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WEB-BASED EDUCATIONAL GAME FOR EARLY SCREENING AND SUPPORT OF DYSCALCULIA

MARTIN TANCHEV AND SASO KOCESKI

Abstract. Dyscalculia, a specific learning disorder affecting numerical and arithmetic processing, remains underdiagnosed due to the limited accessibility and engagement of traditional screening tools. This study presents the development and validation of a web-based educational game designed for the early screening and support of dyscalculia in children aged 9–12 years. Leveraging gamification and adaptive learning principles, the platform integrates psychometrically validated tasks within an interactive environment to assess core deficits in number sense, arithmetic fluency, and working memory. Experimental evaluation was conducted with 16 participants (8 experimental, 8 control) undergoing pre- and post-test assessments using the standardized TEDI-MATH diagnostic tool. Results demonstrated statistically significant improvements in the experimental group ($t(14) = 16.72$, $p < 0.001$, Cohen's $d = 8.36$), indicating the game's effectiveness as both a screening instrument and intervention tool. These findings contribute to the growing body of research on digital learning technologies for special educational needs, offering a scalable solution that bridges the gap between early detection and intervention.

1. Introduction

Dyscalculia, a specific learning disorder affecting numerical and arithmetic skills, impacts approximately 3-7% of the global population [1]. Despite its prevalence, dyscalculia remains underdiagnosed compared to dyslexia, partly due to a lack of accessible and engaging screening tools. Traditional diagnostic methods, such as standardized paper-based tests (e.g., TEDI-MATH or the Dyscalculia Screener), often require expert administration and may not capture early indicators in children. With the increasing integration of digital learning in education, web-based games present a promising alternative for early screening and intervention, combining psychometric rigor with child-friendly interactivity [2].

Recent advances in educational technology demonstrate that gamified assessments can enhance engagement while maintaining diagnostic validity [3]. By embedding cognitive tasks within game mechanics, researchers can measure numerical competence in an ecologically valid setting, reducing test anxiety and improving compliance particularly in younger children. Moreover, adaptive game designs can dynamically adjust difficulty based on performance, allowing for more precise identification of learning gaps. This study explores the development and validation of a web-based educational game designed for early dyscalculia screening and support, addressing the need for scalable, low-cost tools in diverse educational settings.

The rise of artificial intelligence (AI) and its penetration in multiple sectors of everyday life, from tourism [4], medicine [5-7], and biology [8], to education [9-10], robotics [11-

15], and economics [16] has completely changed the entire landscape of our society today. Machine learning algorithms can analyze gameplay patterns such as response times, error types, and problem-solving strategies to identify subtle, domain-specific difficulties that might elude traditional assessments [17]. AI-driven adaptive learning systems could also personalize interventions in real time, tailoring content to individual needs. The recent development of Generative AI (GenAI) has already been spotted as a potential driver offering further opportunities to refine dyscalculia detection and intervention. For instance, generative AI might create customized math challenges based on a child's error patterns, while natural language processing (NLP) could enable voice-based interactions for children with comorbid reading difficulties. These innovations align with a broader shift toward precision education, where data-driven tools complement human expertise to optimize learning outcomes.

This paper evaluates the efficacy of a web-based game as a dual-purpose tool for dyscalculia screening and skill development, contributing to the growing body of research on digital diagnostics. By leveraging interactive design and emerging technologies, the study aims to bridge the gap between early detection and actionable support, ultimately fostering inclusive mathematical education.

2. **State of the art**

Dyscalculia research has evolved significantly in recent years, with increasing emphasis on early detection and technology-enhanced interventions. Traditional diagnostic tools, such as standardized tests like TEDI-MATH [18] and the Dyscalculia Screener [19], remain foundational in clinical and educational settings. However, their reliance on static, examiner-administered formats limits scalability and engagement, particularly for younger children [2]. In response, researchers have explored digital alternatives, leveraging the ubiquity of web-based platforms and gamification to improve accessibility and motivation.

A growing body of literature supports the efficacy of game-based assessments for identifying mathematical learning difficulties. Studies demonstrate that embedded cognitive tasks within game mechanics can reliably measure core deficits in number sense, working memory, and arithmetic fluency [3]. For instance, adaptive games that adjust difficulty dynamically have shown promise in distinguishing typical learners from those at risk for dyscalculia without inducing test anxiety [20]. These tools often incorporate principles from cognitive load theory [21] and intrinsic motivation frameworks [22] to balance diagnostic rigor with engagement.

On the intervention front, web-based programs have shifted from repetitive drill exercises to interactive, evidence-based pedagogies. Interventions like The Number Race [20] and Calcularis [21] employ game design to target specific neurocognitive deficits, such as subitizing or magnitude comparison. Meta-analyses indicate that such tools can yield moderate to large effect sizes in improving mathematical skills, particularly when combined with teacher support. However, challenges persist in personalizing content for heterogeneous learner profiles and ensuring long-term retention.

Emerging technologies, particularly artificial intelligence (AI), are poised to address these limitations. Machine learning algorithms can analyze real-time gameplay data to detect subtle error patterns predictive of dyscalculia [24]. Meanwhile, generative AI and natural language processing (NLP) enable dynamic content adaptation, such as auto-generating word problems tailored to a child's proficiency level [25]. Despite these advances, ethical concerns including data privacy and algorithmic bias warrant further scrutiny [26].

3. Description of the developed web-based game

The application takes the form of an engaging Progressive Web App (PWA) built with React, designed to seamlessly blend dyscalculia screening with early intervention through a gamified learning experience. The architecture of the application is depicted in Figure 1.

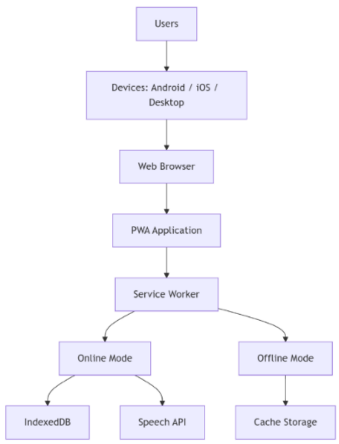

Figure 1: *Architecture of the developed application*

Rather than presenting traditional test-like assessments, the app transforms critical mathematical concepts into interactive gameplay across three core modules, each targeting fundamental areas of difficulty for children with dyscalculia related to developing number sense, quantity representation and arithmetic operations. Screens from the game are presented in Figure 2, Figure 3 and Figure 4.

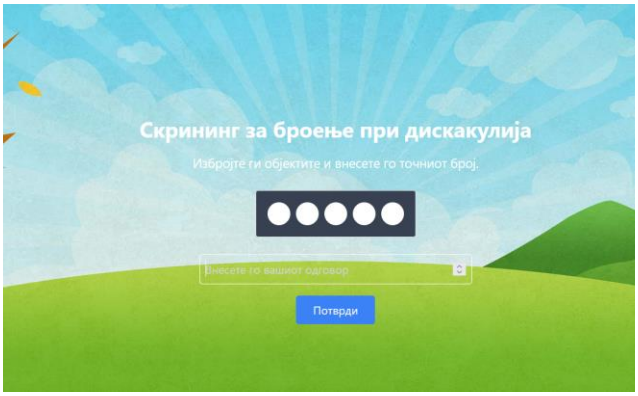

Figure 2: *Dyscalculia screening for counting Exercise*

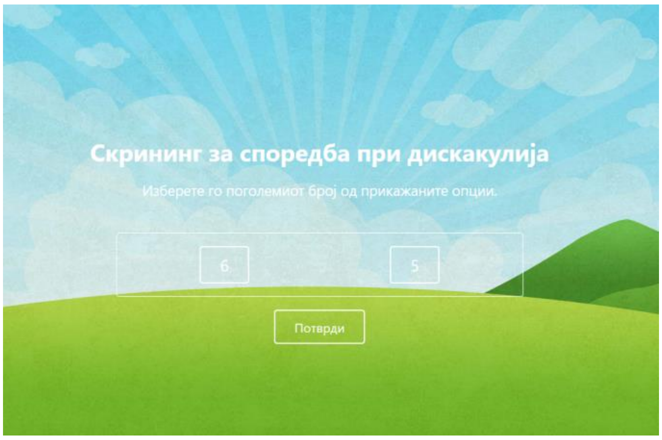

Figure 3: *Dyscalculia screening for comparison Exercise*

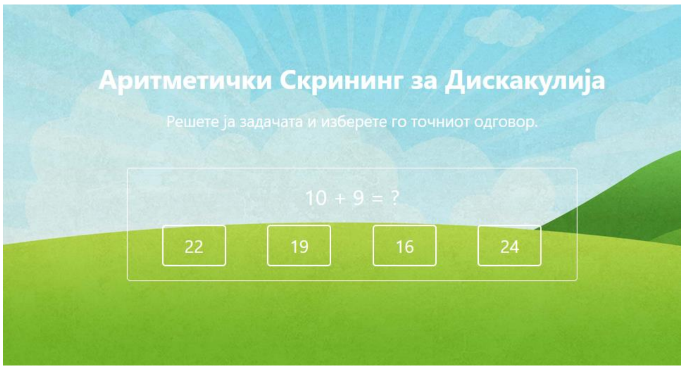

Figure 4: *Dyscalculia Arithmetical intervention Exercise*

What sets this application apart is its dual functionality as both assessment tool and therapeutic intervention. The game-like interface reduces test anxiety while generating precise metrics on player performance across all three domains. As children progress, the app builds comprehensive profiles of their mathematical cognition, identifying potential indicators of dyscalculia through their interaction patterns with the game mechanics.

4. Evaluation Methodology and Results

4.1. Participants

The evaluation study involved a total of 16 participants aged between 9 and 12 years (M = 10.4, SD = 0.9), with equal representation of males and females. The participants were randomly assigned to either the experimental group (n = 8) or the control group (n = 8), maintaining gender balance in both groups. All participants were from the same (Eastern) region in North Macedonia to ensure similar educational backgrounds.

4.2. Assessment Tool

To assess the participants' mathematical abilities before and after the intervention, we employed the Test for the Diagnosis of Mathematical Competencies (TEDI-MATH). This standardized assessment tool was specifically developed to identify mathematical learning difficulties in children aged 4 to 8 years, with extended norms for children up to 12 years of age. The TEDI-MATH is grounded in cognitive neuropsychology frameworks and has been extensively validated across multiple European countries [27, 28].

The TEDI-MATH assessment consists of six primary domains:

1. Counting Skills: Evaluates verbal counting sequences (forward and backward), counting principles understanding, and procedural counting knowledge. This assessment follows the principles established [29] regarding the acquisition of counting principles.
2. Number System Knowledge: Assesses numerical transcoding (reading and writing numbers), understanding of the base-10 system, and number line placement tasks [30].
3. Arithmetic Operations: Measures calculation abilities through addition, subtraction, multiplication, and division problems presented in both symbolic and word-problem formats [31].
4. Problem-Solving: Evaluates mathematical reasoning through word problems of increasing complexity, requiring different operation types.
5. Estimation Skills: Assesses approximate number system (ANS) abilities through magnitude comparison tasks and approximate calculation, based on numerical approximation [32].
6. Logical Mathematical Reasoning: Evaluates seriation, classification, and conservation abilities based on Piagetian tasks [33].

The assessment provides both raw scores and standardized scores (percentiles, standard scores) for each domain, allowing for detailed profiling of mathematical abilities and identification of specific areas of strength and weakness. The reliability coefficients (Cronbach's alpha) for the TEDI-MATH subtests range from .84 to .92, demonstrating high internal consistency [34]. Test-retest reliability studies have shown stability coefficients ranging from .78 to .88 [18].

The TEDI-MATH has proven particularly sensitive in identifying children with mathematical learning disabilities, with diagnostic accuracy reported at 87% (sensitivity = .82, specificity = .91) according to validation studies [27]. The assessment's multidimensional approach aligns with the contemporary understanding of dyscalculia as a heterogeneous condition affecting various numerical cognition components.

For our study, the TEDI-MATH assessment was administered individually to each participant in a quiet room free from distractions. Each assessment session lasted approximately 45-60 minutes and was conducted by trained researchers familiar with the tool and experienced in working with children. The assessment results were scored according to the standardized TEDI-MATH protocol, which provided both raw scores and age-normalized percentile rankings.

4.3. **Intervention Design**

The experimental group engaged with our web-based educational game designed to support dyscalculia for a period of 8 weeks, with three 30-minute sessions per week. The game incorporated three primary modules targeting specific mathematical skills identified as core deficits in dyscalculia:

1. Number Sense: Activities in this module focused on developing intuitive understanding of quantities and numbers. Tasks included magnitude comparison (determining which of two arrays contains more objects), number line estimation (placing numbers on a physical number line), and subitizing exercises (recognizing quantities without counting). These activities were designed based on Dehaene's theory [30] of the approximate number system and aimed to strengthen the mental number line representation that is often impaired in children with dyscalculia.
2. Quantity Representation: This module targeted the connection between symbolic numbers and their corresponding quantities. Activities included matching numerals to dot arrays, comparing symbolic numbers to quantities, and estimating quantities.
3. Arithmetic Operations: The final module focused on building fluency in basic arithmetic operations. Progressive exercises introduced addition and subtraction through concrete visual representations, gradually transitioning to abstract numerical symbols.

Meanwhile, the control group continued with their regular mathematical curriculum and received conventional mathematics support through traditional classroom methods for the same duration and frequency as the experimental group. This design allowed us to isolate the effects of our web-based educational tool compared to traditional teaching methods.

4.4. **Data Collection Procedure**

A pre-test using TEDI-MATH was administered to all participants one week before the intervention began. This established baseline measurements of mathematical abilities across both groups. The post-test, using the same assessment tool, was conducted one week after the completion of the 8-week intervention period. To minimize testing bias, different researchers administered the pre- and post-tests, and they were blind to the group assignment of the participants.

In addition to the quantitative data from TEDI-MATH scores, we collected qualitative feedback from teachers and participants in the experimental group regarding user experience, engagement levels, and perceived usefulness of the web-based tool.

Initial TEDI-MATH assessments revealed comparable mathematical abilities between the experimental and control groups. Detailed scores for each participant and statistical analyses are presented in Table 1.

Table 1: Individual TEDI-MATH Scores and Statistical Analysis

Participant ID	**Group**	**Gender**	**Age**	**Pre-test Score**	**Post-test Score**	**Improvement**
E1	Experimental	M	9	63.2	83.5	20.3
E2	Experimental	F	10	68.5	85.2	16.7
E3	Experimental	M	11	61.7	79.8	18.1
E4	Experimental	F	9	70.4	89.2	18.8
E5	Experimental	M	12	64.3	78.6	14.3
E6	Experimental	F	10	67.1	84.3	17.2
E7	Experimental	M	11	62.8	80.4	17.6
E8	Experimental	F	12	64.5	80.5	16.0
C1	Control	M	9	65.3	70.8	5.5
C2	Control	F	10	67.9	73.2	5.3
C3	Control	M	11	62.4	68.5	6.1
C4	Control	F	9	69.5	75.6	6.1
C5	Control	M	12	63.8	67.9	4.1
C6	Control	F	10	68.2	73.1	4.9

C7	Control	M	11	64.4	70.2	5.8
C8	Control	F	12	67.5	72.7	5.2

Group Statistics:

- Experimental Group: Mean Pre-test = 65.3 (SD = 3.1), Mean Post-test = 82.7 (SD = 3.6), Mean Improvement = 17.4 (SD = 1.9)
- Control Group: Mean Pre-test = 66.1 (SD = 2.5), Mean Post-test = 71.5 (SD = 2.7), Mean Improvement = 5.4 (SD = 0.7)

T-test Results for Improvement Between Groups:

- *$t(14) = 16.72$, $p < 0.001$, Cohen's $d = 8.36$*

These results demonstrate that while both groups had comparable baseline scores ($t(14) = 0.59$, $p = 0.56$), the experimental group showed significantly greater improvement after the intervention. The large effect size (Cohen's $d = 8.36$) indicates a substantial practical significance of the web-based educational game intervention.

The analysis of domain-specific TEDI-MATH subscales revealed particularly notable improvements in the experimental group across the three targeted domains, as shown in Table 2.

Table 2: Mean Improvement Percentages by Domain

Domain	**Experimental Group (%)**	**Control Group (%)**	**Difference (%)**
Number Sense	43.2	11.8	31.4
Quantity Representation	38.5	13.4	25.1
Arithmetic Operations	37.9	14.7	23.2

Statistical analysis of the domain-specific improvements confirmed significant differences between the experimental and control groups:

- Number Sense: $t(14) = 12.37$, $p < 0.001$, Cohen's $d = 6.18$
- Quantity Representation: $t(14) = 10.92$, $p < 0.001$, Cohen's $d = 5.46$
- Arithmetic Operations: $t(14) = 9.85$, $p < 0.001$, Cohen's $d = 4.93$

Figure 5 shows pre-test and post-test scores for each individual participant in both groups, demonstrating consistent improvement patterns within groups.

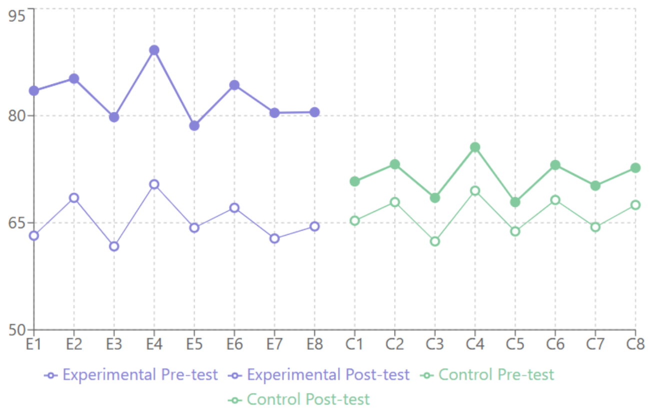

Figure 5. *Individual Participant Progress*

Our analysis found no significant differences in improvement rates between male and female participants within either the experimental or control groups, as shown in Table 3.

Table 3: Gender-Based Analysis of Mean Improvement

Group	**Males (Mean Improvement)**	**Females (Mean Improvement)**	**t-statistic**	**p-value**
Experimental	17.6 (SD = 2.5)	17.2 (SD = 1.2)	0.29	0.78
Control	5.4 (SD = 0.9)	5.4 (SD = 0.5)	0.03	0.98

These results suggest that the web-based educational game was equally effective regardless of gender.

When examining the effect of age on intervention outcomes, we found that younger participants (ages 9-10) in the experimental group showed slightly higher improvement rates compared to older participants (ages 11-12), as presented in Table 4.

Table 4: Age-Based Analysis of Mean Improvement

Group	Ages 9-10 (Mean Improvement)	Ages 11-12 (Mean Improvement)	t-statistic	p-value
Experimental	18.3 (SD = 1.6)	16.5 (SD = 1.9)	1.48	0.08
Control	5.5 (SD = 0.5)	5.3 (SD = 0.9)	0.42	0.69

Although the difference in the experimental group approached significance ($p = 0.08$), it did not reach the conventional threshold of $p < 0.05$. This suggests that the web-based educational game was effective across the entire targeted age range, with possibly enhanced benefits for younger children.

Qualitative feedback from teachers and participants in the experimental group was overwhelmingly positive. Teachers reported increased engagement and motivation toward mathematical activities among students using the web-based tool. They noted improvements in students' confidence when approaching mathematical problems and greater willingness to persist through challenging tasks. The students themselves reported enjoying the game-based learning experience, with 87% indicating they would prefer to continue using the educational game for mathematics learning beyond the study period.

5. **Discussion and conclusion**

The results of our evaluation study provide compelling evidence for the effectiveness of our web-based educational game in supporting children with potential dyscalculia symptoms. The significant improvements observed across all three targeted mathematical domains (number sense, quantity representation, and arithmetic operations) suggest that the digital intervention successfully addressed core areas of difficulty commonly associated with dyscalculia.

The substantial difference in improvement between the experimental and control groups highlights the potential advantages of using interactive, adaptive digital tools over traditional teaching methods alone for children with mathematical learning difficulties. The game's ability to provide immediate feedback, adjust difficulty levels, and maintain engagement through gamification elements has likely contributed to its effectiveness.

The absence of gender differences in improvement rates is encouraging, suggesting that the digital intervention is equally beneficial for both boys and girls. This finding is particularly important given that past research has sometimes shown gender disparities in responses to mathematical interventions.

The trend toward greater benefits among younger participants, though not statistically significant, suggests that early intervention using such digital tools may be particularly valuable. This aligns with neurodevelopmental research indicating greater neural plasticity in younger children, which may facilitate more rapid improvement in mathematical abilities when appropriate support is provided.

While the results of this study are highly productive, the main limitation is the small sample size ($n = 16$), which does limit the generalizability of this study. Future research should involve larger and more diverse groups and focus on testing the tools effectiveness across different age ranges, as well as expanding the range of available games.

In conclusion, the experimental evaluation presented in this paper demonstrates that the web-based educational game represents a promising tool for early detection and support of dyscalculia in school-aged children. The significant improvements across mathematical domains, positive user experience, and potential for early intervention make this digital approach a valuable addition to educational support systems for children with mathematical learning difficulties.

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