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INTELLIGENT WRITING ANALYSIS SYSTEM BASED ON TOUCH TRAJECTORIES AND SPLINE FILTERING

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The article presents the development of an intelligent writing analysis system based on touch trajectories and spline filtering methods, focused on the diagnosis and development of graphomotor skills in preschoolers in digital writing learning. The relevance of the study is due to the need for early detection of difficulties in the formation of handwriting and motor coordination using objective digital tools, which is especially important when preparing children for school.

Polygonal approximation, piecewise linear functions, and Catmull-Rom spline interpolation are used as the basis for mathematical analysis of trajectories. An algorithm for processing user input is proposed, which includes the stages of normalization, smoothing, comparison with a digital standard, and error categorization. The system allows you to take into account the specifics of the tool used (finger or stylus), distinguish between types of tasks (lines, continuous and discontinuous letters), as well as analyze spatial and temporal parameters of execution.

As part of the testing, an experimental test of the effectiveness of the Dexterous Fingers application was conducted on a sample of 110 children aged 4-6 years. The results demonstrated a statistically significant improvement in graphomotor skills in the experimental group compared with the control group using paper records ($p < 0.001$). There was an increase in the proportion of children with a high level of skills, a decrease in the error rate and an increase in motivation to learn writing.

The proposed system provides teachers with a tool for automated handwriting analysis, building individual development trajectories and selecting corrective tasks, and also creates the basis for further integration of artificial intelligence technologies into the processes of digital pedagogy and monitoring of children's development.

Keywords: graphomotor skills, preschoolers, digital writing training, Catmull–Roma spline, intelligent handwriting analysis system, digital handwriting diagnostics.

ИНТЕЛЛЕКТУАЛДЫ СЕНСОРЛЫҚ ТРАЕКТОРИЯ ЖӘНЕ СПЛАЙНДЫ СҮЗУ НЕГІЗІНДЕ ЖАЗУДЫ ТАЛДАУ ЖҮЙЕСІ

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Мақалада цифрлық жазуды оқыту жағдайында мектеп жасына дейінгі балаларда графомоторлық дағдыларды диагностикалауға және дамытуға бағытталған сенсорлық траекториялар мен сплайндық сүзу әдістеріне негізделген жазуды талдаудың интеллектуалды жүйесін әзірлеу ұсынылған. Зерттеудің өзектілігі объективті цифрлық құралдардың көмегімен қолжазбаны қалыптастырудағы және моторды үйлестірудегі қиындықтарды ерте анықтау қажеттілігіне байланысты, бұл әсіресе балаларды мектепте оқуға дайындауда өте маңызды.

Траекторияларды Математикалық талдаудың негізі ретінде көпбұрышты жуықтау, бөлік-сызықтық функциялар және катмулл–Ром сплайн интерполяциясы қолданылады. Қалыпқа келтіру, тегістеу, сандық эталонмен салыстыру және қателерді санаттау қадамдарын қамтитын пайдаланушы енгізуін өңдеу алгоритмі ұсынылған. Жүйе қолданылатын құралдың ерекшеліктерін (саусақ немесе қалам) ескеруге, жұмыс түрлерін (сызықтар, үзілмейтін және үзілмейтін әріптер) ажыратуға, кеңістіктік және уақыттық орындалу параметрлерін талдауға мүмкіндік береді.

Апробация аясында 4-6 жастағы 110 баланың үлгісіндегі” епті саусақтар ” қосымшасының тиімділігіне эксперименттік тексеру жүргізілді. Нәтижелер қағаз жазбаларын пайдаланған бақылау тобымен салыстырғанда эксперименттік топта графомоторлық дағдылардың статистикалық маңызды жақсарғанын көрсетті ($p < 0,001$). Дағдылары жоғары балалардың үлесінің артуы, қателіктердің азаюы және жазуды үйренуге деген ынтаның артуы тіркелді.

Ұсынылған жүйе мұғалімдерге қолжазбаны автоматтандырылған талдау, дамудың жеке траекторияларын құру және түзету тапсырмаларын таңдау құралын ұсынады, сонымен қатар жасанды интеллект технологияларын цифрлық педагогика мен балалардың дамуын бақылау процестеріне одан әрі интеграциялау үшін негіз жасайды.

Түйін сөздер: графомоторлық дағдылар, мектеп жасына дейінгі балалар, цифрлық жазуды оқыту, сплайн Кэтмулл–Рома, интеллектуалды қолжазбаны талдау жүйесі, цифрлық қолжазбаны диагностикалау.

ИНТЕЛЛЕКТУАЛЬНАЯ СИСТЕМА АНАЛИЗА ПИСЬМА НА ОСНОВЕ ТРАЕКТОРИЙ КАСАНИЯ И СПЛАЙНОВОЙ ФИЛЬТРАЦИИ

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В статье представлена разработка интеллектуальной системы анализа письма на основе траекторий касания и методов сплайновой фильтрации, ориентированной на диагностику и развитие графомоторных навыков у дошкольников в условиях цифрового обучения письму. Актуальность исследования обусловлена необходимостью раннего выявления трудностей в формировании почерка и моторной координации с помощью объективных цифровых инструментов, что особенно важно при подготовке детей к обучению в школе.

В качестве основы для математического анализа траекторий использованы полигональная аппроксимация, кусочно-линейные функции и интерполяция сплайном Кэтмулл–Рома. Предложен алгоритм обработки пользовательского ввода, включающий этапы нормализации, сглаживания, сопоставления с цифровым эталоном и категоризации ошибок. Система позволяет учитывать специфику используемого инструмента (палец или стилус), различать типы заданий (линии, неразрывные и разрывные буквы), а также анализировать пространственные и временные параметры выполнения.

В рамках апробации была проведена экспериментальная проверка эффективности приложения «Ловкие пальчики» на выборке из 110 детей 4 - 6 лет. Результаты продемонстрировали статистически значимое улучшение графомоторных навыков в экспериментальной группе по сравнению с контрольной, использовавшей бумажные прописи ($p < 0,001$). Зафиксировано увеличение доли детей с высоким уровнем навыков, снижение частоты ошибок и рост мотивации к обучению письму.

Предложенная система предоставляет педагогам инструмент для автоматизированного анализа почерка, построения индивидуальных траекторий развития и подбора корректирующих заданий, а также создает основу для дальнейшей интеграции технологий искусственного интеллекта в процессы цифровой педагогики и мониторинга развития детей.

Ключевые слова: графомоторные навыки, дошкольники, цифровое обучение письму, сплайн Кэтмулл–Рома, интеллектуальная система анализа почерка, цифровая диагностика почерка.

Introduction. Digital writing training and writing analysis on a device is a promising area combining pedagogy, neurotechnology, artificial intelligence and digital interfaces. Digitization of handwriting, digital handwriting diagnostics and the creation of digital standards of letters is one of the urgent interdisciplinary problems of modern education, medicine and criminology.

Much attention in the scientific literature is paid to assessing the development of graphormotor skills of preschoolers using digital devices. The article [1] discusses a tablet-based platform designed to quantify graphomotor skills, focused on both the speed of pen movement and the quality of graphics output. In the article [2], the author studied the development of handwriting and fine motor skills in preschoolers using digital devices and analyzed the influence of handwriting on academic success.

The article [3] discusses an experimental study that tests an innovative tactile device designed to analyze graphomotor performance and coordination of movements in real time. The article [4] discusses an original approach to the diagnosis of graphomotor disorders using an objective analysis of handwritten text on the Internet. It presents the ”Graphomotor and Handwriting Disorders Assessment Scale” (GHDRS), which allows for a detailed assessment of children’ s difficulties with writing. The article [5] discusses the assessment of graphomotor skills in preschoolers and elementary school students using graphic tablets. The article [6] presents an analysis of graphomotor skills using graphic tablets, which focuses on a tool for the preliminary diagnosis of dysgraphy.

The relevance of this study is due to the fact that the development of models, methods and algorithms for early diagnosis of graphomotor skills of preschoolers when learning to write using digital devices will help to timely select corrective tasks, which will have a positive impact on school preparation.

The purpose of the study is to substantiate and test the use of the Catmull-Rom spline for letter spelling analysis in digital writing training, as well as the developed algorithm for error analysis in writing training.

The hypothesis of the study is that the use of an electronic application containing an intelligent writing analysis system ”Dexterous Fingers” will increase the interest of preschoolers in learning to write, and the built-in intelligent writing analysis system will help educators to timely select corrective tasks for preschoolers.

Materials and methods. When digitally teaching preschoolers to write using electronic applications, the images shown in Figure 1 were obtained.

It was revealed that when doing tasks on the tablet, preschoolers make the same mistakes as when doing tasks in the registration form.

The most commonly used tools for solving problems of the accuracy of writing letters and lines of various trajectories on digital devices are [7]:

- Polygonal approximation - dividing the trajectory into segments;

- Piecewise linear model - analysis of shapes and angles in letter elements;

- Splines (for example, Catmull-Rom) - smoothing of trajectories for shape analysis;

- Speed filtering - removing noise, identifying significant phases of movement;

- Similarity metrics: DTW (dynamic Time Alignment), Hausdorff Distance, etc.

In our case, the mathematical apparatus underlying the analysis of the results of drawing a curve on a tablet screen is a polygonal chain (Piecewise linear function). The input data for constructing the trajectory is formed from a sequence of user touch points $S = \{P_0, P_1, \ldots, P_m\}$, where each point $P_j = (x_j, y_j)$ represents coordinates on the touch screen. This sequence of points is used to form a polygonal chain (polyline) [8].

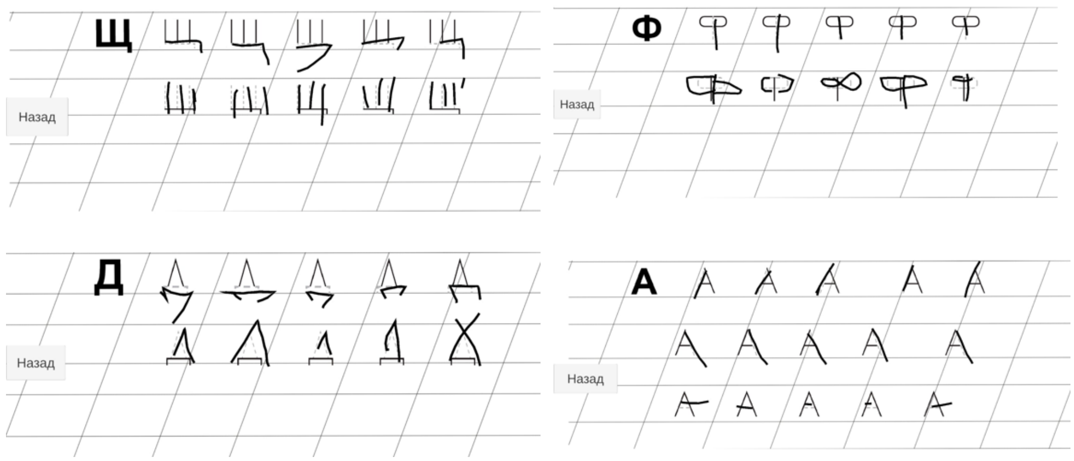

Fig.1 - Examples of completing tasks

A polygonal chain L is defined as the union of straight line segments connecting consecutive points of tangency.

$$L = U_{j=0}^{m-1}\overline{P_j P_{j+1}}. \tag{1}$$

Each segment $\overline{P_j P_{j+1}}$ is a linear function. Thus, the entire trajectory at this stage is a piecewise linear function.

To improve the visual quality and eliminate the sharp angles characteristic of a polygonal chain, smoothing based on the Catmull-Rum spline is used. The Catmull-Roma spline is a type of cubic Hermitian spline that has the property of interpolation, that is, the constructed curve passes through all specified control points.

To construct a segment of the $C_k(t)$ curve of the Catmull-Roma spline between two control points P_k and P_{k+1} (where P_k are the points of the original polygonal chain), four consecutive control points are used: P_{k-1}, P_k, P_{k+1}, P_{k+2}. The parameter t varies from 0 to 1. The segment of the curve C_k (t) for t [0,1] can be represented in the following matrix form (2):

$$C_k(t) = [t^3 t^2 t 1]\, M_{CR} \begin{bmatrix} P_{k-1} \\ P_k \\ P_{k+1} \\ P_{k+2} \end{bmatrix} \tag{2}$$

where M_{CR} is the Catmull-Rum basis matrix:

$$M_{CR} = \frac{1}{2}\begin{bmatrix} -1 & 3 & -3 & 1 \\ 2 & -5 & 4 & -1 \\ -1 & 0 & 1 & 0 \\ 0 & 2 & 0 & 0 \end{bmatrix} \tag{3}$$

This shape corresponds to the standard Catmull-Roma spline with a tension parameter τ=0.5, which provides a so-called ”centripetal” spline that copes well with possible self-intersections and sharp angles with uneven point distribution.

For the extreme segments of the polygonal chain (initial and final), special processing is required, for example, by duplicating the extreme points ($P_{-1} = P_0$ и $P_{m+1} = P_m$) in order to provide a sufficient number of control points for the formula [9].

Using the Catmull-Rom spline allows you to achieve continuity of the curve at the points where the segments connect (with the possible exception of the start and end points of the entire curve), which ensures a smooth transition between segments and eliminates visual kinks. This approach effectively combines the accuracy of the basic polygonal chain approximation with the aesthetics of a smooth curve without the need for additional manual correction [10].

A system of parameters reflecting the key characteristics of the writing process has been developed for the quantitative and qualitative assessment of a child' s graphomotor skills. These parameters allow you to capture and interpret the features of the outline of the lines, providing an objective diagnosis of deviations and developmental dynamics. The analysis methods are based on mathematical representations of trajectories and consideration of time characteristics. Table 1 shows the key parameters for analyzing a letter based on sources [11-15].

To analyze the quality of material assimilation, it is advisable to use a two-way analysis of variance, the purpose of which is to assess the level of graphomotor skills relative to the group and time parameters.

The hypotheses tested within the study are:

Main effect of group: Is there a significant difference in results between the experimental and control groups (regardless of time)?

Main effect of time: Is there a significant difference in results "before" and "after" (regardless of group)?

Interaction of group and time: The improvement in results in the experimental group is significantly greater than in the control group. This hypothesis is key to proving the effectiveness of your application. If you find a significant interaction, it will be direct evidence that the use of your application led to an improvement in skills.

As a result of processing the experimental data, the following conclusions were obtained:

Significant main effect of "time" ($p<0.05$): This means that, overall, all children' s skills improved. This is an expected result, as children grow and develop.

Insignificant main effect of "group" ($p>0.05$): This may indicate that at the start of the experiment, the groups were approximately the same in terms of skill level, which is a good sign of proper randomization.

Significant interaction of "group x time" ($p<0.001$): This result is the most important. It shows that the positive change in the experimental group was statistically significantly greater than in the control group, which confirms the effectiveness of your application.

Table 1 - Key parameters for letter analysis

Parameter	Analysis method	Characteristic of the measured parameter
Curvature and angles of rotation	Polygonal chain	Frequency and sharpness of direction changes
Length and regularity of segments	Piecewise linear function	The stability of the writing pace
Smoothness and continuity	Catmull Spline-Roma	Assessment of motor coordination, detection of tremors
Writing speed	All methods (by point time)	Associated with confidence and experience
Fluctuations and jerks	Spline + velocity filtering	Indicators of motor disorders or overwork

A comparative analysis of the characteristics of various input methods makes it possible to increase the accuracy of interpretation of graphomotor data and adapt processing algorithms taking into account the specifics of the device. Special attention is paid to the differences between the stylus and the finger as the main tools for user interaction with the screen. These differences affect both the physical and technical parameters (accuracy, sensitivity, pressure support) and the shape features, which affects the choice of filtering, smoothing, and interpretation methods. Table 2 shows the key differences between a stylus and a finger, which are taken into account in the analysis process based on sources [16-19].

Table 2 - Key differences between a stylus and a finger

Parameter	Stylus	Finger
Positioning accuracy	High (up to ~0.1mm)	Medium/Low (~2-4 mm)
Sensor frequency	Higher (60-240 Hz)	No Lower (30-60 Hz)
Pressure support	Yes (for many models)	No
The presence of tilt (tilt)	Yes (for some models)	No
Line thickness	Variable (depending on pressure)	Static or severely limited
The naturalness of writing	Closer to the paper	Less controlled, more rounded

When analyzing a curve drawn with a finger, the permissible deviations increase when compared with the reference. For a stylus, a lower error is allowed, and the accuracy requirements are higher.

To analyze the spelling of letters, it is necessary to create a digital reference letter or font. For example, for the letter ”L” it can be three points: upper, lower center, upper right. For more complex curves, more points will be needed to adequately describe the shape. Letter standards, including their coordinate representation and metadata, should be stored in the application as JSON or XML files (Figure 2).


```
"letter": "A",
"strokes": [
  {
    "order": 1,
    "points": [ {"x": 50, "y": 10}, {"x": 20, "y": 90}, {"x"
      : 80, "y": 90} ],
    "direction_start_point_index": 0,
    "direction_end_point_index": 2
  },
  {
    "order": 2,
    "points": [ {"x": 35, "y": 50}, {"x": 65, "y": 50} ],
    "direction_start_point_index": 0,
    "direction_end_point_index": 1
  }
],
"total_strokes": 2
```


Fig.2 - An example of a letter structure in JSON

For an objective assessment of graphomotor skills, the algorithm for error analysis in writing training presented in Figure 3 provides a comprehensive error analysis when the user performs graphomotor tasks in the Dexterous Fingers electronic application. The process begins with receiving input data and ends with the formation of an assessment and feedback.

A: The beginning. This block represents the entry point to the error analysis algorithm.

B: Data from the user (points, events). At this stage, the system receives primary data about user actions. This data includes a sequence of coordinate points (x, y) recorded when touching the touchscreen, timestamps for each point, and the type of accompanying event (for example, the beginning of the touch is ACTION_DOWN, movement is ACTION_MOVE, and the end of the touch is ACTION_UP). This information forms the ”raw” trail left by the user.

C: A reference for standard assignments/letters.

In parallel with user input, the system accesses its database to download a reference representation of the current task. The standard is a digital model of perfect execution. It can be a trajectory for a simple graphic element (”Track”), the shape of an unbroken letter, or a set of strokes indicating their characteristics (shape, order, direction) for discontinuous letters. Benchmarks are usually stored in a structured format (for example, JSON) and contain all the necessary information for comparison.

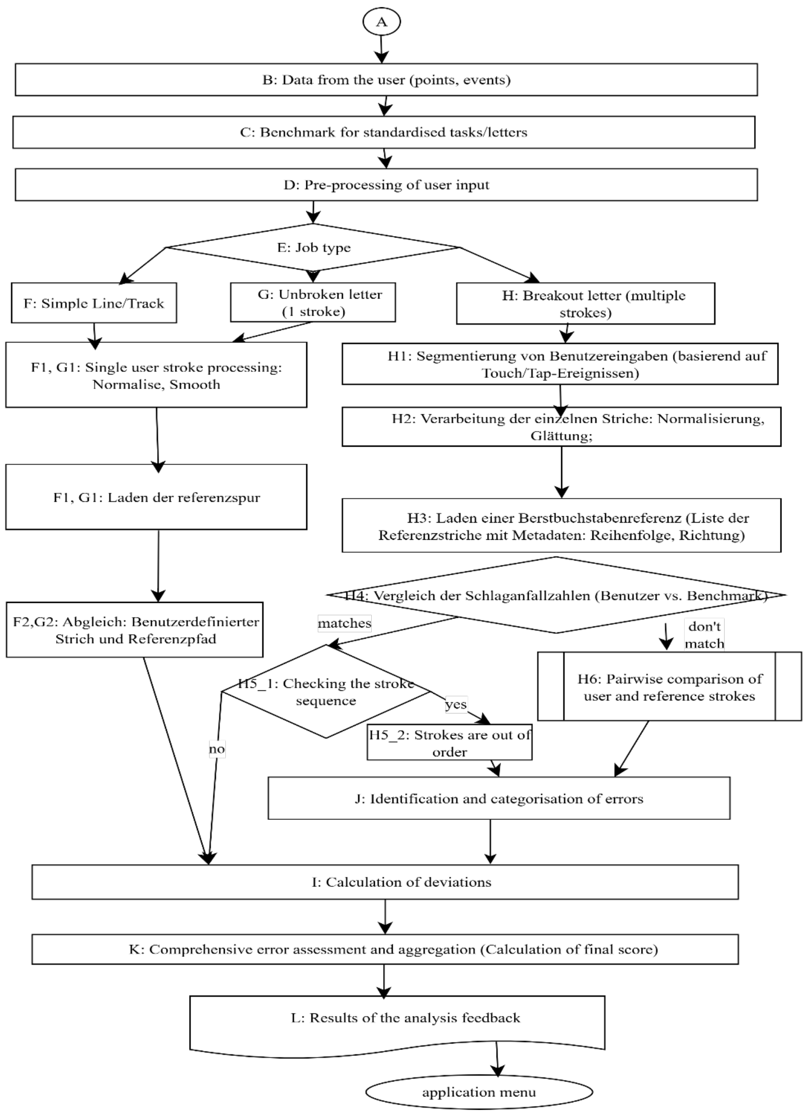

Fig.3 - Error analysis algorithm for learning writing

D: Preprocessing user input.

Before the main analysis, the user’ s ”raw” data goes through a preprocessing stage. This may include:

– determining the type of input tool (stylus or finger, which may affect the thresholds for analysis),

– filtering noise (for example, removing points that are too close due to shaking),

– preparing data for further segmentation and analysis.

E: The type of task. This is a key decision-making node, where the algorithm determines the nature of the current task in order to choose the appropriate analysis path. There are three main types of tasks:

F: A simple line/Track (for example, tracing straight, wavy lines).

G: An unbroken letter (1 stroke) (letters that are written in one continuous motion).

H: A discontinuous letter (several strokes) (letters consisting of two or more separate elements/strokes).

Processing for paths F (Simple Line/Track) and G (Continuous Letter): Since both of these types of tasks usually involve a single continuous stroke on the user’ s part, their initial processing is similar:

F1, G1 (Step 1): Processing a single user stroke: Normalization, Smoothing. The custom stroke is first normalized – its size and position are adjusted to the standard form so that the comparison with the reference is invariant to the scale and place of writing. Then the normalized stroke is smoothed, for example, using the Catmull-Rum spline, to eliminate small vibrations and obtain a clearer representation of the intended trajectory.

F1, G1 (Step 2): Loading the reference path. The corresponding reference for a given line or continuous letter is extracted.

F2, G2: Matching a custom stroke with a reference path. The processed custom stroke is directly compared with the reference path. The results of this comparison (data on similarities and differences) are transferred to the general deviation calculation unit (I).

Processing for the path H (Discontinuous letter):

This path is designed to analyze letters consisting of several separate strokes, and involves more complex logic.:

H1: Segmentation of user input into strokes. All user input for a given letter is divided into separate strokes. Stroke boundaries are used for events when the tool is lifted off the screen (ACTION_UP) and then touched again (ACTION_DOWN).

H2: Processing each user stroke: Normalization, Smoothing. Each identified custom stroke undergoes an individual normalization and smoothing procedure, similar to that described in F1, G1 (Step 1).

H3: Loading the broken letter reference. A reference is loaded, which for such letters is a list of individual reference strokes, including metadata about their correct execution order and, possibly, direction.

H4: Comparing the number of strokes (user and reference).

If the number of strokes drawn by the user does not match the reference one, the algorithm proceeds according to the scheme to Block H6: Step-by-step comparison of the user’ s strokes and the reference one. This implies an attempt to perform an analysis based on the available data, perhaps to identify missing or superfluous strokes, or for the best possible comparison. The results of such a comparison are then sent to the error identification unit (J).

If the number of strokes matches, the check continues in Block H5_1: Checking the sequence of strokes. It analyzes whether the time order of custom strokes corresponds to the prescribed order in the reference.

If the sequence is correct (”yes”), then the analysis process proceeds to Block I: Calculation of deviations, where a detailed comparison of each pair of matched strokes (user and reference) will be carried out.

If the sequence is broken (”no”), this is recorded as an error in Block H5_2: The stroke order is broken, and information about this error is transmitted directly to Block J: Error identification and categorization.

General stages of analysis (Blocks I, J, K, L):

After the custom strokes (or stroke) are compared with the reference ones (for paths F, G, or a successful branch H), or if the analysis has moved on to processing structural errors (from H4/H6, H5_2), the following general steps are performed:

I: Calculation of deviations. This block quantifies the differences between the actual spelling and the reference for the compared strokes. Metrics are calculated, such as: the average and maximum distance from the points of the user curve to the reference line, the difference in angles between segments, deviations in the starting/ending points of strokes, as well as possibly more complex metrics of curve similarity (for example, the Frechet distance). For multi-stroke letters, the relative position and proportions of strokes can also be analyzed here.

J: Identification and categorization of errors. Based on the calculated deviations (from block I) and information about structural errors (for example, an incorrect number of strokes from H4/H6 or a violation of the order from H5_2), the algorithm identifies and classifies specific types of errors. Examples of categories: significant distortion of the shape, going beyond the contour, incorrect direction of movement, incorrect number or order of elements, violation of proportions.

K: Comprehensive assessment and aggregation of errors (Calculation of ErrorCount / Final Score). All identified errors and their severity are aggregated into a single comprehensive assessment. This can be a numerical indicator, such as ErrorCount (the total number of errors, as in the user’ s CSV file), or the percentage of accuracy (for example, calculated using the formula P = (1 - E/n) × 100%), or a more detailed error profile. At this stage, weights can be applied for different types of errors depending on their criticality.L: Analysis results / Feedback. The final assessment and information about specific errors (possibly with recommendations for their correction) are generated to provide feedback to the user directly in the application, as well as for saving and subsequent use in reports for parents and teachers.

Based on the types and number of errors, the application can give the user specific hints (for example, ”Start this line a little higher”, ”Lead the line more smoothly”, ”You missed one element”).

Results and discussion. The results of a randomized controlled trial of 110 children aged 4-6 years in kindergartens in Petropavlovsk and the North Kazakhstan region were used as an empirical basis to confirm the effectiveness of an electronic application containing an intelligent writing analysis system ”Dexterous Fingers”. The children were randomly divided into two groups: an experimental group (using the app) and a control group (performing tasks on paper). The level of graphomotor skills development in 4-6-year-olds before the introduction of the Dexterous Fingers electronic application is shown in Table 3.

Table 3 - The level of graphomotor skills development in children aged 4-6 years (before the introduction of the Dexterous Fingers electronic application)

Groups	Level		
	high	medium	low
experimental (54 children)	8 (14%)	23 (43%)	23 (43%)
control (56 children)	8 (14%)	21 (38%)	27 (48%)

For classes on the development of writing and graphomotor skills in the experimental group, an electronic application containing an intelligent writing analysis system ”Dexterous Fingers” was used. At the end of each lesson, the teacher in the experimental group generated an Excel report file on the quality of tasks performed by preschoolers. An example of the report is shown in Figure 4. The report shows how many children from the group completed the task correctly and how many children made mistakes. When you click on the ”NAME” link, the teacher receives a list of children.

	A	B	C	D	E	F
1	Task	Writing a letter		"A"		
2						
3	You did it right			7		Name
4						
5	Made mistakes			21		Name
6						
7	Failed to comply			0		Name
8						
9	Total			28		
10						

Fig.4 - Task completion report for the tutor

	A	B	C	D
1	Letter	"A"		
2				
3	Done	80	%	Mistakes
4				
5	Letter	"Б"		
6				
7	Done	100	%	Mistakes
8				
9	Letter	"Г"		
10				
11	Done	100	%	Mistakes
12				
13	Letter	"Д"		
14				
15	Done	30	%	Mistakes

Fig.5 - Individual report on the progress of writing letters

A file is also generated for each child in accordance with Figure 5, which records the progress of writing letters in percentage terms. The percentage of completion is calculated according to the error analysis algorithm. A database of mistakes is formed for each letter, so that in the future the teacher can select corrective tasks.

During the prescribed period, the children systematically completed tasks aimed at developing graphomotor skills, taking into account the recommendations of the Dexterous Fingers electronic application. The results of the survey are presented in Table 4 and Figure 6.

Table 4 shows that the experimental group is characterized by better development of graphic skills: the majority of children are at intermediate and high levels (79%), while in the control group almost half of the children have a low level (45%).

Table 4 - The level of graphomotor skills development in 4-6-year-olds (after the introduction of the Dexterous Fingers electronic application)

Groups	**Level**		
	high	medium	low
experimental (54 children)	25 (46%)	18 (33%)	11 (21%)
control (56 children)	10 (18%)	21 (37%)	25 (45%)

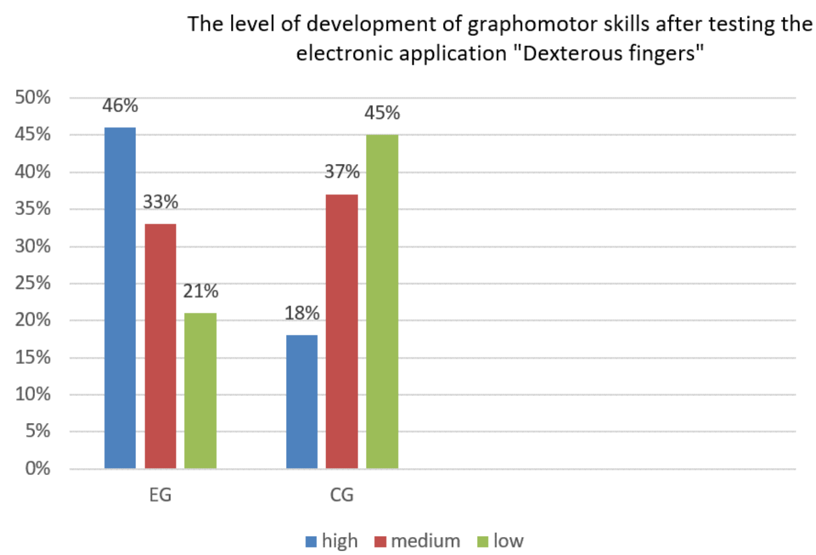

Fig.6 - The level of development of graphomotor skills in children aged 4-6 years after testing the electronic application ”Dexterous fingers”

Statistical analysis showed no differences between the groups at the entrance and a significant improvement in the results in the experimental group after using the application, especially in the age subgroups of 4-5 and 5-6 years ($p < 0.001$). Improved accuracy, smoothness and coordination of movements were recorded. Qualitative observations by teachers confirmed the high level of motivation and involvement of children in working with the digital tool.

Conclusions. The conducted research has confirmed the effectiveness of the use of intelligent systems in digital writing teaching among preschoolers. The developed system for analyzing writing trajectories based on polygonal approximation, piecewise linear models and the Catmull-Rom spline provides accurate and visual diagnostics of graphomotor skills. Unlike traditional approaches, the proposed algorithm allows taking into account the individual characteristics of the tasks, automatically identifying typical errors and forming feedback for both the child and the teacher.

The results of the approbation conducted in preschool institutions of the North Kazakhstan region showed a statistically significant improvement in graphomotor skills in children using the Dexterous Fingers electronic application. Improving the accuracy of movements, improving coordination, reducing the number of typical errors and increasing motivation to learn to write indicate the high practical importance of the developed system.

The introduction of such a digital tool into educational practice allows not only to personalize learning, but also lays the foundation for the formation of a flexible digital environment for diagnosis and correction. In the future, it is possible to integrate this system with adaptive learning platforms, develop automated classification of writing disorders, and expand functionality through neural network data analysis methods.

Based on the analysis, this study successfully demonstrates the effectiveness of the ”Dexterous Fingers” intelligent system in developing graphomotor skills in preschoolers. A two-way analysis of variance confirmed that the application’ s use resulted in a statistically significant improvement in children’ s skills. While a general improvement in skills was observed over time in all participants, the most crucial finding was the highly significant interaction between group and time. This result confirms that the positive change in the experimental group was substantially greater than in the control group, establishing the application as the primary driver of the observed progress. Based on these findings, we recommend integrating the system into early childhood educational programs as an objective and effective tool for diagnosis and correction, with a view to exploring the potential of neural networks in future research to further enhance its diagnostic accuracy and adaptability.

Thus, the system of intellectual analysis of writing presented in the work can be used as an effective diagnostic and developmental tool in the practice of preschool education and primary education.

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Note: *During the preparation of the article, artificial intelligence tools were used, including the GPT-4 language model provided by OpenAI. The model was used exclusively to assist in text editing and structuring scientific presentation [20].*

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