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DESIGNING AN INTELLIGENT SYSTEM FOR PERSONALIZED DEVELOPMENT OF GRAPHOMOTOR SKILLS IN PRESCHOOL CHILDREN BASED ON ANALYSIS OF DEVIATIONS FROM THE STANDARD

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This study's object is the process that forms and develops graphomotor skills in preschool children by using digital educational technologies. Graphomotor skills, which are a subset of fine motor skills, are critical for the development of writing and academic success, especially in the early stages of schooling. The problem relates to the lack of individualization, objective diagnostics, and adaptive correction in conventional methods. When teaching using traditional methodology, handwriting analysis is often subjective while the process of skill formation is complex and requires the integration of cognitive, motor, and motivational factors.

The electronic application "Dexterous Fingers" uses mathematical modeling, in particular piecewise linear approximation followed by smoothing with Catmull-Rom splines, for automatic and objective analysis of writing trajectories in real time. This makes it possible not only to quantitatively and qualitatively assess deviations from reference samples but also generate personalized recommendations and tasks. The electronic application maintains a high level of motivation and involvement of children due to interactive and game elements, and ensures the availability of specialized assistance, especially in resource-limited settings. The application includes an effective monitoring and reporting system, providing parents and teachers with detailed data on the child's progress.

The results after the implementation of the application demonstrate a pronounced positive trend in children in the experimental group. The proportion of children with a high level of graphomotor skills increased to 46%, while the number of children with a low level decreased to 21%

Keywords: personalized learning, graphomotor skills, digital diagnostics, piecewise linear function, automation of learning, electronic application, graphomotorics

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1. Introduction

One of the important problems of modern preschool education is the task of developing graphomotor skills in preschoolers.

Graphomotor skills are a subset of fine motor skills specifically related to the ability to perform writing tasks, covering the coordination of cognitive processes with hand and finger movements to create graphic images.

The formation of graphomotor skills is a complex, step-by-step process that requires systematic support. Early detection of difficulties and targeted activities help prevent writing disorders and build confidence in the child's own abilities. Graphomotor skills are not just writing, but the basis for academic success, self-expression, and independence of the child [1].

For successful writing, gradual training adapted to the child's level of development is important. Interventions should be multi-level: from strengthening motor skills to teaching a sequence of movements. Support from teachers and parents is critical.

Electronic applications are used to implement the task of developing graphomotor skills in preschoolers. The advantage of using electronic applications is the ability to track the child's development progress, select exercises, and track writing with a stylus and finger. Modern electronic applications store data on development and progress in databases, owing to which it is possible to analyze and adjust the child's development trajectory at any time. However, despite the abundance of educational applications, there is a lack of specialized solutions aimed at developing graphomotor skills taking into account age and regional characteristics. A small number of applications simultaneously support several languages, for example, English, Kazakh, Russian. Therefore, the relevance of our topic is due to several key factors:

1. Insufficient development of graphomotor skills in preschool children is a serious problem that directly affects the success of their adaptation and education in primary school. This is especially important in the context of early schooling, such as in the Republic of Kazakhstan, where children go to first grade at the age of six.

2. Modern children actively interact with digital devices from an early age. This opens up opportunities for using electronic applications as effective learning tools that complement conventional methods.

3. There is a need for tools that make it possible not only to train writing skills but also objectively assess their development, identify individual difficulties of the child, and track their progress. In the modern context of education, a personalized approach is needed that takes into account the individual pace and characteristics of the child, which could significantly improve the effectiveness of learning.

2. Literature review and problem statement

Works [2–4] emphasize that successful mastery of writing depends not only on motor components but also on the development of executive functions, attention, and motivation. The authors note the significant role of visual-motor integration, fine motor skills of the hand, and even emotional factors that affect the legibility and speed of writing. Moreover, studies show that deviations from standard development (25% below the age norm) are associated with cognitive and sensorimotor deficits, which requires early diagnosis [5]. However, it should be emphasized that these works do not address the use of modern information technologies. They form an important understanding of the nature of graphomotor difficulties but do not offer digital tools for their assessment and correction.

It should be noted that artificial intelligence (AI)-supported handwriting analysis is becoming a promising tool for the early detection of specific learning disabilities such as dysgraphia and dyslexia. These systems can analyze subtle physical differences in handwriting, including writing speed, pressure, pen movement, letter size and spacing, as well as spelling problems and letter formation errors, to identify indicators of these conditions [6].

Study [7] has shown that early writing is closely related to writing speed, handwriting legibility, and spelling accuracy. Slower writing in primary school is associated with lower legibility but better spelling, suggesting the importance of a balance between speed and quality. These findings highlight the need for a phased approach to handwriting development with an emphasis on graphomotor and spelling skills in primary school. This creates a conceptual conundrum: how to reconcile population variation (useful for initial diagnosis and identification of significant delays) with individual progress and optimal tempo (necessary for truly personalized intervention). An intelligent system should use population norms for initial screening but then adapt its analysis of "outliers" to each child's unique learning trajectory, providing dynamic and context-sensitive feedback rather than just a binary pass/fail assessment.

Study [8] found that legibility and fluency of handwriting in children are closely related to spelling skills, graphomotor skills, and selective attention. Legibility of handwriting depends more on graphomotor and spelling skills, while fluency depends on the level of attention. These results highlight the importance of an integrated approach to writing development that includes training in motor skills, spelling, and cognitive functions. However, the cited paper does not consider how modern information technologies can support the development of these skills. The authors only describe behavioral and cognitive patterns without offering digital tools for handwriting assessment or correction. Therefore, they are useful as a fundamental base but do not answer the question about the limitations of information technologies in personalizing writing development.

Study [9] analyzed the role of handwriting and spelling skills in the formation of written speech in older preschool children. The data indicate a statistically significant influence of graphomotor skills on the structural characteristics of written statements, while spelling has a more pronounced effect on the lexical and grammatical design of the text. The most significant predictor of the number of written words and the coherence of the text is the legibility of handwriting. The authors emphasize the need to integrate the development of graphomotor and spelling skills into the early teaching of written speech. From the point of view of the application of IT solutions, these conclusions remain limited since they do not consider the possibilities of digital diagnostics or skill training using interactive applications, tablets, or AI handwriting analyzers.

In work [10], it was found that spelling and writing speed continue to evolve until the fifth grade, while the quality of handwriting stabilizes already in the second. In younger students, the graphic complexity of words significantly affects all aspects of writing, and in older students, a compromise is observed: high writing speed is associated with better spelling but reduces the quality of handwriting. These results emphasize the need for a step-by-step and differentiated approach to the formation of transcription skills in primary school. The problem of the study is the insufficient empirical base reflecting the associated development of spelling, speed, and quality of writing in the dynamics over the entire period of primary education.

A more technologically oriented study is reported in [11], which analyzes the development of intelligent tutoring systems (ITS). The authors describe the evolution from simple programs to adaptive platforms with elements of artificial intelligence that can personalize learning through knowledge modules, a student model, and dialogue. At the same time, ethical and organizational risks are emphasized, including data privacy, algorithmic bias, and a decrease in critical thinking skills due to excessive dependence on AI. In the context of graphomotor skills, these findings mean that even if an ITS platform can adapt tasks to a child, it will not replace pedagogical support and motivation. The work describes architecture but does not take into account motor features. There is no analysis of the tactile and emotional components of learning to write.

The market for electronic applications for children is one of the fastest growing markets. It includes games, educational applications, educational platforms, interactive books, and multimedia programs. These products are targeted at different age groups and are aimed at developing cognitive, motor, language, and social skills in children.

The demand for quality digital content for children is constantly growing, which is facilitated by the widespread use of mobile devices, the increase in digital literacy of parents, and the interest of educational institutions in using modern technologies in teaching. Developers strive to take into account the age characteristics of the audience, creating bright, intuitive interfaces, gamification elements, and adaptive methods for presenting information.

At the same time, the market faces a number of challenges such as the need to ensure data security, limit screen time, and control over content quality. All this makes the segment of apps for children not only promising but also requiring a responsible approach from developers and regulators. The main means are digital platforms such as graphics tablets, digital notepads, and styluses, which are increasingly used to capture rich, dynamic handwriting data. Unlike conventional paper-based methods, these tools can record various parameters of the writing process, including pen pressure, timestamps, precise pen movements, and orientation. This digital capture capability offers significant advantages in terms of accuracy and efficiency for handwriting analysis compared to manual assessment methods [6]. Mobile apps are also becoming universal platforms for the development of graphomotor skills, providing interactive environments for practice and assessment [12]. Digital tools fundamentally change the approach to handwriting analysis, moving from a static assessment of the finished product to a dynamic capture of the writing process in real time. This provides richer data for deviation analysis and immediate feedback. Conventional handwriting analysis is often based on subjective assessment or general criteria. However, online handwriting analysis makes it possible to use parameters such as pressure, timestamps, and pen movements, which significantly increases the effectiveness of analysis [6].

AI models can detect motor difficulties by analyzing writing speed, pressure, and pen movements, as well as examine visual aspects of handwriting, including letter size and spacing. The researchers proposed an innovative system for analyzing children's handwriting using artificial intelligence for the early detection of dyslexia and dysgraphia. Study [13] highlights the potential of AI as an effective tool for early screening of writing and reading disorders, which can improve the accuracy of diagnosis and timeliness of pedagogical interventions. Digital pens also expand the capabilities of the writing process [14]. This shift from analyzing a static final product to capturing the dynamic writing process in real time provides a much more comprehensive data set. This richer data is necessary to accurately identify deviations, understand how an error occurs, and provide immediate, targeted feedback, which is essential for personalized learning. AI-enabled interventions demonstrate measurable effectiveness in improving graphomotor skills, especially in children with developmental disabilities, and offer a scalable solution to increase the availability of specialized therapy. Randomized controlled trials, such as the one described in [15], provide compelling empirical evidence for the effectiveness of AI-enabled occupational therapy programs, demonstrating statistically significant improvements across multiple handwriting parameters. This establishes a direct cause-and-effect relationship: AI intervention leads to improvements in graphomotor skills. Furthermore, it is highlighted that AI-assisted handwriting analysis can serve as a solution to the shortage of speech and occupational therapists who are critical specialists for the diagnosis and treatment of such conditions [13].

This means that AI not only makes interventions more effective but also significantly increases their availability and reach, especially in under-resourced areas. This dual benefit of efficiency and scalability makes AI a transformative force in the development of graphomotor skills. It is worth noting that for preschool-aged children, mobile applications are of great importance in the development of skills, including graphomotor ones. As noted by researchers, mobile applications are becoming effective tools for the development of graphomotor skills in preschoolers. For example, the electronic application "Dexterous Fingers" showed significant improvement in graphomotor abilities in preschoolers in a randomized controlled trial [12].

Such applications use interactive elements and game mechanics to make the learning process engaging and motivating [16]. Haptic feedback systems represent another innovative approach. A pilot study showed that an innovative haptic device providing haptic feedback can effectively help preschool-aged children develop graphomotor skills. Children demonstrated high engagement with the haptic device, completing more repetitions than with conventional tablets, while the quality of their tracings was comparable [17]. Augmented reality (AR) media have also shown a very positive impact on fine motor development in early childhood, offering an attractive and motivating learning experience [18]. The integration of interactive elements, gamification, and haptic feedback into digital tools significantly increases children's engagement, which is a critical factor in the effectiveness and sustainability of personalized graphomotor skill development systems. The success of digital interventions depends not only on the underlying algorithms but also on how they are delivered to the child. The use of the electronic application "Dexterous Fingers" resulted in significant improvements in graphomotor skills [12]. Tactile devices lead to high engagement and enthusiasm of children, while providing comparable improvements in skills [17]. The applications described in [16] include interactive elements and game mechanics such as achievement and reward systems, progress statistics, and leaderboards. This clearly establishes a cause and effect relationship: engaging and motivating design elements lead to increased child engagement and sustainable practice, which in turn contributes to the effectiveness and long-term success of personalized intervention. This highlights the importance of user experience and motivational design in intelligent systems for young children. Digital technologies such as graphics tablets and styluses are transforming handwriting analysis from static assessment to dynamic data capture. This allows for more accurate quantification of deviations using mathematical models such as splines and AI algorithms. These technologies provide immediate feedback and increase child engagement through interactive and tactile elements. Paper [10] reports a fuzzy model for assessing preschoolers' competencies and a study of graphomotor skills using graphic tablets, which lays the foundation for designing holistic intelligent systems. The research demonstrates how effective data management and consideration of subjectivity in assessments can be applied to create more accurate and personalized educational solutions.

Analysis of modern research reveals that digital solutions – mobile applications, interactive tablets, AI handwriting analysis – have significant potential. The authors of work [19] present an overview of twenty years of experience in using digital interventions for dysgraphia. The authors note that AI-supported programs do speed up diagnostics and help develop individual learning paths. However, their use raises issues of scalability, cultural adaptation, and sustainability of results, which limits the possibility of their use in mass preschool education. The study conducted in preschool organizations [20] reports the development of an ontological model for automating the processing of questionnaire data, which makes it possible to formalize the structure of concepts and relationships used in surveys. The proposed approach ensures intelligent interpretation and unification of responses, reducing the influence of the subjective factor in the analysis of results. The results of testing the model confirm its effectiveness in accelerating processing, increasing the accuracy of analysis and adaptation to various research tasks in the social and educational spheres. The study does not present a substantiated methodology for validating the model, which makes it difficult to assess its sustainability when transferring to new samples; the mechanism of its automatic adaptation to changing data is also not disclosed. There is no comparative analysis with alternative approaches to processing questionnaire information, including methods of statistical content analysis, and potential risks of distortion of results in conditions of semantic ambiguity of answers are not considered. Based on study [21] of the information and educational environment in preschool organizations, a fuzzy model for managing the process of forming IT competencies was proposed, based on the use of fuzzy logic and systems analysis methods. The model makes it possible to take into account qualitative and quantitative parameters of the educational process, including the level of knowledge acquisition, practical skills, and individual trajectories of 5-6-year-old children in preschool organizations. The results of testing demonstrate that the use of a fuzzy model contributes to a more accurate diagnosis of the level of competence and increases the efficiency of managing educational programs in the field of ICT. The researchers propose a promising fuzzy model for managing IT competencies of preschoolers, but the research problem requires additional theoretical specification and empirical validation. The model is characterized by insufficient operationalization of key concepts, lack of consideration of the dynamics of IT competencies development in ontogenesis, a lack of pedagogically oriented interpretation of results for practical application, as well as potential excessive complexity, which complicates its implementation in the educational practice of preschool organizations.

Paper [22] describes the development and testing of a model for managing information processes in the digital educational environment of preschool organizations, aimed at personalizing educational routes. The proposed model provides automated collection, analysis, and visualization of data on child development, which helps improve the efficiency of pedagogical support and management decisions. The results demonstrate a significant reduction in the time required to adapt the educational programs and confirm the practical applicability of the model in preschool education. To increase its applied value, the model requires revision and adaptation to the various capabilities of preschool organizations.

Particular attention in modern education is paid to automated systems based on artificial intelligence. Paper [23] describes the architecture of AI models that analyze writing speed, pressure, and pen trajectories for early detection of dysgraphia. The authors emphasize that despite the accuracy of the algorithms, the problem is the insufficient validation of such systems for preschool age, as well as the high cost and ethical issues of data confidentiality. In addition, such systems focus on motor parameters but do not take into account the motivational and cognitive aspects of writing development.

Study [24] confirms that one of the key areas of digital transformation of education is EdTech – a set of technologies aimed at creating an interactive and personalized educational environment. Particular attention in this context is paid to children's electronic applications as the most dynamically developing segment. The use of EdTech solutions in children's electronic applications allows for the implementation of the principles of personalization, taking into account age and cognitive characteristics, as well as the formation of sustainable motivation for learning through game and visual elements. The study reflects the relevance of EdTech in preschool education. However, it requires clarification of concepts, an empirical basis and practical applicability to increase scientific and applied value.

The authors of work [25] conducted a large-scale study on the role of the educational environment and family context in the development of graphomotor skills in preschool children, with more than 250 children aged 4 to 6 years participating. The study analyzed the following parameters: the quality of the home educational environment; the nature of pedagogical support in preschool institutions; the level of family involvement in the educational process. The key conclusion of the study is that up to 43% of the variability in the development of graphomotor skills is explained not by the use of technology but by home and pedagogical conditions. The authors note that even children with access to modern digital tools (tablets, educational applications) demonstrated higher results only in cases where these technologies were used in combination with the support of parents and teachers. The study emphasizes the importance of the family and pedagogical environment but does not specify in detail the assessment methods and characteristics of the sample. It is not disclosed which digital tools were used and how external factors were taken into account. The findings are compelling but require more rigorous methodological detailing.

Thus, even the most advanced digital solutions are unable to compensate for the lack of social and motivational support. This highlights the need for a hybrid approach, in which digital tools are not used autonomously but as a supplement to traditional teaching methods with active adult participation.

The results of study [26] confirm the high efficiency and applicability of digital tools (smart pens and tablets with applications) for objective assessment of writing skills in primary school children. Parameters such as time in the air and pen tilt variability demonstrated the ability to accurately differentiate between levels of handwriting development. The tools demonstrated high ease of use and acceptability, opening up prospects for their implementation in the practice of early diagnosis of writing disorders in educational and clinical environments, including distance formats. The paper reports the results of a study of digital tools for assessing handwriting in children. It is shown that parameters such as tempo, pressure, pen micromovements, and letter spacing can be accurately recorded using digital tablets and electronic pens. However, there are unresolved issues related to the applicability of these systems to the 4–6 year old age category. This may be due to objective difficulties associated with insufficient motor maturity of preschoolers, as well as the lack of adapted digital methods and standards for this age group. A way to overcome these difficulties may be to develop specialized applications taking into account age-related characteristics and interfaces focused on motivational and game mechanisms.

This problem can be overcome through the design of hybrid assessment systems that combine the capabilities of digital registration and analysis of graphomotor indicators with pedagogically oriented interpretative models. This approach will make it possible to take into account the individual characteristics of the child and will provide more accurate diagnostics and support for the development of written speech based on multidisciplinary interaction of specialists. A similar attempt was made in [27], in which neurophysiological data were used to substantiate the role of the motor act of writing. However, the data were not integrated into applied pedagogical tools.

A systematic review found that occupational therapy is effective in promoting writing skills in 4- to 6-year-old children, regardless of impairment. Although randomized controlled trials are lacking, positive effects and value in preschool settings are noted. The authors emphasize the need for further high-quality research to confirm long-term effects and justify widespread implementation of the method [28].

Paper [29] describes research data on typical preschoolers and primary school children. The importance of early intervention and adapted methods is emphasized. The specific needs of different categories of children with writing difficulties (e.g., dysgraphia, motor disorders) are not considered separately, adapted methods are not systematized by age groups and levels of complexity, and empirical data on the effectiveness of specific interventions are not analyzed. In addition, digital and multimodal tools, which are increasingly used in teaching writing, especially for children with special educational needs, remain outside the field of attention.

The COVID-19 pandemic period, when many children were unable to attend in-person preschools and schools, had a particular impact on the growth of the children's app market. At that time, parents and teachers faced the issue of teaching their children the basics of writing and practicing graphomotor skills [30]. The cited study is diagnostically oriented, not at the mass application of EdTech, and is therefore not suitable for substantiating digitalization trends in preschool writing education.

In work [31], a review of modern automated systems for diagnosing dysgraphia in children was conducted with an emphasis on methods based on artificial intelligence. The authors analyzed the data used, graphomotor features, and machine learning algorithms. As a result, the authors proposed a new model for diagnosing and assessing writing disorders that takes into account the shortcomings of existing approaches. The study presents a promising AI model for diagnosing dysgraphia. However, its applicability at preschool educational institutions is limited. Empirical testing, pedagogical adaptation, and consideration of ethics are required.

Paper [32] investigated the effectiveness of using tablet computers in preschool education by studying how easily preschool children get used to tablet technology and its effectiveness in engaging them in drawing. The authors conclude that the tablet is an effective tool for working with preschool children. It provides preschool teachers with another tool for implementing technology standards and curriculum to prepare children to become digital citizens with technological literacy.

The use of digital technologies at preschool organizations optimizes the processes of perception, formation, understanding and memorization of elements that contribute to the rapid assimilation of the given material. It also increases the efficiency and quality of preparation for writing, and most importantly, significantly increases the interest of preschool children in the educational process at preschool organizations and increases their readiness for school [33]. One of the main structural components of educational activities, as emphasized in study [34], is the motivational and target aspect, which involves stimulating the cognitive needs of children with the help of various stimuli (including information and telecommunication technologies). The study demonstrates the potential of AR in teaching preschoolers. However, it requires clarification of the methodology, assessment of effectiveness, and adaptation of age.

Work [35] emphasizes the importance of accurate and objective assessment tools for the early detection of writing disorders in children. Modern approaches to the diagnosis of graphomotor skills based on digital analysis of handwriting and hand movements are presented. The authors also suggest using technologies to individualize diagnostics and monitor motor development in the educational environment. In study [36], the authors showed that when practicing graphomotor skills, the design of an electronic application for children is important, which attracts attention and improves writing skills on a tablet. The study has a limited sample, which reduces the generalizability of the results. Individual neuropsychological characteristics of children were not taken into account in the analysis. There is no extended longitudinal approach necessary to assess the sustainability of the effect. Larger empirical data are needed for reliable conclusions.

Analysis of modern studies reveals that the formation of graphomotor skills in preschoolers is a multifactorial process that includes sensorimotor, cognitive, and motivational components. However, they do not address digital tools and do not answer the question of their capabilities and limitations.

Despite the evolution of digital technologies, the problem of integrating digital tools into the personalized development of preschoolers' graphomotor skills remains unresolved. Current solutions are limited by narrow functionality, do not take into account the cognitive, motivational, and sensorimotor characteristics of children, and are poorly adapted to educational practice. It is necessary to design a comprehensive system that combines digital diagnostics, pedagogical interpretation of data, as well as adult participation in supporting the development of writing skills.

3. The aim and objectives of the study

The aim of our study is to design an electronic application for personalized diagnostics, development, and monitoring of graphomotor skills in children aged 4–6 years using algorithmic analysis of trajectory deviations. This allows for early detection of deviations in graphomotor development through trajectory analysis, providing teachers and parents with a personalized tool for targeted intervention and preparation for learning.

To achieve this aim, the following objectives were accomplished:

– to develop a multi-stage algorithm for quantitative and qualitative analysis of handwriting that takes into account various trajectory parameters and input type (finger or stylus), and also enables the construction of individual skill development trajectories;

– to develop a comprehensive algorithm for quantitative and qualitative analysis of writing errors that compares the user's trajectory with digital reference samples and adapts to various types of tasks and input tools;

– to design a system for collecting, storing, and aggregated analyzing of data on the progress of a child's graphomotor skills, including key metrics and making it possible to track the dynamics of development;

– to test the electronic application "Dexterous Fingers".

4. The study materials and methods

The object of our study is the process that forms and develops graphomotor skills in preschool children using digital educational technologies.

The hypothesis of the study assumes that the introduction and systematic use of the electronic application "Dexterous Fingers" could improve the development of graphomotor skills in children aged 4–6 years compared to conventional teaching methods.

Assumptions adopted:

1. Hybrid approach: the application was developed with the assumption that it would be used not as an independent tool but as a supplement to traditional teaching methods with the active participation of adults (teachers and parents).

2. The importance of personalization: the study is based on the assumption that a personalized approach that takes into account the individual pace and characteristics of the child could significantly improve the effectiveness of teaching graphomotor skills.

3. Relevance of digital technologies: it is assumed that modern children actively interact with digital devices, and this opens up opportunities for using electronic applications as effective teaching tools.

4. Age and regional features: the project takes into account that the market lacks specialized solutions for developing graphomotor skills taking into account age (4–6 years) and regional features, as well as applications that support several languages (English, Kazakh, russian).

Simplifications adopted:

1. Focus on motor parameters: although our paper notes cognitive and motivational aspects, the main algorithm and analysis are focused on motor parameters such as writing speed, pressure, pen movements, as well as visual aspects, including letter size and spacing.

2. Use of existing mathematical models: instead of devising fundamentally new mathematical models, existing ones (piecewise linear approximation and Catmull-Rom splines) were applied and adapted to improve the accuracy and smoothness of trajectory representation.

3. Limited validation for preschool age: the development is carried out taking into account the fact that there is a problem of insufficient validation of similar systems for the age category of 4–6 years, which may be due to insufficient motor maturity of preschoolers and the lack of adapted methodologies and standards.

The theoretical basis is the principles of human-centered design set out in:

– ISO 9241-210 standard;

– requirements for ensuring the accessibility of digital products (ISO/IEC TR 29138);

– international and national regulations on the development of educational electronic resources (in particular, ST RK 34.017-2005);

– standards governing the security and privacy of children's personal data, including the provisions of COPPA and GDPR-K.

Taking into account the psychological characteristics of the child audience when designing the user interface and interactive scenarios is ensured on the basis of modern approaches in UX/UI design, focused on the perception and motivation of children aged 4–6 years.

A polygonal chain (piecewise linear function) is used as the mathematical apparatus underlying the analysis of results of drawing a curve on the tablet screen. The input data for constructing the trajectory are formed from a sequence of user touch points $S=\{P_0, P_1, \ldots, P_m\}$, where each point $P=(x_j, y_j)$ represents coordinates on the touch screen. This sequence of points is used to form a polygonal chain (broken line).

A polygonal chain L is defined as the combination of straight line segments connecting successive touch points

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

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 visual quality and eliminate sharp corners typical of a polygonal chain, smoothing based on the Catmull-Rom spline was used. The Catmull-Rom spline is a type of cubic Hermitian spline that has the interpolation property, that is, the constructed curve passes through all specified control points.

To construct a segment of the curve $C_k(t)$ of the Catmull-Rom 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 $t \in [0,1]$ can be represented in the following matrix form

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

where M_{CR} is the Catmull-Rom 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 form corresponds to the standard Catmull-Rom spline with a tension parameter of $\tau=0.5$, which provides the so-called "centripetal" spline, which copes well with possible self-intersections and sharp angles with an uneven distribution of points.

The extreme segments of the polygonal chain (start and end) require special processing, for example, duplicating the extreme points ($P_{-1}=P_0$ and $P_{m+1}=P_m$) to provide a sufficient number of control points for the formula.

Using the Catmull-Rom spline makes it possible to achieve C^1-continuity of the curve at the connection points of the segments (except, perhaps, the start and end points of the entire curve), which ensured a smooth transition between segments and eliminated 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.

The most important stage was the development of algorithms for digital processing of user input. Each act of interaction with the screen was recorded as a sequence of coordinate points, touch time, pressure parameters, and input device type. These data were transformed into polygonal chains describing the trajectory of movement. In order to increase the accuracy of visual analysis and subsequent assessment of the smoothness of movement, approximation and smoothing methods were used, in particular interpolation using the Catmull-Rom spline. Comparative analysis of the user trajectory with the reference template was carried out based on an assessment of deviations in the shape, order, and direction of graphic elements. Mathematical models based on the use of piecewise linear functions were implemented, which made it possible to formalize trajectories in the form of parametric descriptions suitable for quantitative analysis. The developed metrics included indicators of angular deformation, dispersion of segment lengths, curvature, and smoothing coefficient.

To implement the experimental software product, an electronic application called "Dexterous Fingers" was developed for interactive training, diagnostics, analysis, and correction of graphomotor skills. The development was carried out in Android Stydio, using the Python (Kotlin) programming language, which ensured cross-platform, modular architecture, as well as flexibility in the implementation of data processing algorithms. Graphic components and reference templates were created using Adobe Photoshop and CorelDRAW editors. Touchscreen mobile devices running the Android operating system (version 7.0 and higher), as well as laptops with touch input support, were considered as the hardware base for testing and operation.

Both theoretical and design methods were used in our study. Modern psychological and pedagogical approaches to the formation of graphomotor skills were investigated, existing digital solutions and educational applications were analyzed, a comparative analysis of their functionality, degree of interactivity, and diagnostic value was carried out. Based on the identified features, a transition to the design of our own digital product was carried out. Functional and non-functional requirements were determined, the application architecture was developed, interface solutions were formed taking into account the cognitive capabilities of the target age group.

One of the key components of the system was the monitoring and feedback system. In real time, the user was provided with visual and sound signals informing about the correctness of the task. All data on interaction with the application was stored in the database, which made it possible to build individual skill development trajectories. Subsequently, based on the accumulated data, an analysis of the dynamics of the child's graphomotor skills development was carried out, reports were generated that were available to parents and teachers, containing quantitative and qualitative progress assessments, recommendations for correction and selection of the follow-up exercises.

5. Results of developing the electronic application "Dexterous Fingers"

5. 1. Multi-stage algorithm for quantitative and qualitative analysis of handwriting styles

Efficient analysis of handwriting styles when teaching children to write requires taking into account individual motor skills, sensory input parameters, and the ability to track the dynamics of changes. This system implements an adaptive algorithm for processing trajectories, including the stages of determining the input method, filtering, and smoothing data, comparing them with reference samples, as well as saving the results and generating progress reports. The scheme of the writing analysis algorithm with elements of saving and tracking progress is shown in Fig. 1.

Changing the input method – stylus or finger – significantly affects the line drawing analysis algorithm, especially in the tasks of assessing the quality of children's writing. These two input methods differ in the technical characteristics of the sensor, accuracy, pressure level, and trajectory characteristics, which requires adaptation of the algorithm.

Below is a description of the main modules of the algorithm diagram shown in Fig. 1:

1. Module B determines the input type (finger or stylus) using the sensory API. It separates the data into two streams: TOOL_TYPE_STYLUS and TOOL_TYPE_FINGER.

Changing the smoothing and filtering parameters. For example, for finger input, use more aggressive filtering (e.g., median filters or a spline with a large smoothing parameter).

For stylus input, smooth with a lower level that preserves details.

A system of parameters reflecting the key characteristics of the writing process has been built for quantitative and qualitative assessment of a child's graphomotor skills. These parameters make it possible to record and interpret the features of line drawing, providing objective diagnostics of deviations and development dynamics. The methods of analysis are based on mathematical representations of trajectories and taking into account temporal characteristics.

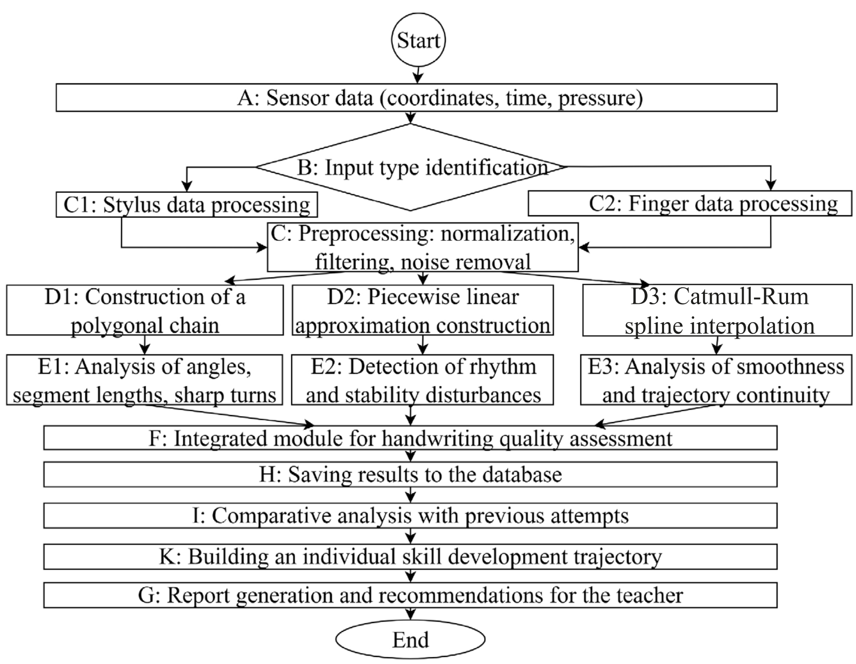

Fig. 1. Writing analysis algorithm

Table 1 gives basic parameters used in the writing analysis algorithm, the corresponding methods for calculating them, as well as the semantics of parameters from a pedagogical point of view.

Comparative analysis of the characteristics of different input methods makes it possible to increase the accuracy of interpretation of graphomotor data and to adapt processing algorithms taking into account the specificity of the device. Particular attention is paid to the differences between the stylus and the finger as the main tools of user interaction with the screen. These differences affect both physical and technical parameters (accuracy, sensitivity, pressure support) and features of the drawing, which affects the choice of filtering methods, smoothing, and interpretation of results. Table 2 gives key differences between the stylus and the finger, taken into account in the analysis.

When analyzing a curve drawn with a finger, the permissible deviations are increased when compared with the standard.

For a stylus, a smaller error is allowed, the accuracy requirements are higher.

2. Modules C1 and C2 contain different filtering parameters (softer for a stylus, harder for a finger); different norms of permissible deviations and sampling frequencies.

3. Module F aggregates the results from all three approaches, forming a comprehensive characteristic of the child's handwriting, taking into account both the line structure and its dynamic features.

4. Module H saves numerical metrics, analysis type, timestamps, device type, preschooler ID.

5. Module I conducts a comparative analysis comparing current data with previous data (child profile, date, age).

6. Module J evaluates the level of assimilation by calculating the dynamics of key metrics (improved smoothness, reduced fluctuations, etc.).

7. Metrics used in J:
– average angular deformation (by polygonal chain);
– segment length dispersion (piecewise linear function);
– average curvature and its continuity (spline);
– trajectory smoothing coefficient;
– motor stability index (by pressure and speed fluctuations).

8. Module K. Formation of an individual trajectory. Output of the writing skill level (low, medium, high), tasks are offered.

9. Module G. Generating a report on the formation of graphomotor skills in preschool children.

5. 2. Complex algorithm for quantitative and qualitative analysis of spelling errors

A letter standard should not just be a static image but a sequence of anchor points and, possibly, additional information about the order and direction of the stroke.

The main stages for forming standard letters and storing them are given below:

1. Graphic representation. A sequence of anchor points (x, y): this is the main technique. Each letter (or its individual element/stroke) is specified as an array of coordinates through which the line should pass. In fact, this is a piecewise linear function, similar to the one that a child draws.

For example, for the letter "L" these can be three points: upper, lower central, upper right. For more complex curves, more points will be needed to adequately describe the shape.

2. Bezier curves or splines. For smoother and more complex standard curves, one can use mathematical descriptions such as Bezier curves or splines, for example, Catmull-Rom. The control points of these curves will define the standard.

3. Standard metadata. Number of strokes (elements): How many individual lines form the letter.
– stroke order. In what order should the letter elements be drawn? (critical for teaching the correct writing technique);
– the direction of each stroke. The start and end points of each element, indicating the correct direction of movement;
– key points. Particularly important points on the trajectory through which the line must pass (for example, the start, end, bend points);
– acceptable deviations (tolerance): one can set a "corridor" around the reference line, within which the writing is considered acceptable.

4. Techniques for creating references. Manual drawing by an expert, i.e., a teacher or designer draws an ideal letter in a graphics editor, then the coordinates of the key points are exported.

Software definition: based on standard fonts and copybooks, followed by vectorization and selection of reference points.

Example of storing references. Letter references, including their coordinate representation and metadata, should be stored in the application as JSON or XML files (Fig. 2).

Table 1

Key parameters for writing skill analysis

Parameter	Analysis method	Semantics of the parameter
Curvature and rotation angles	Polygonal chain	Frequency and abruptness of change in direction
Length and regularity of segments	Piecewise linear function	Stability of writing tempo
Smoothness and continuity	Catmull-Rom spline	Assessment of motor coordination, detection of tremors
Writing speed	All methods (by time points)	Associated with confidence and experience
Fluctuations and jerks	Spline + velocity filtering	Indicators of motor disorders or fatigue

Table 2

Key differences between a stylus and a finger

Parameter	Stylus	Finger
Positioning accuracy	High (up to ~0.1 mm)	Medium/low (~2–4 mm)
Sensor frequency	Higher (60–240 Hz)	Lower (30–60 Hz)
Pressure support	Yes (many models)	None
Tilt	Yes (some models)	None
Line thickness	Variable (depending on pressure)	Static or very limited
Natural writing	Closer to paper	Less controlled, more rounded

```json
{
  "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. Example structure for letter in JSON

To objectively assess graphomotor skills, a comprehensive writing analysis algorithm has been developed that takes into account various input parameters and reference samples. The algorithm shown in Fig. 3 provides a comprehensive analysis of errors when the user performs graphomotor tasks in the "Dexterous Fingers" electronic application. The process begins with receiving input data and ends with forming an assessment and feedback:

1. A: Start. This module symbolizes the entry point into the error analysis algorithm.

2. B: Data from the user (points, events). At this stage, the system receives primary data on the user's actions. This data includes a sequence of coordinate points (x, y) recorded when touching the touch screen, time stamps for each point, and the type of accompanying event (e.g., start of touch – ACTION_DOWN, movement – ACTION_MOVE, end of touch – ACTION_UP). This information forms a "raw" trace left by the user.

3. C: Standard task/Letter reference. In parallel with the user input, the system accesses its database to load a reference representation of the current task. The reference is a digital model of the ideal execution – this can be a trajectory for a simple graphic element ("Path"), the shape of a continuous letter, or a set of strokes with their characteristics (shape, order, direction) for discontinuous letters. References are usually stored in a structured format (e.g., JSON) and contain all the necessary information for comparison.

4. D: User input pre-processing.

Before the main analysis, the "raw" user data undergoes a pre-processing stage. This may include:

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

– filtering noise (e.g., removing too closely spaced points caused by jitter),

– preparing the data for further segmentation and analysis.

4. E: Task type. This is the key decision node where the algorithm determines the nature of the current task in order to select the appropriate analysis path. There are three main types of tasks:

5. F: Simple line/Path (e.g., strokes of straight, wavy lines).

6. G: Continuous letter (1 stroke) (letters that are written with one continuous stroke).

7. H: Broken letter (multiple strokes) (letters that consist of two or more separate elements/strokes).

8. Processing for paths F (Simple line/Path) and G (Continuous letter).

Since both of these types of tasks typically involve one continuous stroke from the user, their initial processing is similar:

a) F1, G1 (step 1): processing a single user stroke: Normalize, Smooth. The user stroke is first normalized – its size and position are brought to a standard form so that the comparison with the reference is invariant to the scale and writing location. The normalized stroke is then smoothed, for example using a Catmull-Rom spline, to remove small vibrations and obtain a clearer representation of the intended trajectory;

b) F1, G1 (step 2): loading the reference path. The corresponding reference for a given line or continuous letter is retrieved;

c) F2, G2: matching the user stroke with the reference path. The processed user stroke is directly compared with the reference path. The results of this matching (similarity and difference data) are fed to the general deviation calculation module (I).

9. Processing for the H (Break letter) path.

This path is designed to analyze letters consisting of several individual strokes and includes more complex logic:

a) H1: segment user input into strokes. All user input for a given letter is divided into individual strokes. The stroke boundaries are the events of lifting the tool off the screen (ACTION_UP) and then touching it again (ACTION_DOWN);

b) H2: process each user stroke: normalization, smoothing. Each identified user stroke undergoes an individual normalization and smoothing procedure similar to that described in F1, G1 (step 1);

c) H3: load the break letter template. The template is loaded, which for such letters is a list of individual template strokes, including metadata about their correct order of execution and, possibly, direction;

d) H4: compare the number of strokes (user vs template).

If the number of strokes drawn by the user does not match the reference, the algorithm, according to the scheme, proceeds to Module H6: Step-by-step comparison of user and reference strokes. This involves an attempt to perform an analysis based on the available data, possibly to identify missing or extra strokes, or to make the best possible match. The results of this comparison are then sent to the Error Identification Module (J).

If the number of strokes matches, the check continues in Module H5_1: Checking the stroke sequence. Here, it is analyzed whether the time order of the user strokes matches the prescribed order in the standard.

If the sequence is correct ("yes"), the analysis process moves to Module I: Calculating deviations, where a detailed comparison of each pair of matched strokes (user and standard) will be performed.

If the sequence is broken ("no"), this is recorded as an error in Module H5_2: Stroke order is broken, and information about this error is passed directly to Module J: Error identification and categorization.

10. General analysis steps (Modules I, J, K, L):

After the user strokes (or strokes) have been matched to the standard (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:

a) I: Calculating deviations. In this module, the differences between the actual writing and the reference for the matched strokes are quantified. Metrics such as the average and maximum distance from the user curve points to the reference line, the difference in angles between segments, deviations in the start/end points of the strokes, and possibly more complex curve similarity metrics (e.g., the Fréchet distance) are calculated. For multi-stroke letters, the relative position and proportions of the strokes can also be analyzed here;

b) J: Error identification and categorization. Based on the calculated deviations (from module I) and the information about structural errors (e.g., incorrect number of strokes from H4/H6 or order violation from H5_2), the algorithm identifies and categorizes the specific types of errors made. Examples of categories: severe shape distortion, contour overrun, incorrect direction of movement, incorrect number or order of elements, violation of proportions;

c) K: Comprehensive error assessment and aggregation (ErrorCount/Total score calculation). All detected 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 an accuracy percentage (e.g., calculated using formula $P = (1 - E/n) \times 100\%$), or a more detailed error profile. At this stage, weighting factors can be applied to different error types depending on their severity;

d) L: Analysis results/Feedback. The final score 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 to save and later use in reports for parents and teachers.

Based on the types and number of errors, the application can give the child specific hints (e.g., "Start this line a little higher", "Draw the line more smoothly" and "You missed one element").

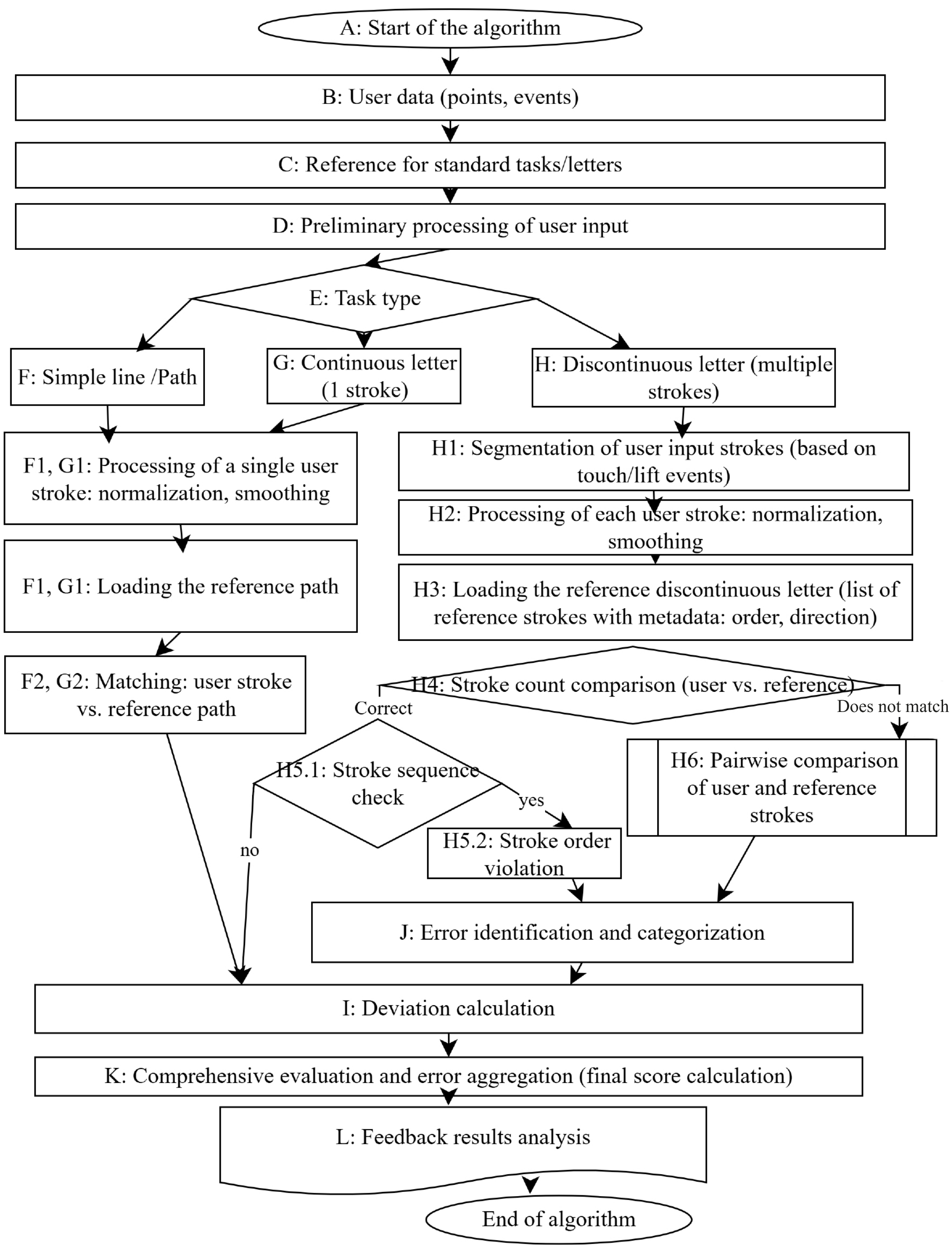

Fig. 3. Error analysis algorithm

5. 3. System for collecting, storing, and aggregated analysis of data on the progress of a child's graphomotor skills

Error analysis involves comparing the trajectory drawn by the child (piecewise linear function) with the reference trajectory.

Input data:

1. Child's trajectory: user input, raw data of one touch is converted into an array of points

$$P_{user\_raw\_input} = \{\text{point}_i = (x_i, y_i, t_i, \text{event\_type}_i) \mid i = 1 \ldots K\}, \quad (4)$$

where (x_i, y_i) – coordinates of the touch point; t_i – timestamp of the point received from the touch screen; event_type$_i$ – event type (DOWN, MOVE, UP).

This trajectory is already a piecewise linear function.

2. Segmented user stroke: after segmentation (e.g., by UP events), the k-th user stroke is a sequence of points: $S_{user}^{(k)} = \{u_j = (x_j, y_j, t_j) \mid j = 1 \ldots n_k\}$. Each $S_{user}^{(k)}$ is a piecewise linear function.

3. The reference letter L_{target}: it is represented as a set of reference strokes: $L_{etalon} = \{S_{etalon}^{(s)} \mid s = 1 \ldots M_L\}$, where M_L is the number of strokes in the letter reference L_{target}. Each reference stroke $S_{etalon}^{(s)} = \{v_l = (x_l, y_l) \mid l = 1 \ldots m_s\}$. Additional attributes for $S_{etalon}^{(s)}$:

– Order$_s$: the serial number of the stroke execution;

– Direction$_s$: the expected direction (can be represented as a vector from v_1 to v_{ms} or through key points).

4. The normalization operator N: $S'_{user} = N(S_{user}(k), W_{norm}, H_{norm})$, where S'_{user} is the normalized user stroke, reduced to the standard size (W_{norm}, H_{norm}) and the origin. Similarly for reference strokes, if they are not predefined in normalized form: $S'_{etalon} = N(S_{etalon}(s), W_{norm}, H_{norm})$.

5. The smoothing operator S (for example, the Catmull-Rom spline): $S_{user\_smooth}^{(k)} = S(S'_{user})$, where $S_{user\_smooth}^{(k)}$ is the smoothed version of the normalized user stroke. For the curve segment $C(t)$ between points U_i and U_{i+1} (from S'_{user}), using control points U_{i-1}, U_i, U_{i+1}, U_{i+2}: $C(t) = T(t) M_{CR} P_{geom}$, where

$$T(t) = [t^3\ t^2\ t^1];$$

M_{CR} – Catmull-Rom basis matrix (e.g., for $t_{ension} = 0$);

$$M_{CR} = \frac{1}{2}\begin{pmatrix} -1 & 3 & -3 & 1 \\ 2 & -5 & 4 & -1 \\ -1 & 0 & 1 & 0 \\ 0 & 2 & 0 & 0 \end{pmatrix}; \quad (5)$$

$P_{geom} = [U_{i-1}\ U_i\ U_{i+1}\ U_{i+2}]^{\mathrm{T}}$ – column vector of control points.

Thus, the general form of the smoothing operator will be as follows

$$C(t) = 0.5 \cdot \left(1\ t\ t^2\ t^3\right) \begin{pmatrix} 0 & 2 & 0 & 0 \\ -\tau & 0 & \tau & 0 \\ 2\tau & \tau - 6 & 6 - 2\tau & -\tau \\ -\tau & 4 - \tau & \tau - 4 & \tau \end{pmatrix} \begin{pmatrix} P_{i-1} \\ P_i \\ P_{i+1} \\ P_{i+2} \end{pmatrix}, \quad (6)$$

where τ is the tension parameter.

6. Deviation metrics (for matched strokes $S_{user\_smooth}^{(k)}$ and $S'^{(s)}_{etalon}$:

– *Shape deviation Δ_{shape}.*

Average minimum distance from points $S_{user\_smooth}^{(k)}$ to segments $S'^{(s)}_{etalon}$

$$\bar{d}\left(S_{user\_smooth}^{(k)}, S'^{(s)}_{etalon}\right) = \frac{1}{\left|S_{user\_smooth}^{(k)}\right|} \sum_{u \in S_{user\_smooth}^{(k)}} \min_j d\left(u, segment_j\left(S'^{(s)}_{etalon}\right)\right), \quad (7)$$

where $d(u, segment)$ is the Euclidean distance from the point u to the section segment.

– *Angular deviation Δ_{angle}.*

Comparison of angles between corresponding segments $S_{user\_smooth}^{(k)}$ and $S'^{(s)}_{etalon}$

$$\Delta\Theta = \frac{1}{N_{seg} - 1} \sum_{i=1}^{N_{seg}-1} \left|\Theta_{user,i} - \Theta_{etalon,i}\right|, \quad (8)$$

where Θ_i is the angle of the i-th segment relative to the previous one.

Deviation of the starting/ending point $\Delta_{endpoints}$

$$d_{start} = \left\|u_1 - v_1\right\|_2; \ d_{end} = \left\|u_{n_k} - v_{m_s}\right\|_2. \quad (9)$$

Curve similarity metric $\Delta_{similarity}$ (e.g. Fréchet distance)

$$F\left(S_{user\_smooth}^{(k)}, S'^{(s)}_{etalon}\right). \quad (10)$$

Estimation of the number of errors e_i for the i-th letter (based on complex analysis)

$$e_i = f\begin{pmatrix} N_{strokes\_diff}^{i}, O_{errors}^{i}, D_{errors}^{i}, \\ \sum_k w_{shape}^{(k)} \Delta_{shape}^{(k,s)}, \sum_k w_{angle}^{(k)} \Delta_{angle}^{(k,s)}, \ldots \end{pmatrix}, \quad (11)$$

where $N_{strokes\_diff}^{i}$ is the difference in the number of strokes for the i-th letter; O_{errors}^{i} is the estimate of the stroke order errors; D_{errors}^{i} is the estimate of the stroke direction errors; $\Delta^{(k,s)}$ are the deviation metrics for the k-th user and s-th reference matched strokes; w are the weighting coefficients for different types of deviations. This e_i corresponds to the ErrorCount from the CSV and the analysis model.

Total time to write the i-th letter t_i

$$t_i = \sum_k t_{end}^{(k)} - t_{start}^{(k)}, \quad (12)$$

where $t_{end}^{(k)}$ and $t_{start}^{(k)}$ are the start and end times of the k-th stroke of the i-th letter.

The input data is formed from a sequence of touch points, transformed into polygonal chains (piecewise linear functions). To improve visual quality and eliminate sharp corners, smoothing was used based on the Catmull-Rom spline, which provides a smooth transition between segments and eliminates visual kinks. The developed algorithm compares the user trajectory with the reference template, assessing deviations in the shape, order, and direction of graphic elements.

The error calculation includes the difference in the number of strokes, errors in the order and direction of stroke execution, as well as deviation metrics for matched strokes, using weighting coefficients for different types of deviations.

The system allows for aggregated analysis, filtering data by user ID and task goal, which ensures tracking of individual dynamics of fine motor skills development and performance quality. Progress is assessed as the difference in values between attempts, indicating skill development. This makes it possible to dynamically change the difficulty and type of tasks depending on the child's current progress and identified problems, providing adaptive correction.

Detailed, structured reports are generated for parents and teachers, including a general summary, average accuracy for mastered letters, and the dynamics of overall accuracy and average number. These reports promptly inform adults about the dynamics of the child's development and help make informed decisions regarding further learning strategies or the need for consultation with specialists. Unlike many existing programs that only provide a "correct/incorrect" indicator or a basic accuracy assessment, the "Dexterous Fingers" application provides a detailed analysis of errors by criteria.

5. 4. Testing the electronic application "Dexterous Fingers"

Progress monitoring is a key function of the electronic application. It motivates the child and helps adults evaluate the effectiveness of the tasks. The algorithm for collecting and analyzing data in the electronic application "Dexterous Fingers" systematically records the child's interactions with the screen while performing developmental tasks, such as "Paths" and writing letters. The following parameters are automatically recorded for each attempt: unique user IDs (UserID) and sessions (SessionID), timestamp (Timestamp), task type (ExerciseType), specific task target (ExerciseTarget), selected assistant character (CharacterMascot), the number of errors made (ErrorCount), calculated based on the comparison of the user trajectory with the reference one, as well as the task completion time (WritingTimeMillis). Additionally, such indicators as the average screen pressure (AveragePressure) and the number of sharp line breaks (JitterCount), reflecting motor instability, can be taken into account. The task completion status (CompletedStatus) records whether the attempt was completed. All collected data is saved to a local database (e.g., a CSV file or SQLite). Primary analysis is based on the number of errors and execution time, which allows for a quick assessment of the success of the attempt. For a more in-depth assessment of progress and acquisition of skills, an aggregated analysis is implemented, including data filtering by specific parameters. Filtering parameters include user ID and task goal, which makes it possible to track individual dynamics of fine motor skills development and the quality of task completion.

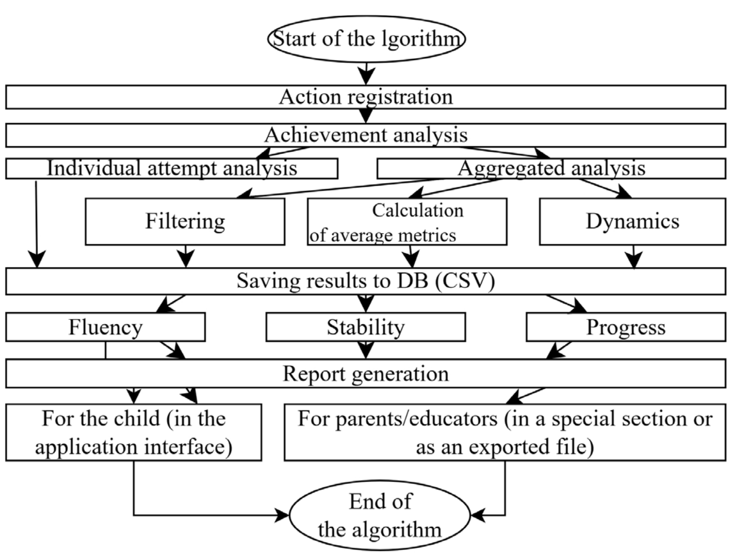

Fig. 4. Progress analysis algorithm

Data collection and analysis algorithm (data collection during task execution):

1. Activity logging. The Dexterous Fingers app records each child's interaction with the screen while completing tasks ("Paths", writing letters). The following parameters are saved for each attempt:

– UserID: child's identifier;

– SessionID: identifier of the current game session;

– Timestamp: exact time of the attempt;

– ExerciseType: exercise type "Letter" or "Path");

– ExerciseTarget: specific letter (e.g., "A", "B") or "Path" name;

– CharacterMascot: selected assistant character;

– ErrorCount: key indicator – the number of errors detected by the analysis algorithm when comparing the user's trajectory with the standard (for details, see the description of the error analysis algorithm based on the scheme);

– WritingTimeMillis: time spent on this specific attempt, in milliseconds;

– AveragePressure (optional): average pressure on the screen;

– JitterCount (optional): number of sharp bends in the line ("jitter");

– CompletedStatus: status (completed/not completed);

– save: this data is written to a database (e.g., a local CSV file or a SQLite database on the device).

2. Analysis of achievements begins with an individual analysis of the attempt. Immediately after completing the task, ErrorCount and WritingTimeMillis provide an initial assessment.

Aggregated analysis (for assessing assimilation and progress) includes filtering. To analyze a specific letter (e.g., "A") or skill, the system selects all attempts of a given UserID for the corresponding ExerciseTarget.

Calculation of average indicators. For a certain period (e.g., the last week, all the time) or for the last N attempts, the following are calculated: average number of errors, average writing time.

We determine the dynamics (personal growth) – the system compares the current average indicators with previous periods or tracks their change over time.

Mathematical description for calculating the quality of assimilation.

Let $A_{u,l,k}$ be the k-th attempt of user u for letter l.

$e_{u,l,k}$ is the ErrorCount for this attempt.

$t_{u,l,k}$ is the WritingTimeMillis for this attempt.

Average number of errors for user u for letter l over N attempts

$$\bar{e}_{u,l} = \frac{1}{N}\sum_{k=1}^{N} e_{u,l,k}. \qquad (13)$$

Average typing time for user u for letter l in N attempts

$$\bar{t}_{u,l} = \frac{1}{N}\sum_{k=1}^{N} t_{u,l,k}. \qquad (14)$$

Quality of learning of writing a letter ($Q_{u,l}$).

Quality of learning is a complex metric.

Based on ErrorCount (deviation from the standard).

Accuracy indicator ($P_{u,l}$) can be introduced. If ErrorCount (($e_{u,l,k}$) is an unstandardized number of errors, then accuracy can be defined relative to some "complexity" or "maximum permissible number of errors" ($E_{\max,l}$) for letter l

$$P_{u,l}=\max\left(0.1-\frac{\overline{e}_{u,l}}{E_{\max,l}}\right)\times 100\%. \qquad (15)$$

If $E_{\max,l}$ is not defined, threshold values $\overline{e}_{u,l}$ can be used for qualitative assessment.

Accuracy levels:

– high: $\overline{e}_{u,l}\leq 1–2$;

– medium: $3\leq \overline{e}_{u,l}\geq 8$;

– low $\overline{e}_{u,l}\geq 9$.

These thresholds should be calibrated for the application as a whole.

Fluency: $\overline{t}_{u,l}$. is taken into account. A decrease in time while maintaining or improving accuracy indicates an increase in skill.

Stability: assessed through variance $\overline{e}_{u,l}$ and $\overline{t}_{u,l}$ over several attempts. Low variance with good accuracy is a sign of a stable skill.

Progress (personal growth): $\Delta Q_{u,l}$ is estimated as the difference between the $Q_{u,l}$ values of the last attempt and the previous one. Positive dynamics of $\Delta Q_{u,l}$ or a decrease in $\overline{e}_{u,l}$ indicate skill development.

3. Generating a report in the electronic application "Dexterous Fingers". Instantly, motivational feedback is generated for the child (in the application interface). Visualization of success by the appearance of stars and fireworks. Sound accompaniment also plays an important role in maintaining the child's interest. Instead of focusing on mistakes – a soft offer to try again or a small hint (flashing the starting point of the stroke, showing the correct outline in color).

For parents/educators (in a special section or as an uploaded file): information on the dynamics of development, strengths, and weaknesses, providing data for decision-making. It has a structured format with text and a graph of score growth. The general summary contains:

– child's name, reporting period;

– general activity (number of lessons, time);

– average accuracy for all mastered letters (percentage and quality level: low, medium, high);

– the dynamics of overall accuracy and average number of errors compared to the previous period (e.g., "Accuracy increased by 10%, average number of errors decreased from 2.5 to 1.8").

After each completed (or interrupted) attempt to complete an exercise, a new row with data (UserID, SessionID, Timestamp, ExerciseTarget, ErrorCount, WritingTimeMillis, etc.) is added to the end of the CSV file. Average indicators (ErrorCount, WritingTimeMillis) are calculated by sessions or time windows (e.g., by days, weeks) to build progress graphs. To assess the dynamics, data for the current and previous reporting periods are selected, after which the aggregated indicators are compared.

The results of a randomized controlled trial were used as an empirical basis to confirm the effectiveness of the developed electronic application "Dexterous Fingers".

The study using the electronic application covered 110 children aged 4–6 years. Children were randomly divided into two groups: experimental (using the application) and control (performing tasks on paper). The study was conducted on the basis of five preschool educational institutions:

– GKKP "Nursery-garden "Lastochka", GKKP "Nursery-garden "Aray", CHDO nursery-garden "Erke-ai", located in the city of Petropavlovsk;

– mini-centers "Bobek" at the KGU "Pokrovskaya Secondary School" of the Mamlyutsky District and at the KGU "Kazan Secondary School" of the Zhambyl District, located in the North Kazakhstan Region.

For a comprehensive assessment of the effectiveness of the system being developed, a comparative analysis was conducted with the most popular digital solutions aimed at developing graphomotor skills in preschool children. Comparative analysis covers key parameters: target audience, alphabet support, implementation of task mechanics, depth of error analysis, feedback forms, monitoring capabilities, and unique features of each solution. This makes it possible to determine the competitive advantages and innovative aspects of the proposed electronic application "Dexterous Fingers". The results of our analysis are given in Table 3.

Table 3

Extended comparative analysis of systems for the formation of graphomotor skills

Comparison flag	"Dexterous Fingers"	LetterSchool	Writing Wizard for Kids	ABC Kids – Tracing & Phonics	Kaligo
Target age	4–6 years	3–7 years	3–7 years	2–6 years	3–7+ years
Supported alphabets	Kazakh, russian, English (declared)	English, Spanish, German, French, etc.	English, Spanish, French, German	English	English, French
Task mechanics	Stroke lines ("Paths"), writing letters (printed)	Animated outline of letters and numbers	Letter and word outline, game elements	Letter tracing, Letter search games	Exercises on a tablet with a stylus; it covers the entire process of learning to write
Error analysis	Recording the number of errors, time; percentage of correct spelling; deviation from the standard (based on a piecewise linear function)	Basic tracing accuracy assessment	Accuracy assessment, repeatability	Simple check for correct stroke	Detailed AI-based analysis, evaluation of shape, order, direction, speed
Feedback	Accuracy level assessment (Low, Medium, High), recommendations (planned)	Positive reinforcement, animations	Sound and visual effects	Positive sounds and animations	Immediate visual and audio feedback
Progress monitoring	Recording results, generating reports for parents/teachers (planned)	Progress tracking for multiple children	Progress reports, difficulty settings	Basic tracing of learned letters	Teacher dashboard with detailed analytics
Unique features	Focus on Kazakh alphabet, use of Catmull-Rom spline for smoothing, pressure analysis (implemented)	Wide choice of languages, game motivation	Create your own word lists	Free, focus on phonics	Using AI for analysis, supporting school programs
Platforms	Android (tablet, smartphone, laptop with touchscreen)	iOS, Android	iOS, Android	iOS, Android	iOS, Android, Windows

The set of our studies demonstrates a stable vector for the integration of digital and intelligent solutions into educational processes – from the preschool level to higher education (Table 3). We present a randomized controlled trial of the effectiveness of the electronic application "Dexterous Fingers" for the development of graphomotor skills in preschoolers in Kazakhstan. The results showed a statistically significant improvement in the accuracy and coordination of movements in children in the experimental group compared to the control group.

At the ascertaining stage, in order to comprehensively study the difficulties associated with the formation of graphomotor skills in preschoolers (Table 4), a comprehensive diagnostic work was carried out. It covered three key aspects: determining the leading hand, assessing the level of development of fine motor skills, and diagnosing graphic skills.

For an in-depth assessment of the graphic skill of preschool children, specific methodologies were adapted and applied: "Paths" – to assess the accuracy of hand movements; "Forest" – to determine the accuracy and continuity of lines; and "Stitches" – for the analysis of eye-hand coordination. The combined use of these methodologies made it possible to obtain a complete and objective picture of the state of graphic skills. The collected data on the development of graphomotor skills in children aged 4–6 years are summarized in Table 4 and in the diagram in Fig. 5, demonstrating the holistic result of our study. More detailed information on the ascertaining stage of the study can be found in [12].

Table 4

Levels of development of graphomotor skills in children aged 4–6 years (based on the results of comprehensive diagnostics)

Diagnostic direction/indicator	Development level	Number of children	% of total
Determination of the leading hand	right	100	91%
	left	10	9%
	ambidexterity	0	0%
Diagnostic direction/indicator	high	–	–
	medium	61	55%
	low	49	45%
Graphic skill by methodologies			
"Paths"	high	10	9%
	medium	44	40%
	low	56	51%
"Forest"	high	0	0%
	medium	15	14%
	low	95	86%
"Stitches"	high	13	12%
	medium	32	29%
	low	65	59%
Total	–	110	–

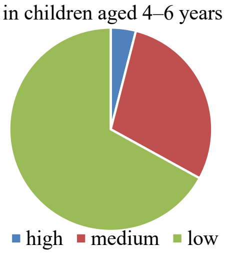

Fig. 5. Distribution of levels in the development of graphomotor skills in children aged 4–6 years

During the set period, children systematically completed tasks aimed at developing graphomotor skills.

For an objective assessment of the level of preschoolers' graphic skills, we identified and described in detail 13 key criteria. These criteria made it possible to comprehensively consider the accuracy, precision, correctness of the execution of graphic elements, as well as the degree of proficiency in writing instruments, awareness, and completeness of writing. Each criterion was assessed on a five-point scale.

The results of the survey are given in Table 5 and shown in Fig. 6.

Table 5

Levels of development of graphomotor skills in children aged 4–6 years (after the introduction of the electronic application "Dexterous Fingers")

Groups	Level		
	High	Medium	Low
Experimental (54 children)	25 (46%)	18 (33%)	11 (21%)
Control (56 children)	10 (18%)	21 (37%)	25 (45%)

Table 5 demonstrates that the experimental group is characterized by better development of graphic skills: the majority of children are at average and high levels (79%), while in the control group almost half of the children have a low level (45%).

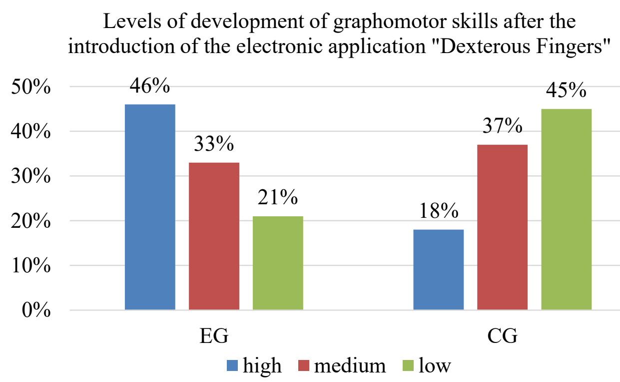

Fig. 6. Levels of development of graphomotor skills in children aged 4–6 years after testing the electronic application "Dexterous Fingers"

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

6. Discussion of results based on developing the "Dexterous Fingers" application

The personalized feedback system in the "Dexterous Fingers" application differs from many existing programs in that it provides not just a "correct/incorrect" indication but a detailed analysis of errors by criteria. This approach makes it possible to identify specific difficulties in the formation of graphomotor skills: impaired eye-hand coordination, problems with line accuracy or continuity, etc. Unlike works [13, 28], in which diagnostics are often subjective, our application allows for an objective and quantitative assessment of progress, which ensures targeted pedagogical intervention. This is achieved through automated comparison of the trajectory with the standard and the formation of analytical reports for parents and teachers, which many conventional methodologies do not provide.

Fig. 1 shows a diagram of the writing analysis algorithm. The key processing stages are visualized: determining the input type, filtering, smoothing, comparison with the standard, and report generation. The introduction of adaptive processing depending on the input method (finger/stylus) makes it possible to increase the accuracy of analysis and take into account the individual motor characteristics of children. The corresponding parameters given in Table 1 provide quantitative and qualitative diagnostics: curvature, rotation angles, length and regularity of segments, smoothness, speed, oscillations. These metrics make it possible to identify not only graphic errors but also possible signs of motor disorders or fatigue.

Table 2 compares the characteristics of finger and stylus input, which make it possible to adjust the tolerances during analysis and offer a more precise algorithm setting depending on the device used.

The system uses mathematical models to automatically recognize and analyze the trajectories of a child's pen movement on a graphics tablet. The use of piecewise linear approximation and Catmull-Rom splines for smoothing and processing data makes it possible to accurately determine such parameters as speed, pressure, smoothness, and coordination of movements. This approach provides an objective diagnosis of graphomotor skills, which is a significant advantage compared to subjective assessments in conventional methodologies. The accuracy of the trajectory analysis makes it possible to identify subtle deviations that may indicate the risk of developing dysgraphia and dyslexia at early stages.

Table 3 demonstrates a comparative analysis of applications aimed at developing graphomotor skills. The application "Dexterous Fingers" stands out for its complex error analysis system, support for three languages (Russian, Kazakh, English), the use of mathematical models (Catmull-Rom spline) and the implementation of individual development trajectories. This allows us to consider it as a unique product focused on regional characteristics and educational standards in the Republic of Kazakhstan.

Fig. 2 shows what a template for a reference letter for storage in an application might look like.

The algorithm shown in Fig. 3 is the key element that ensures objectivity, accuracy, and personalization in the study, thereby directly affecting its effectiveness. The algorithm begins with obtaining and discretizing the writing trajectory, which replaces the subjective assessment of the teacher or parent with an objective digital analysis. The key contribution is made by the use of piecewise linear approximation and, especially, smoothing with the Catmull-Rom spline. This stage makes it possible to minimize noise and artifacts that occur when typing with a finger or stylus and obtain the most accurate and smooth digital representation of the trajectory, which is critical for reliable analysis. The central link of the algorithm is the comparison of the processed trajectory with the standard and the subsequent detailed analysis of errors if the deviation exceeds the permissible values. This mechanism makes it possible not only to state the error but identify its nature, which serves as the basis for the formation of personalized recommendations for the user. The algorithm is closed on the formation of recommendations, creating a full cycle: from data entry to their analysis and provision of feedback. This turns the application from a simple diagnostic tool into a full-fledged interactive system of training and correction, which is the main goal of our study.

Fig. 4 shows a module diagram providing a detailed and personalized analysis of errors. The algorithm demonstrates its effectiveness by differentiating the analysis depending on the type of task ("Simple line" or "Simple letter"). This makes it possible to apply the most relevant and informative metrics for each task. Instead of a simple "correct/incorrect" assessment, the algorithm calculates a whole set of quantitative and qualitative indicators, such as the spread of points, similarity, length ratio, average curvature, and speed. For letters, it additionally analyzes deviations from reference points and angular deviation. Such a comprehensive analysis provides a holistic picture of the state of the child's graphomotor skills. The results of this detailed error analysis serve as the basis for the formation of personalized recommendations, which were mentioned in the previous algorithm. It is this data that allows the application to provide specific and targeted feedback, which significantly increases the effectiveness of correctional work and makes learning truly adaptive. The algorithm completely automates the assessment process, eliminating the subjectivity inherent in conventional methods. This ensures high reliability and reproducibility of the research results.

Before the application was introduced, as shown in Table 4 and Fig. 5, most children had an insufficient level of graphomotor skills. Thus, a high level according to the "Paths" method was detected only in 9% of children, according to the "Forest" method – was not recorded at all. These data indicate the need for targeted pedagogical intervention and the relevance of developing individual correction programs.

The proposed algorithms make it possible to analyze deviations from standard samples and, based on this, formulate individual recommendations and tasks for each child. Unlike general exercises in conventional copybooks, the "Dexterous Fingers" application offers adapted learning trajectories. This makes it possible to focus on specific problems of the child, ensuring targeted development of weaknesses and consolidation of already formed skills. Such personalization significantly increases the effectiveness of correctional work and reduces the time for mastering the necessary skills.

The results after the application was introduced, given in Table 5 and shown in Fig. 6, demonstrate a pronounced positive trend in children of the experimental group. The proportion of children with a high level of graphomotor skills increased to 46%, while the number of children with a low level decreased to 21%. At the same time, there were no significant changes in the control group, which makes it possible to talk about the direct influence of the digital tool on the development of writing skills.

The results of a randomized controlled trial, which showed a statistically significant improvement in graphomotor skills in the experimental group ($p < 0.001$) compared to the control group, confirm the effectiveness of the digital approach. On a sample of 110 children, it demonstrates a comprehensive positive effect on the accuracy, smoothness, and coordination of movements, which indicates the potential of the intelligent application as a powerful tool for developing graphomotor skills. This is especially important in the context of preparation for school education, where, as noted in [19], early detection and correction of difficulties significantly improve academic performance.

The introduction of game elements and an interactive learning format in the mobile application helps maintain a high level of motivation and engagement in children aged 4–6. Children perceive the learning process as a game, which reduces stress and increases their readiness to complete tasks.

Our application generates detailed reports on the child's progress, which are available to parents and teachers. The reports contain not only quantitative indicators (e.g., number of errors, speed of completion), but also qualitative characteristics (e.g., type of deviations). The data from the reports allow adults to be informed in a timely manner about the dynamics of the child's development and make informed decisions regarding the further teaching strategy or the need for consultation with specialists (defectologists, speech therapists).

The data obtained indicate the prospects for scaling up the approach within the framework of regional and national educational programs, especially in the context of a shortage of specialized specialists (speech therapists, defectologists) and the growing digitalization of preschool education.

Our study has a number of key advantages over existing alternative solutions, both conventional and digital:

1. The "Dexterous Fingers" application allows for an objective and automated assessment through mathematical modeling of writing trajectories and algorithms for quantitative and qualitative analysis of deviations from the standard. The developed application integrates a comprehensive approach to diagnostics and personalized learning, taking into account the specific psychological, pedagogical, and technical requirements for preschoolers aged 4–6 years.

2. The introduction of mathematical models based on Catmull-Rom splines for smoothing trajectories and the developed algorithm for analyzing errors taking into account key criteria allows for a significantly more accurate and objective assessment of graphomotor skills compared to subjective visual methods.

3. The result reported in this study (adaptive correction system) makes it possible to dynamically change the complexity of tasks and the type of tasks depending on the child's current progress and identified problems.

4. The Dexterous Fingers app completely solves the problem of lack of individualization since each child receives personalized tasks and feedback based on his/her unique needs and level of development.

A limitation of this study is that the principal conclusions about the effectiveness of the application are based on a study involving children without pronounced special educational needs. The results are adequate for the mass preschool segment. The effectiveness of the application for different categories of such children (for example, with different types of developmental disabilities) cannot be unambiguously confirmed and requires specialized research. When working with children with special educational needs, modifications to the interface or tasks, as well as adaptation of methodological support may be required.

A disadvantage of the system is that direct validation of the automated assessment of the algorithm by comparing it with the assessments of independent human experts (psychologists, defectologists) was not carried out. This reduces objective confidence in the absolute accuracy and compliance of the automated assessment with human perception.

To eliminate this shortcoming, it is necessary to conduct an additional study, during which the results of the trajectory analysis obtained using the application will be compared with the assessments of the same work performed by experts. This can be achieved by developing standardized protocols for expert assessment and applying statistical methods to measure agreement between automated and human assessment (e.g., Kappa coefficient, correlation analysis).

7. Conclusions

1. A multi-stage algorithm has been developed that takes into account the input type (finger or stylus), trajectory parameters (curvature, length, smoothness, tempo), and features of motor interaction with the device. The algorithm implements both quantitative and qualitative analysis, allows for tolerances to be adapted when comparing with the standard and ensures the construction of an individual trajectory for the development of writing skills. An analysis of the characteristics of various input methods has been conducted. Curves obtained from the touch screen are processed using the Catmull-Rom spline. The use of adaptive smoothing taking into account the input type (finger or stylus) has significantly increased the accuracy and smoothness of the representation of user trajectories, minimizing noise and preserving important details of the outline.

2. A comprehensive algorithm for quantitative and qualitative analysis of writing errors has been developed and implemented, which compares the user's trajectory with pre-set digital reference samples. The proposed algorithm makes it possible to calculate the shape deviation, angular deviation, start/end point accuracy, and curve similarity. The algorithm includes adaptation to various types of tasks (simple lines, continuous and discontinuous letters), as well as to the type of input tool, which ensures flexibility and high accuracy of assessment. The implementation of the electronic application "Dexterous Fingers" makes it possible to automate the process of diagnostics and training, making it accessible and interactive for children aged 4–6 years, which is a significant step compared to manual assessment methods.

3. An effective system for collecting, storing, and aggregated analysis of data on the results of children's assignments has been designed, including such metrics as ErrorCount and WritingTimeMillis, as well as optional AveragePressure and JitterCount. This system allows for automatic tracking of a child's individual progress, calculating average indicators and identifying the dynamics of graphomotor skills development.

4. A randomized controlled trial (involving 110 children from 5 preschool organizations in Petropavlovsk and the North Kazakhstan region) was conducted. The study confirmed a statistically significant improvement in graphomotor skills in the experimental group compared to the control group ($p < 0.001$), especially in terms of accuracy, smoothness, and coordination of movements. Testing the application on preschoolers confirmed its high effectiveness as a monitoring and development tool.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The manuscript has associated data in the data warehouse.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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