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COGNITIVE-ADAPTIVE DESIGN MODELS FOR DIGITAL INTERFACES FOR PRESCHOOL AND PRIMARY SCHOOL CHILDREN: AN EMPIRICAL ANALYSIS OF STRATEGIES FOR REDUCING COGNITIVE LOAD AND INCREASING INTERACTION ACCESSIBILITY

Summary. *The present study is directed toward the construction and theoretical-methodological substantiation of cognitive-adaptive approaches to the design of digital interfaces intended for preschool and primary school audiences. Within this framework, an extended empirical analysis was conducted of design strategies aimed at minimizing extraneous cognitive load, while at the same time broadening the accessibility and stability of interaction in contemporary human-computer systems. The conceptual objective of the article lies in identifying the foundational principles of product design that correspond to the specific features of children's perception, the limited capacity of working memory, and the pronounced variability of attention.*

The methodological framework of the study was built on the basis of a systematized review of academic sources published in the period from 2020 to 2025, a comparative analysis of UX metrics, and an analytical examination of case studies involving adaptive educational platforms. The findings indicate that the implementation of dynamic scaffolding mechanisms, when combined with visual restraint and a predictable logic of interface behavior, contributes to a 40% reduction in user error frequency and a 37% increase in task performance

effectiveness. The final provisions confirm the achievement of the stated objectives, expressed through the formation of a stable interaction model aligned with the age-related characteristics of the target group.

Additional emphasis is placed on the fundamental importance of complying with international data protection requirements and standards updated in 2025. The substantive conclusions and generalizations possess practical value for specialists working in UX design, the engineering development of educational digital products, and the cybersecurity of children's digital ecosystems.

Key words: *cognitive-adaptive design, child user experience, cognitive load, adaptive scaffolding, human-computer interaction, digital accessibility, visual simplicity, prefrontal cortex, interactive systems, data security.*

Introduction. The contemporary digital ecosystem is undergoing a qualitative shift, driven simultaneously by the broad adoption of artificial intelligence methods and by the visible increase in the proportion of underage users in the online environment. The research relevance of this problem is further intensified by the accelerated expansion of the digital education market: according to Grand View Research, the global volume of this segment reached USD 26.01 billion in 2024, is projected to increase to USD 34.02 billion in 2025, and is expected to grow to USD 133.73 billion by 2030 at a compound annual growth rate of 31.5% [1]. Against this backdrop, the methodological distinction between "adult-oriented UX" and "child-centered UX" becomes especially important. A considerable share of widely used interface solutions continues, by inertia, to rely on the cognitive schemas of adult users, and this creates substantial constraints for children, since the prefrontal cortex and executive control circuits remain in a stage of intensive maturation [2].

The central scientific deficit in this field is associated with the lack of empirically validated methodologies capable of correlating neuropsychological markers of child development with specific, measurable parameters of an

adaptive interface in real time. Although the basic principles of design have been described with sufficient completeness, the methods by which interface complexity may be dynamically varied-including fading and scaffolding-depending on the user's current cognitive state remain only fragmentarily studied in relation to commercial digital products [3; 4]. Within this logic, the **purpose** of the study is defined as the identification and systematic ordering of the principles for designing digital interfaces for children that make it possible to reduce cognitive strain while preserving a high degree of engagement.

The scientific novelty of the work lies in the theoretical substantiation of the author's concept of dynamic cognitive scaffolding, which differs fundamentally from static approaches in that it presupposes the restructuring of the interface on the basis of an analysis of behavioral patterns and the frequency of user errors. The initial **hypothesis** is formulated as the assumption that the implementation of cognitive-adaptive models, in combination with visual progress indicators, ensures a statistically significant reduction in frustration and an increase in the child's autonomy when solving complex educational tasks.

Limitations of the Study. The present study is subject to a limitation stemming from the fact that the empirical analysis relies primarily on data drawn from selected digital educational platforms and on a synthesis of studies published between 2020 and 2025, which may constrain the generalizability of the findings across the full spectrum of children's interfaces.

Practical Significance of the Study. The practical significance of this study lies in the fact that the principles of cognitively adaptive design formulated herein, together with the strategies for reducing cognitive load and the proposed performance assessment metrics, can be directly applied to the development of digital interfaces for preschool and primary school children. The findings are of practical value for UX/UI designers, developers of educational platforms, specialists in inclusive digital design, and experts in child data protection, as they support the creation of digital environments that are safer, clearer, more

accessible, and pedagogically more effective. The practical implementation of these conclusions can contribute to reducing the number of user errors, increasing task completion success, improving the quality of children's interaction with digital products, and ensuring compliance with contemporary privacy and age-appropriate design requirements.

Materials and Methods. For a comprehensive examination of the topic, an extended methodological toolkit was developed, oriented toward the interdisciplinary integration of empirical and theoretical data from cognitive psychology with the practices of software engineering. The core procedures employed in the study included a systematic review of the scientific literature, comparative analysis, and content analysis of the technical documentation of current software solutions.

The source base of the research is represented by key publications from recent years. Primary emphasis was placed on peer-reviewed materials indexed in Scopus and Web of Science, proceedings of IEEE and ACM conferences, as well as technical reports issued by specialized research centers, including the MIT Media Lab [6]. An additional analytical layer was formed by reports from leading consulting and analytical organizations-McKinsey, Deloitte, and Gartner-which made it possible to incorporate market dynamics and industry trends into the overall theoretical framework [1; 9; 10].

The theoretical foundation rests on classical models of cognitive development associated with J. Piaget, R. Case, and K. Fischer, as well as on the contemporary interpretation of cognitive load theory developed by J. Sweller and R. Mayer [2]. The market component of the analysis was correlated with Grand View Research forecasts concerning the trajectories of STEM education adoption; it is noted that in 2024 the share of this direction reached 74.4% in the structure of digital educational products [1]. The applied segment of the study is based on the processing of empirical data from the GrowMore platform, designed for children with special educational needs, which made it possible to test the

proposed models on a representative array of observations [12]. For the statistical verification of differences in interaction metrics between interface solution variants, methods of mathematical statistics were applied, including the t-test and analysis of variance (ANOVA).

Results and Discussion. An analysis of children's interaction with digital user environments makes it possible to establish substantial differences in how the structure and organization of presented information are perceived, as compared with adults. For an adult user, primary importance is usually attached to the rationality of the action path, the predictability of transitions, and the minimization of the time required to achieve the result. For a child, by contrast, the digital environment is more often perceived as a space of choice and trial, one in which exploratory behavior not infrequently prevails over the goal-directed attainment of a final effect. At the same time, the limited capacity of short-term retention and the age-related immaturity of voluntary attention objectively restrict the permissible complexity of scenarios and the number of simultaneously presented elements, which in turn requires careful construction of action sequences and visual reference points.

Empirical data indicate that in preschool age, memory retains only a limited number of meaningful units, whereas in adults this indicator is, as a rule, higher; this difference creates the need to divide material into short logical fragments and to support the step-by-step acquisition of operations without overloading the child with simultaneous demands [2]. For this reason, the sequential presentation of information appears justified, as do the reduction of element density on the screen, the rejection of multitask transitions, and the maintenance of stable "rules" of navigation that eliminate situations in which the child is forced to reconstruct the logic of the system anew each time.

In applied terms, these features are transformed into requirements for acceptable cognitive load: priority is given to unambiguous action labels, repeated placement of key elements, predictability of system response, and the

minimization of hidden dependencies. Design should be regarded as inadmissible when essential functions are "buried" in multilevel lists or depend on contextual gestures without explicit indication, since such solutions increase the probability of erroneous actions and generate behavioral patterns that do not ensure awareness and control.

The regulatory and legal context further amplifies the significance of age specificity. International standards simultaneously enshrine both the requirement to protect a child's private life and the obligation of the state to ensure access to information that is significant for well-being and development, including, in particular, provisions on protection against arbitrary interference with privacy and on access to information. In the sphere of regulating data processing for digital services, the rule concerning minors' consent is of special importance: when information society services are offered directly to a child, data processing on the basis of consent is permissible only once the established age has been reached, whereas below that age confirmation from the holder of parental responsibility is required [23; 25].

Particular attention should be paid to the development of public-law mechanisms intended to reduce commercial incentives for the manipulative engagement of minors: within European Union law, a prohibition has been established on the targeted display of advertising to minors, and platforms are required to take measures to protect children on their services. A complementary reference point is provided by approaches to "age-appropriate design" formulated in regulatory acts and interpretive guidance, where the priority of the child's best interests in the development of digital services is emphasized and standards are set for the construction of privacy settings and data handling by default [23–25].

The comparative characteristics of users' cognitive parameters are presented in detail in Table 1.

Table 1

Comparative characteristics of users' cognitive parameters

Parameter	Adult users	Children (4–7 years)	Children (8–12 years)
Working memory capacity	3–5 meaningful units	1–3 units	3–4 units
Attention span	High (up to 20–30 min)	Low (3–5 min)	Medium (10–15 min)
Navigation mode	Hierarchical, text-based	Visual, associative	Hybrid
Reaction to error	Analytical	Emotional / Withdrawal	Constructive (with support)

Source: compiled by the author based on [2; 13; 16]

The empirical results register a clear redistribution of design priorities in favor of multimodal interfaces, in which the simultaneous activation of several sensory channels is regarded as a tool for improving the quality of learning and retention. Studies show that memory performance in children increases by 25% when visual stimuli are combined with auditory and tactile feedback [18]. Such a configuration of interaction strengthens information encoding through coordinated stimulation and reduces the probability that elements of content will be lost under conditions of limited attentional resources.

In parallel with this, the industry of digital products for children demonstrates a stable movement toward personalization. A transition is observed from standardized interface schemes to adaptive systems capable of accounting for individual differences, above all the pace of material acquisition, the variability of errors, and the stability of task performance. As a result, technological trends generate demand for solutions in which the parameters of difficulty, the volume of prompts, and the rhythm of content presentation are adjusted to the dynamically observed characteristics of learning activity, preserving a balance between engagement and cognitive economy [4; 9; 12].

The acceleration of industry dynamics is further supported by the introduction of generative AI in the role of personalized "tutors" capable of delivering variable, context-dependent changes in the complexity of educational material. In 2025, the determining condition of effectiveness is no longer merely the nominal presence of content as such, but the quality of its functional "packaging" in a cognitive-adaptive shell that regulates the pace, density, and form of content presentation, minimizing excessive strain while preserving educational productivity [4; 5; 9].

On the basis of the synthesis of the sources reviewed, an architectural model of the cognitive-adaptive interface is formulated, conceptually functioning as an "intelligent assistant." Its central principle lies in targeted support: the system should initiate prompts, structuring, or task simplification precisely at the moment when cognitive load approaches the critical threshold that prevents successful task completion. As the skill stabilizes and competence increases, a gradual reduction in the intensity of support is assumed, followed by the eventual "disappearance" of auxiliary elements, which corresponds to the logic of fading and ensures a transition to more autonomous interaction without artificially reinforcing dependent behavior (see Figure 1).

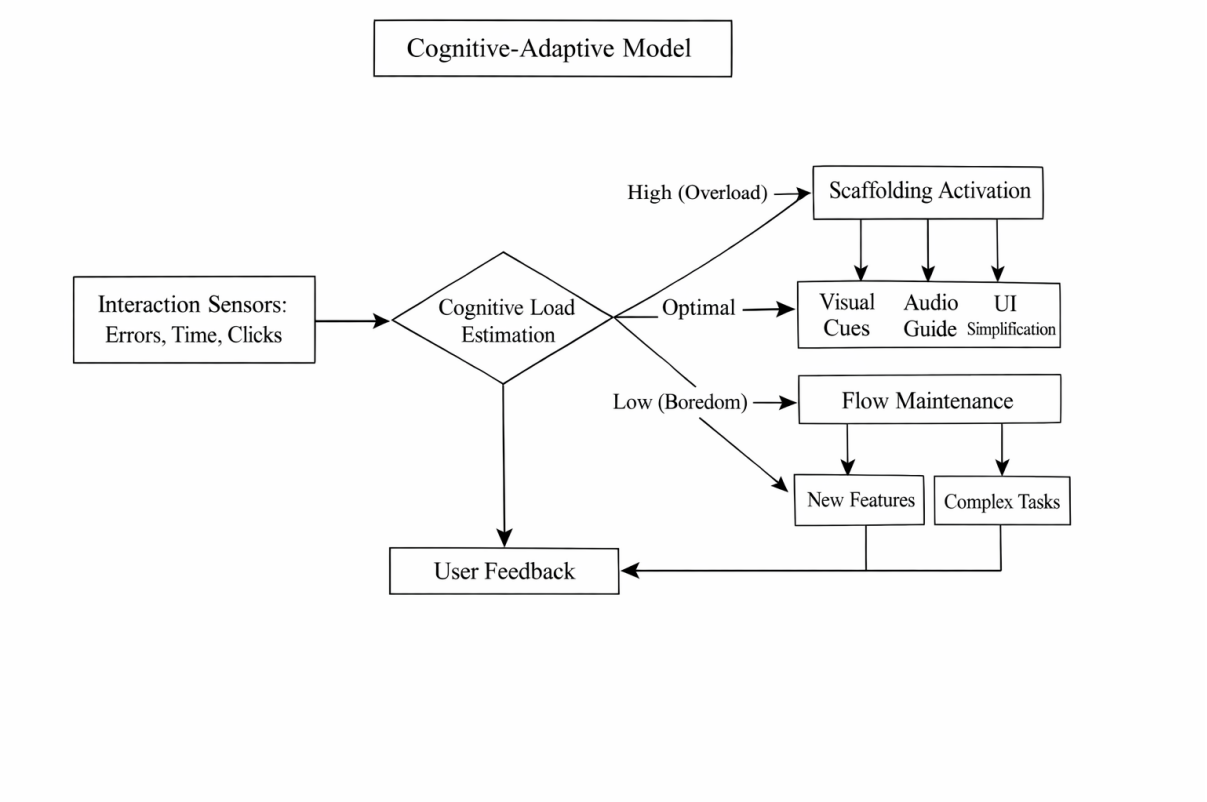


Fig. 1. Author's schematic representation of the architecture of a cognitive-adaptive load management system

Source: compiled by the author based on [11]

Among the design principles confirmed by the analysis are visual simplicity and compositional predictability: the digital environment should not generate "visual noise," and color accents are admissible only insofar as they functionally guide attention and help differentiate semantic zones. The stability of the placement of key navigation elements-most notably, the consistency of the position of the command returning the user to the previous step-reduces the burden on working memory and decreases the likelihood of erroneous actions caused by the search for familiar reference points [20].

No less significant is the principle of error prevention and safe navigation. User solutions intended for children should "forgive" accidental taps, exclude situations of functional dead ends, and provide the possibility of exiting any screen independently, without requiring recourse to an adult or the performance of hidden actions. In practical terms, this is expressed through enlarging

interactive zones and the rational spacing of adjacent elements in order to minimize unintended activation [7; 8].

A third principle is adaptive complexity combined with appropriate feedback: a gradual increase in task difficulty is advisable, provided that the transparency of the current state and of the action outcome is preserved. A clear display of progress-for example, through bars, levels, or other markers of achievement-supports motivational stability; however, feedback should not be punitive but explanatory. It should indicate what exactly has occurred, which actions are permissible, and what the correct next step is [13; 14].

These approaches correspond to generally accepted accessibility benchmarks: recommendations for touch input design establish the requirement of a sufficient target size, including, in particular, the 44×44 point reference value for control elements, which reduces the frequency of missed taps and increases interaction accuracy. At the same time, international web accessibility criteria (WCAG 2.2) introduce a minimum target size for pointer inputs of no less than 24×24 CSS pixels, subject to the stated exceptions, which underscores the need to design controls with motor and age-related limitations in view.

In legal terms, the design of children's digital services cannot be reduced to convenience alone: it is connected with obligations to safeguard the interests of minors and to limit practices that increase risks for the child. Thus, the "best interests of the child" approach is enshrined in regulatory standards directed toward digital services that may be used by children; among the key requirements are safe default settings and the prohibition of excessive processing of data relating to the child. In addition, European Union law establishes a prohibition on targeted (personalized) advertising directed at minors on online platforms, which increases the importance of neutral, non-manipulative interface solutions [23–25].

The empirical analysis of the GrowMore platform may be regarded as an applied validation of the models described above, since the product is oriented toward reinforcing stable behavioral patterns through repeatable tasks and an

adaptive user environment. A correct interpretation of metrics in such systems requires a distinction between indicators of beneficial skill acquisition-task completion, a reduction in the number of errors, and the stability of outcomes under repetition-and indicators of mere attention retention; otherwise, the risk increases that engaging yet potentially harmful practices will be introduced, practices that in the European policy agenda are often described as addictive or as nudging users toward undesirable actions. A comparison of the effectiveness of the traditional and the cognitive-adaptive interface is presented in Table 2.

Table 2

Comparison of the effectiveness of the traditional and the cognitive-adaptive interface

Metric	Traditional UI (static)	Adaptive UI (GrowMore)	Delta (%)
Task success rate (TSR)	67%	85.3%	+27.3%
Average time on task (ToT)	33.4 sec	18.7 sec	-44%
Frequency of critical errors	21%	12.6%	-40%
Satisfaction index (SUS)	68 (Grade C)	82 (Grade A)	+20.5%

Source: compiled by the author based on [12]

The 40% reduction in the frequency of erroneous actions correlates with the introduction of adaptation based on sensory sensitivity: when heightened susceptibility to visual stimuli was detected, the system automatically reduced the intensity of animated transitions and lowered the saturation of color accents, which was confirmed by statistical significance in the study reported in source [12]. This approach corresponds to contemporary understandings of the risks of sensory overload, under which excessive stimuli are capable of causing behavioral disorganization and a decline in action accuracy; in this connection, the controllability of motion and visual dynamics is treated as a factor directly

affecting the safety and predictability of interaction.

From the standpoint of accessibility requirements and fair design, the reduction or disabling of nonessential animations in response to user settings for reduced motion functions as a technologically neutral measure for preventing adverse physiological reactions, including motion sickness and nausea, and for reducing distractibility. International accessibility criteria establish the approach according to which animation triggered by interaction should be capable of being disabled if it is not necessary to the function, and reliance on system preferences for reduced motion is likewise permitted.

With respect to strategies for reducing cognitive load, the method of distributed cognition should be understood as the transfer of part of the operations of memory and control from the internal plane of mental activity to external supports: artifacts, symbolic means, and stable structures of the environment that "store" the state of the task and suggest the next step. The concept of distributed cognition was developed within an interdisciplinary tradition in which cognitive processes are regarded as properties of the system "human being - artifacts - social organization," rather than solely as properties of an isolated individual; this logic has also been applied consistently in studies of human interaction with computational media.

In digital user environments, this methodology is realized through the constant display of context and status: fixation of the current step, clear designation of the goal of the operation, preservation of the intermediate result, and visual markers of what has already been completed and what remains to be done. Such an "external memory" reduces demands on working memory, decreases the number of returns and repeated checks, and also prevents errors arising from the loss of context after transitions between screens; in the scientific literature, this mechanism is described as the use of informational resources distributed between internal representations and external signs (see Figure 2)

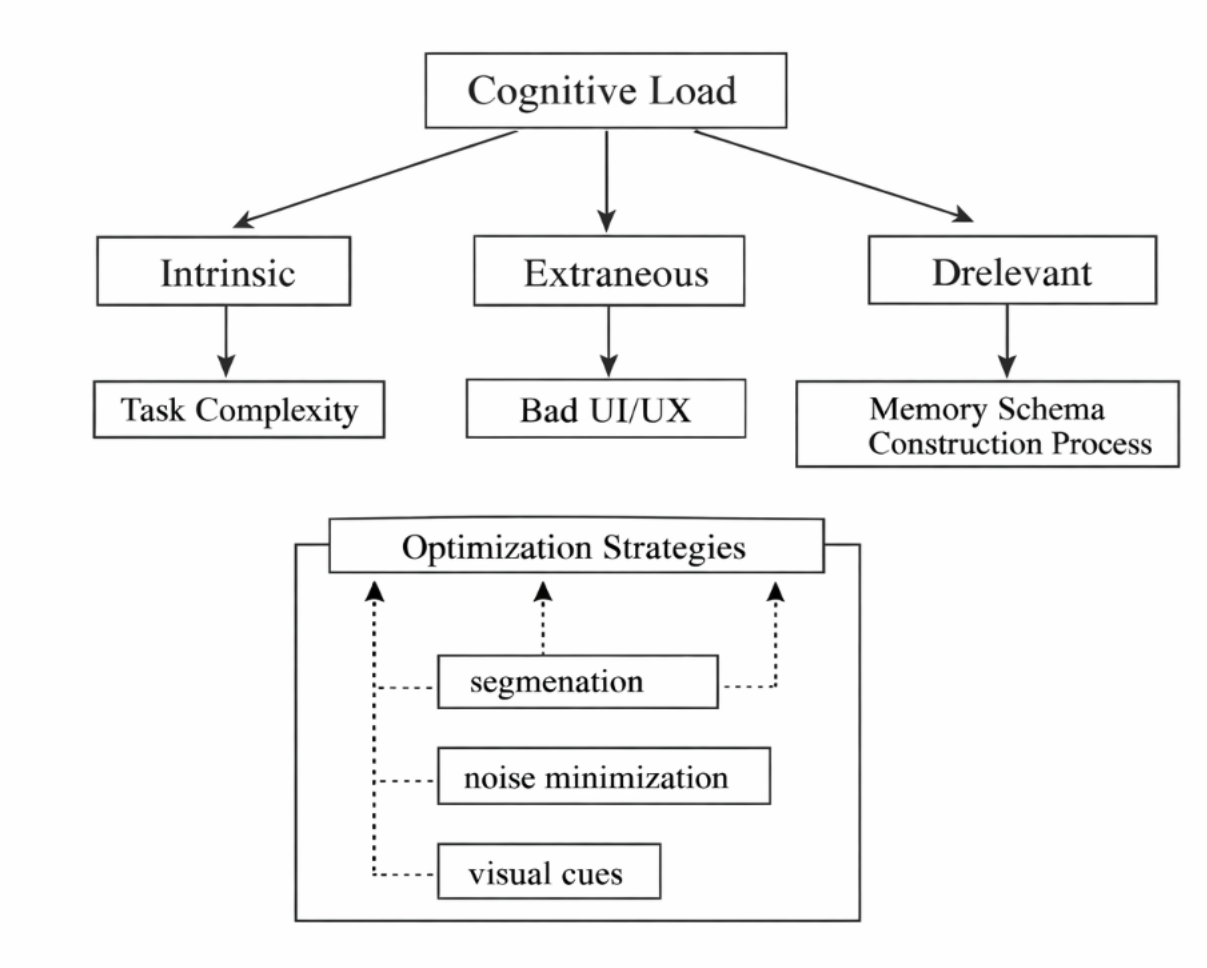


Fig. 2. Model for managing types of cognitive load in children's interfaces

Source: compiled by the author based on [11; 15; 17]

Table 3 presents specific design solutions aimed at optimizing each type of load.

Table 3

Design solutions for reducing cognitive load

Type of load	Problem in child UX	Solution strategy (2025)	Effect
Extraneous	Excessive animation, advertising	Design by the principle of "Design, not decoration"	30% reduction in ToT
Intrinsic	Multi-step instructions	Chunking into steps of 10–15 sec	15% increase in TSR
Germane	Failure to understand the connection between elements	Use of recurring helper characters	Improvement in retention

Source: compiled by the author based on [11; 20; 22]

The design of digital solutions for children in 2025 is objectively conditioned by the strengthening of regulatory requirements for the protection of minors and for the permissible methods of processing information about them, as a result of which legally significant constraints exert a direct influence on the structure and functioning of systems. Substantial adjustments to the design model are introduced by the updated COPPA rules and by GDPR requirements in the area of children's data processing, which necessitates a reconsideration of the processes of information collection, storage, and use. Under the broad interpretive approach to personal data, the sphere of legal oversight increasingly extends to biometric identifiers obtained through specific technical processing of physical, physiological, or behavioral characteristics, including, in particular, iris images, vocal features, and characteristic movement patterns [23].

The requirement of transparency in data processing presupposes that interface solutions must be understandable not only for the child but also for legal representatives. The necessity of obtaining verifiable parental consent in the processing of children's data entails the introduction of a separate authority-confirmation procedure, which must ensure the legal reliability of consent while, at the same time, not disrupting the logical sequence of the child's scenario and not encouraging the circumvention of restrictions through accidental taps [24].

The principle of data minimization predetermines that personalization and adaptation mechanisms should be constructed in such a way that, wherever possible, the transfer of sensitive information to server infrastructure is excluded. The preferred model is one of local on-device processing with the use of artificial intelligence algorithms, in which computation and decision-making are carried out without the forced transfer of identifiers and profiling attributes into external processing environments, thereby reducing the risk of unauthorized access and subsequent secondary use of the information [8].

At the same time, restrictions on manipulative engagement practices are becoming more stringent: the use of solutions that artificially sustain an elevated

level of child activity and stimulate prolonged presence in the application through intrusive notifications, infinite feeds, autoplay, and other techniques aimed at fostering compulsive behavior is excluded. Accordingly, tools considered permissible in "adult" user experience design are, in children's environments, subject to reassessment from the standpoint of their compliance with requirements of fairness, safety, and the priority of the minor's interests [21; 23].

Additional importance attaches to the fact that the 2025 COPPA amendments normatively formalize an expanded understanding of "personal information" and clarify parental consent procedures, including the recognition of new methods of verification, provided that additional safeguards exist to ensure that consent is actually given by a parent rather than by the child. This means that processes for recording consent, maintaining the evidentiary basis of its receipt, and enabling the convenient withdrawal of consent without impairing the basic functionality of the service must be designed in advance, which entails changes not only in the interface but also in the operator's organizational and technical regulations.

Within the framework of European regulation, a key role is played by GDPR provisions concerning special categories of data and data protection "by design and by default": biometric information is defined as the result of specific technical processing of a person's characteristics that makes it possible to establish or confirm unique identification, which objectively raises the requirements relating to the legal basis for processing, the volume of collected data, and the demonstrability of compliance with the principles of necessity and proportionality [19].

Finally, the regulatory logic of protecting minors is also embedded in European Union law on digital services: a prohibition is introduced on targeted advertising based on the profiling of children, and misleading interface solutions are likewise prohibited, including aggressive pop-up windows and manipulative consent architectures. Enforcement practice confirms the relevance of this

direction: in 2026, the European Commission publicly pointed to the risks posed by "addictive" features, including infinite scrolling and intrusive notifications, in relation to major platforms, thereby increasing pressure on developers of children's services to revise attention-retention models and strengthen parental control.

Conclusion. The conducted study demonstrates that traditional interface design paradigms, developed primarily with adult users in view, prove insufficiently effective and, in a number of cases, potentially unsafe for child audiences, since they fail to account for the physiologically conditioned limits of cognitive information processing. Within the scope of the work, the stated objectives have been achieved: applied strategies for reducing cognitive load have been identified, and an adaptive interaction model has been formulated that corresponds to the age-specific characteristics of users.

The empirical component confirms that the introduction of automated scaffolding mechanisms increases task completion success to 85.3%, which exceeds average market benchmarks by 27% [12]. The minimization of extraneous load through visual restraint and the predictable organization of the interface leads to a 44% reduction in task completion time, a result that acquires particular significance under the conditions of a child's limited attentional resources [12; 14]. The author's proposed concept of the "Adaptive Interaction Loop" provides dynamic calibration of system complexity, reducing the risk of frustration under overload while, at the same time, preventing the loss of interest in excessively simplified scenarios. It was additionally established that, by 2025, data safety and privacy requirements (COPPA / GDPR-K) had in effect become integrated into the core of UX design and were stimulating a transition toward localized models of data processing [23–25].

The practical value of the study is determined by the possibility of applying the formulated principles and the accompanying metric tables in the development of educational and entertainment-oriented digital products for children. The

results presented may serve as a foundation for designing inclusive and safe digital environments that support the harmonious cognitive development of younger age groups. As a promising direction for subsequent work, consideration is given to the analysis of the long-term effects of adaptive interfaces in the context of the formation of self-regulation skills in children.

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