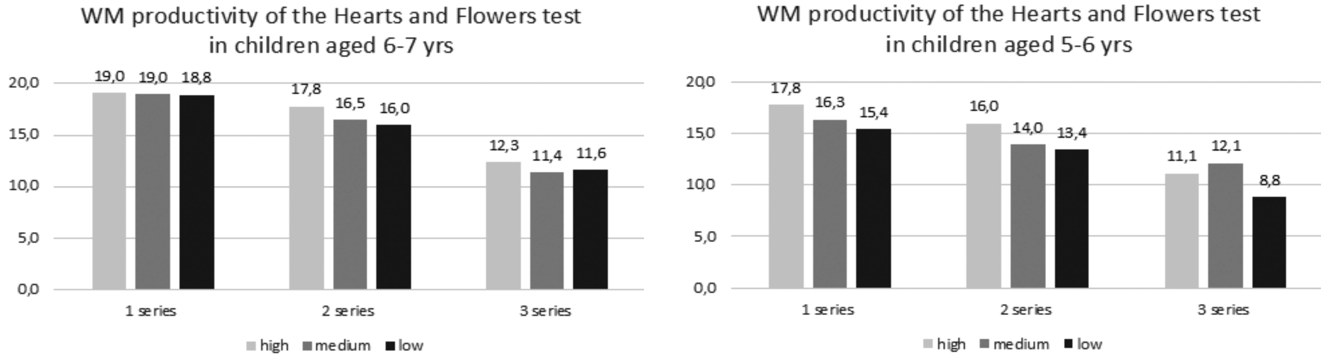

Fig. 4. Productivity of the Hearts and Flowers performance by preschoolers with different degrees of success in learning (designations of subgroups with different success in learning — as in Fig. 1)

at this age did not reveal a difference between children with low and average learning readiness.

Sustained attention in monotonous activities

Age-related changes of the ability to sustain a simple (subtest 1: cross out one type of stimulus) and more complex (subtest 2: cross out two types of stimuli) program during monotonous activity in the *Cancellation Test* was revealed for accuracy (test as a whole: U=3112, p=0.003, subtest 1: U=2910.5, p<0.001, subtest 2: U=2711, p<0.001), the number of incorrect answers in subtest 1 (U=3725, p=0.015), omissions in the entire task (U=1224, p <0.001), as well as in the 1st (U=2994.5, p<0.001) and 2nd (U=2708.5, p<0.001) subtests.

In children aged 6-7 years, subgroup differences associated with the level of learning readiness were found for accuracy (test as a whole: H=10.897, p=0.004; subtest 1: H=9.903, p=0.007, subtest 2: H=8.277, p=0.016), the number of skips (subtest 1: H=10.897, p=0.004; subtest 2: H=8.327, p=0.016), productivity of subtest 1 (H=6.573, p=0.032). Pairwise comparison showed no statistically significant differences between subgroups 2 and 3.

In children aged 5-6 years, the performance of the *Cancellation Test* by the three compared subgroups differed only in terms of the number of incorrect answers in subtest 2 (H=7.471, p=0.024). Pairwise comparison revealed no significant differences between subgroups 1 and 2.

Discussion

The study made it possible to obtain new, previously not described in the specialized literature data on significant *age-related progressive changes* in various EF components in children aged 5—7 years. This was largely facilitated by the combination of the qualitative syndrome analysis, traditional for Russian (Luria) neuropsychology, and more accurate quantitative methods of assessing the individual and age characteristics of children's cognitive activity. With the help of quantitative computer research methods, it was possible to detect an increase in the efficiency of WM (in the *Hands-Legs-Head* and *Corsi Block-tapping Tests*), in the ability to suppress task-irrelevant actions (in the *Hearts and Flowers Task*) and in sustained attention (in the *Cancellation Test*). These data are of high value for further research and practice because the listed indices of quantitative methods can be reasonably used to assess EF in senior preschoolers. Moreover, such assessment implies the acquisition of a large amount of accurate quantitative data that may be validly used to compare children with each other.

In accordance with the main goal of the study, we have managed to show the *relationship between children's EF components (programming, the selective regulation and control of behavior), school readiness, and success in mastering preschool educational programs.* Both 5—6— and 6—7-year-old children with high, medium, and low levels of learning readiness (LR) were found to be significantly different from each other in terms of EF in general–and in terms of programming, regulation and control of behavior in particular. These findings are consistent with the results of previous neuropsychological studies based on the principles of the qualitative syndrome analysis proposed by A.R. Luria [8; 15], as well as with the results of quantitative behavioral studies of EF [26]. It is interesting that 6—7-year-old children with a medium level of LR are similar to their peers with a high LR in terms of EF development. The difference between them concerns only the selective regulation of behavior: children with high learning readiness have fewer manifestations of elementary perseverations and cognitive inertia during task performance. The difference between children with medium and low levels of learning readiness concerns the majority of EF indices. The situation is different for children aged 5—6 years: the difference between participants with high and medium LR levels was observed practically for all EF components. At the same time, the difference between children with high and low LR was shown only for some aspects of the selective regulation of behavior, such as switching difficulty in the form of elementary perseverations. These age-related differences might reflect potential abilities of 5—6-year-old children with low LR, i.e. progressive changes in EF development at older ages, which seems to be a favorable background for the work of teachers and psychologists.

The results of performing *WM* tasks generally indicate low efficiency of WM in both 5—6- and 6—7-year-old children with low LR. It should be noted that the tests showed different sensitivity to the level of learning readiness in two age groups. *The Zoo Task* turned out to be more sensitive in the group of children aged 5—6 years: children with high LR were more productive, made fewer mistakes and corrected their mistakes more often during task performance. More difficult tests based on the 1-back task (*Hands-Legs-Head*) or on a longer sequence of elements (*Corsi Block-tapping Test*) were indicative for children aged 6-7 years: children with high LR memorized longer sequences (average number is 5.4 elements), made fewer mistakes in sequences with 4 and 5 elements (stimuli). It is interesting that in both age groups, children with medium and low levels of LR pressed the element they had already chosen from the sequence in the *Corsi Block-tapping Test* more often. It might be due to the fact that they forgot both the sequence and their own actions. It is worth noting that children aged 6—7 years differ from younger preschoolers not only in the productivity of performing tests but also in the speed of performing WM tasks.

The results of the *Hearts and Flowers Test* showed that the ability to suppress task-irrelevant actions was the most sensitive in relation to the learning readiness index in both age groups: children with high LR showed greater productivity and made fewer mistakes during the performance of subtest 2. This very age period is associated with the vigorous development of inhibitory control [33], which continues to develop during the primary school period [23]. At the same time, the differences between 6—7-year-old children with low and medium levels of LR were also observed during the performance of subtests requiring program switching, which is associated with *cognitive flexibility*; the differences between 5—6-years-old children with high and low LR were observed during the performance of a task requiring the retention of a simple program.

The obtained results indicate the importance of the formation of WM, inhibitory control and cognitive flexibility in senior preschoolers as well as the immaturity of EF components in a significant number of children aged 6—7 years. According to [20], even 7-year-old children have difficulty in performing-tasks that require the retention of several possible characteristics of an object and the switching of attention from one characteristic to another.

The ability to focus *attention on monotonous activities* also appears to be an important LR factor. The results of the Cancellation test differ between children aged 6—7 with a high level of LR and their peers: "successful" children perform this test more accurately and with fewer omissions. At the age of 5-6, children with high LR also make fewer mistakes and correct them more often. At the same time, the ability to detect a mistake and correct it is immature during the primary school period [30].

Conclusion

Academic performance and the effectiveness of almost any behavioral pattern largely depends on the state of executive functions, which provide purposeful activity and the voluntary regulation of behavior, i.e. the ability to be disciplined, to sustain attention for a long time, to switch promptly from one task to another, to control own behavior and its results. This statement is confirmed by numerous neuropsychological and experimental studies [20; 27; 35]. The results of the current study showed how important the formation of EF in senior preschoolers is for learning readiness. Based on our results, the identification of specific EF components (mostly related to school readiness) can contribute to the development of specific evidence-based methods of developmental education and their further inclusion in preschool education programs. This, in turn, can minimize the possible educational, emotional, behavioral and social consequences of children's maladaptation during the preschool and primary school periods.

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Получена 10.08.2022
Принята в печать 25.08.2022

Received 10.08.2022
Accepted 25.08.2022