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Effects of the PCaRD digital game-based learning model on functional mathematical literacy in primary mathematics education

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ABSTRACT

This study investigated the effectiveness of the play, curricular activity, reflection, and discussion (PCaRD) instructional model in improving primary school students' functional mathematical literacy (FML). A quasi-experimental pretest–posttest control group (CG) design using intact classroom groups was employed. The sample consisted of 139 fourth-grade students from two public schools in Almaty, Kazakhstan. The experimental group (EG) received instruction based on the PCaRD model integrated with digital game-based learning (DGBL), whereas the CG received traditional teacher-centered instruction. Independent-samples t-test results confirmed baseline equivalence between the groups. The EG significantly outperformed the CG, indicating a moderate intervention effect. These findings suggest that structured DGBL implemented through the PCaRD model effectively enhances FML among primary school students. The study contributes to the literature by evaluating a structured pedagogical model for DGBL, examining FML as the primary learning outcome, and providing empirical evidence from primary education in Kazakhstan.

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1. INTRODUCTION

Mathematics education has become a central component of modern educational systems due to its strong connection with the development of 21st-century skills, including critical thinking, problem-solving, and analytical reasoning [1]. In contemporary education, the focus has shifted from procedural knowledge acquisition to the development of functional mathematical literacy (FML), which refers to the ability of learners to apply mathematical knowledge in real-life contexts [2]. International assessments such as the Programme for International Student Assessment (PISA) consistently indicate that a considerable proportion of primary school students struggle with applying mathematical concepts in unfamiliar, real-world situations, highlighting persistent challenges in mathematics education globally [3]. This persistent difficulty is particularly concerning because insufficient mathematical competence directly limits students' problem-solving abilities, especially in non-routine and real-life contexts. As a result, students often struggle to transfer mathematical knowledge beyond procedural classroom exercises, which restricts their capacity to make reasoned decisions and solve authentic problems in everyday situations.

Despite ongoing educational reforms in Kazakhstan aimed at improving student learning outcomes [4]–[6], evidence from international large-scale assessments indicates that challenges in mathematics

education remain persistent and systemic. According to the Organisation for Economic Co-operation and Development (OECD) PISA 2022, Kazakhstani students continue to perform below the OECD average in mathematics, with results showing limited improvement across assessment cycles [7]. A similar pattern is observed in the Trends in International Mathematics and Science Study (TIMSS). Primary school students in the country demonstrate comparatively stronger performance in routine procedural tasks but continue to face difficulties in applying mathematical knowledge to non-routine and context-based problems [8]. This gap is particularly urgent because it indicates that students may acquire procedural fluency without developing the deeper cognitive skills required for functional mathematical reasoning. Such a discrepancy has long-term consequences for learners' academic progression and their ability to engage with real-world quantitative problems.

Taken together, these international assessment results indicate that the primary challenge in Kazakhstan's mathematics education is not only related to knowledge acquisition, but more critically to the development of FML, particularly the ability to apply learned concepts in unfamiliar and practical contexts [9]. This limitation directly reflects the need for instructional approaches that move beyond traditional teacher-centered practices and explicitly support the development of transferable mathematical competencies. Previous research on digital game-based learning (DGBL) in mathematics education can be grouped into several major themes. The first stream of research has primarily examined students' motivation and engagement, demonstrating that digital games can increase learners' interest, participation, and positive attitudes toward mathematics [10]. A second stream has focused on mathematics achievement, reporting improvements in students' academic performance and conceptual understanding when digital games are effectively integrated into instruction [11]. However, considerably less attention has been devoted to FML, particularly learners' ability to transfer mathematical knowledge to authentic real-world situations.

Research focusing on mathematics achievement generally reports positive effects of DGBL on students' academic performance and conceptual understanding when game-based activities are supported by appropriate instructional design [12], [13]. At the same time, studies examining pedagogical implementation consistently emphasize that educational benefits depend less on the digital game itself than on the instructional framework in which it is embedded [14]. These findings highlight the importance of structured pedagogical models for maximizing the educational value of DGBL [15], [16].

The play, curricular activity, reflection, and discussion (PCaRD) model, developed by Foster and Shah [17], provides a structured framework for integrating DGBL through four phases: play, curricular activity, reflection, and discussion. It connects game-based experiences with formal mathematical concepts and supports deeper learning through reflection and collaborative discussion. When embedded within the PCaRD framework, DGBL connects gameplay with reflection and curricular activities, thereby supporting deeper conceptual understanding and knowledge transfer [18].

Existing studies predominantly investigate DGBL as a motivational tool rather than as a structured pedagogical intervention [19], [20]. Moreover, few studies have evaluated whether the PCaRD framework enhances FML using rigorous quasi-experimental designs in primary education, particularly in developing educational systems such as Kazakhstan. Consequently, empirical evidence regarding the instructional effectiveness of the PCaRD framework in improving FML remains limited.

This study contributes to the literature in three ways. First, it evaluates the PCaRD model as a structured pedagogical framework rather than examining DGBL as a generic instructional strategy. Second, it investigates FML as the primary learning outcome instead of focusing on mathematics achievement or student motivation. Third, it provides empirical evidence from primary education in Kazakhstan, where experimental research on structured instructional models remains limited.

Accordingly, this study aims to examine whether the PCaRD instructional model improves primary school students' FML. The following research question guided the study: Does this instructional model significantly improve students' FML? Based on this question, the hypothesis was that students in the experimental group (EG) would demonstrate significantly higher FML than those receiving traditional instruction.

2. THEORETICAL FRAMEWORK

The present study is grounded in complementary learning theories that collectively explain how the PCaRD model supports the development of FML. Together, these theoretical perspectives provide a conceptual explanation for the instructional processes through which DGBL facilitates meaningful mathematical learning. Experiential learning theory suggests that learning occurs through a continuous cycle of concrete experience, reflective observation, abstract conceptualization, and active experimentation [21]. Within the PCaRD model, students first engage in mathematical tasks through digital gameplay (play), apply mathematical concepts during curricular activities, reflect on their learning experiences (reflection), and discuss mathematical strategies with peers and teachers (discussion). This learning cycle promotes deeper

conceptual understanding and supports the transfer of mathematical knowledge to authentic situations. Constructivist learning theory further explains that knowledge is actively constructed through interaction with learning environments rather than passively received from teachers [22]. DGBL provides meaningful problem-solving experiences in which learners actively explore mathematical concepts [23], while the structured phases of the PCaRD model facilitate knowledge construction through guided reflection and collaborative discussion. The self-determination theory provides an additional explanation for the motivational value of DGBL [24]. Well-designed game environments support students' autonomy, competence, and relatedness, thereby enhancing intrinsic motivation and sustained engagement in mathematical learning [25]. These motivational processes increase learners' willingness to participate in cognitively demanding mathematical activities.

From the perspective of cognitive load theory, the structured sequence of the PCaRD model helps organize learning activities in ways that reduce unnecessary cognitive load while directing students' attention toward essential mathematical concepts [26]. Reflection and discussion further support schema construction by helping learners integrate new knowledge with prior understanding. Situated learning theory emphasizes that knowledge is acquired most effectively when learning occurs in meaningful and authentic contexts [27]. DGBL situates mathematical problems within realistic scenarios, allowing students to apply mathematical reasoning in contexts that resemble everyday situations [28]. This contextualized learning is closely aligned with the concept of FML. The OECD mathematical literacy framework defines mathematical literacy as the capacity to formulate, employ, and interpret mathematics in a variety of real-world contexts [29]. This framework provides the conceptual foundation for the present study by emphasizing the application and transfer of mathematical knowledge beyond routine classroom procedures. Accordingly, FML represents the primary educational outcome examined in this research. Taken together, these theoretical perspectives explain the instructional mechanism underlying the PCaRD model. Students first engage in mathematical experiences through digital gameplay, apply mathematical concepts during curricular activities, reflect on their learning, and discuss mathematical ideas with peers and teachers. These interconnected processes promote knowledge construction, facilitate the transfer of mathematical knowledge to authentic contexts, and ultimately contribute to the development of FML among primary school students. Figure 1 illustrates the theoretical framework underpinning the present study and the proposed mechanism through which the PCaRD model supports the development of FML.

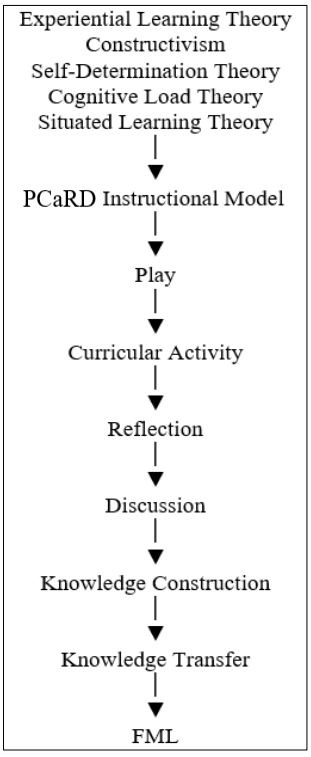


Figure 1. Conceptual framework of the study

3. METHOD

3.1. Research design

This study employed a quasi-experimental pretest–posttest control group (CG) design grounded in the methodological framework of Rogers and Révész [30]. The study involved two intact classroom groups: an EG receiving instruction through the PCaRD model and a CG receiving traditional teacher-centered instruction. Both groups completed identical pretest and posttest assessments to measure changes in FML over time. A quasi-experimental design was appropriate due to the impossibility of random assignment in authentic school environments. The pretest–posttest structure enabled assessment of both baseline equivalence and instructional effects while strengthening internal validity through within-group and between-group comparisons.

3.2. Participants

The participants of this study consisted of 139 fourth-grade primary school students enrolled in public schools in Almaty, Kazakhstan, as shown in Table 1. The study was conducted in two municipal schools located in the Almaly District of Almaty. A quasi-experimental cluster design with a pretest–posttest CG structure was employed using intact classroom groups, as random assignment of individual students was not feasible in the natural school context. A convenience sampling approach was employed because participant selection depended on school accessibility, administrative approval, and institutional willingness to participate in the study. Intact classroom groups were used to preserve the natural instructional environment and avoid disruption to regular school organization. Despite the use of convenience sampling, the quasi-experimental pretest–posttest design provided adequate internal validity by allowing baseline equivalence and intervention effects to be systematically examined.

The CG included 67 students enrolled in three intact 4th-grade classes (4A, 4B, and 4V) at the Municipal State Institution "School-Gymnasium No. 8" of the Education Department of Almaty. These classes consisted of 23, 22, and 22 students, respectively. The EG consisted of 72 students enrolled in three intact 4th-grade classes (4A, 4B, and 4V) at the Municipal State Institution "Gymnasium School No. 46" of the Education Department of Almaty. These classes included 25, 24, and 23 students, respectively. The participants' age ranged from 8 to 9 years (CG: M≈8.70, SD≈0.46; EG: M≈8.69, SD≈0.47).

All participants followed the same national primary mathematics curriculum, and both schools operated under the same municipal educational authority. The participating schools were selected based on institutional willingness to participate, accessibility for intervention implementation, and similarity in curricular organization. To minimize contextual variability, both schools followed standardized curricular requirements and comparable instructional time allocations for mathematics. Ethical approval for the study was obtained from the relevant institutional review board prior to data collection. Informed consent was obtained from school administrators, teachers, and parents of all participating students. Participation was voluntary, and confidentiality and anonymity of all student data were ensured throughout the study. No identifying personal information was collected, and all data were used solely for research purposes.

Table 1. Demographic characteristics of participants

Variable	CG (n=67)	EG (n=72)	Total
Age, M (SD)	8.47 (0.51)	8.52 (0.50)	8.50 (0.50)
Grade level	Grade 4	Grade 4	Grade 4
Boys, n (%)	31 (46.3)	36 (50.0)	67 (48.2)
Girls, n (%)	36 (53.7)	36 (50.0)	72 (51.8)
Number of classes	3	3	6

3.3. Procedure

The study was implemented within regular grade 4 mathematics instruction. The intervention was conducted over a 6-week period (September–October 2025) in two public schools in Almaty, Kazakhstan. The intervention was integrated into regularly scheduled mathematics lessons to preserve the natural classroom environment and maintain consistency with routine instructional practices. The procedure consisted of three sequential stages: pretest administration, intervention implementation, and posttest assessment.

3.3.1. Pretest phase

At the beginning of the study, both the experimental and CGs completed the FML pretest. The assessment was administered during normal classroom instructional periods to maintain normal classroom conditions and minimize disruption to the school timetable. All students completed the assessment under identical testing conditions.

Although the testing took place within regular classroom lesson periods, the administration followed a strictly standardized research protocol. The test was administered by trained researchers using identical written and oral instructions across all classrooms, while teachers remained present only for organizational purposes and did not influence the assessment process. Students completed the test individually within a fixed 45-minute time limit, and no explanations, hints, or clarifications were provided during testing.

3.3.2. Intervention phase

Following the pretest, the EG received instruction using the PCaRD DGBL model, while the CG continued with traditional teacher-centered instruction aligned with the national curriculum. Both groups were taught three times per week and covered identical curricular topics to ensure instructional equivalence. In total, the intervention comprised 18 mathematics lessons delivered over a 6-week period.

Instruction in the EG followed the PCaRD instructional cycle, consisting of four phases: play, curricular activity, reflection, and discussion. In the play phase, students engaged with curriculum-aligned digital mathematics games that presented contextualized problem-solving tasks in arithmetic, fractions, measurement, geometry, and reasoning. The digital activities were delivered through browser-based educational platforms and teacher-managed applications using tablet computers and interactive classroom displays. In the curricular activity phase, game-based experiences were explicitly linked to formal mathematical concepts from the national curriculum. In the reflection phase, students analyzed their solution strategies and articulated their reasoning, while in the discussion phase they participated in teacher-guided interactions to compare solutions and consolidate conceptual understanding.

The digital learning activities were implemented using tablet computers and interactive classroom displays available in the schools. The selected platforms provided structured, age-appropriate mathematics tasks designed for grade 4 learners and supported interactive, game-based problem-solving in classroom settings. Both groups were taught by certified primary mathematics teachers with comparable professional qualifications and 11–12 years of teaching experience. Both groups followed the same national mathematics curriculum and the same instructional schedule (three mathematics lessons per week for six weeks).

Prior to the intervention, the teachers in the EG participated in a structured 6-hour training workshop to ensure the consistent implementation of the PCaRD model, whereas the teachers in the CG received standardized instructions regarding the study procedures and continued delivering conventional teacher-centered instruction. The training included the theoretical foundations of the PCaRD model, demonstration of each instructional phase, and practical classroom implementation procedures. Implementation fidelity was assessed using a 15-item classroom observation checklist completed weekly by two independent observers. The checklist evaluated adherence to each phase of the PCaRD instructional model, including play, curricular activity, reflection, and discussion. Observation records indicated that overall implementation fidelity exceeded 90% across the intervention period.

3.3.3. Posttest phase

At the end of the 6-week intervention, both the experimental and CGs completed the FML posttest. The posttest was identical in structure and administration procedure to the pretest and was conducted under the same controlled conditions. Testing was conducted under standardized classroom conditions under researcher supervision using identical scripts and fixed time limits. No teacher assistance, explanations, or feedback were provided during the assessment process. Table 2 summarizes the weekly structure of the PCaRD intervention.

Table 2. Weekly structure of the PCaRD intervention

Week	PCaRD intervention activities
Week 1	Introduction to digital learning environment; guided implementation of all PCaRD phases
Week 2	PCaRD cycle applied to arithmetic operations and fractions
Week 3	PCaRD activities focused on mathematical problem-solving and reflection
Week 4	Context-based mathematical tasks and collaborative discussion activities
Week 5	Full implementation of all PCaRD phases across lesson activities
Week 6	Consolidation activities and preparation for posttest assessment

3.4. Instruments

The study used a FML test adapted from the OECD PISA mathematical literacy framework and publicly available released items. The instrument was designed to measure students' ability to apply mathematical knowledge in everyday problem-solving situations. The test consisted of 24 items covering number operations, fractions, measurement, geometry, and data interpretation.

To establish content validity, the instrument was reviewed by five experts in primary mathematics education and educational assessment. The experts evaluated the relevance, clarity, and curriculum alignment of each item using a structured evaluation form. Based on their feedback, several items were revised to improve wording clarity and alignment with grade 4 FML objectives. The overall content validity index (CVI) was 0.89, indicating satisfactory content validity. Figure 2 presents the cognitive process dimensions of the FML test.

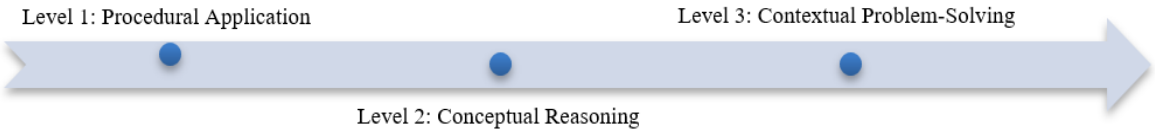


Figure 2. Cognitive process dimension

A pilot study was conducted prior to the main data collection to evaluate the clarity, difficulty level, and appropriateness of the FML test items. The pilot involved 32 grade 4 students from a comparable primary school not included in the main study. Item difficulty and item discrimination analyses were conducted to identify ambiguities in wording and to evaluate the appropriateness of item complexity for the target age group. Based on pilot results, minor revisions were made to improve wording clarity and age appropriateness. No major structural changes were required, as the overall item distribution and difficulty level were appropriate for the target population.

Pilot testing demonstrated acceptable internal consistency (Cronbach's α=0.81), with item discrimination indices ranging from 0.34 to 0.69 and corrected item-total correlations indicating adequate differentiation between lower- and higher-performing students. After refinement, the final instrument demonstrated good reliability (Cronbach's $\alpha \approx 0.82$), confirming its suitability for measuring FML in primary school contexts. The same instrument was administered as both pretest and posttest under standardized conditions to ensure measurement equivalence across time points. Table 3 presents representative sample items across cognitive levels and mathematical domains.

Table 3. Sample FML test items by cognitive level and mathematical domain

Level	Mathematical domain	Sample item
Level 1	Arithmetic operations	A shop sells apples in packs of 5. How many apples are there in 3 packs?
Level 1	Division	A student shares 48 pencils equally among 6 classmates. How many pencils does each classmate receive?
Level 1	Geometry (perimeter)	A square playground has sides of 6 cm on a map. What is its perimeter?
Level 2	Fractions	A student has 3/4 of a chocolate bar and eats 1/4 of it. How much of the chocolate bar remains?
Level 2	Measurement	A bottle contains 1 liter of juice. After 250 ml is removed, how much juice remains in the bottle?
Level 2	Time and distance reasoning	A bus travels 60 km in 1 hour. How far will it travel in 3 hours if the speed remains the same?
Level 3	Proportional reasoning	A recipe uses 2 cups of flour for 4 people. How many cups are needed for 10 people?
Level 3	Financial literacy	A school bag costs 5000 tenge and is sold with a 20% discount. What is the final price?
Level 3	Multi-step spatial reasoning	A classroom floor measuring 8 m by 6 m must be covered with square tiles of 1 m² each. How many tiles are needed to cover the floor completely?

3.5. Data analysis

Data analysis included descriptive and inferential statistics. Independent samples t-tests were used to confirm baseline equivalence between groups. Paired-samples t-tests examined within-group changes over time. A one-way analysis of covariance (ANCOVA) was used as the primary inferential method to assess the effect of the intervention on posttest FML scores while controlling for pretest performance. ANCOVA was selected because it provides a more accurate estimation of treatment effects by adjusting for baseline differences. Assumptions of normality and homogeneity of variance were tested using Shapiro–Wilk and Levene's tests, respectively, and were satisfied. The assumption of homogeneity of regression slopes was also tested by examining the interaction between the covariate (pretest scores) and the group factor, which was found to be non-significant, indicating that the relationship between pretest and posttest scores did not differ across groups. All statistical analyses were performed using IBM SPSS Statistics (version 26).

4. RESULTS

Descriptive statistics in Table 4 showed that both the EG and the CG improved their FML scores from pretest to posttest. However, the EG demonstrated a substantially greater improvement following the PCaRD DGBL intervention than the CG. At posttest, the EG achieved a higher mean FML score than the CG, suggesting greater improvement in FML after the intervention.

Table 4. Descriptive statistics of FML scores

Group	Pretest M (SD)	Posttest M (SD)	Gain
CG	11.82 (2.41)	13.02 (2.48)	+1.20
EG	11.95 (2.38)	15.01 (2.44)	+3.06

An independent samples t-test was conducted to examine baseline differences between the EG and CG at pretest. The results indicated no statistically significant differences between groups, confirming baseline equivalence prior to the intervention. A visual comparison of pretest and posttest performance in Figure 3 further confirmed these findings. Both the EG and CG showed increases in FML scores over time. However, the EG demonstrated more pronounced gains following the intervention.

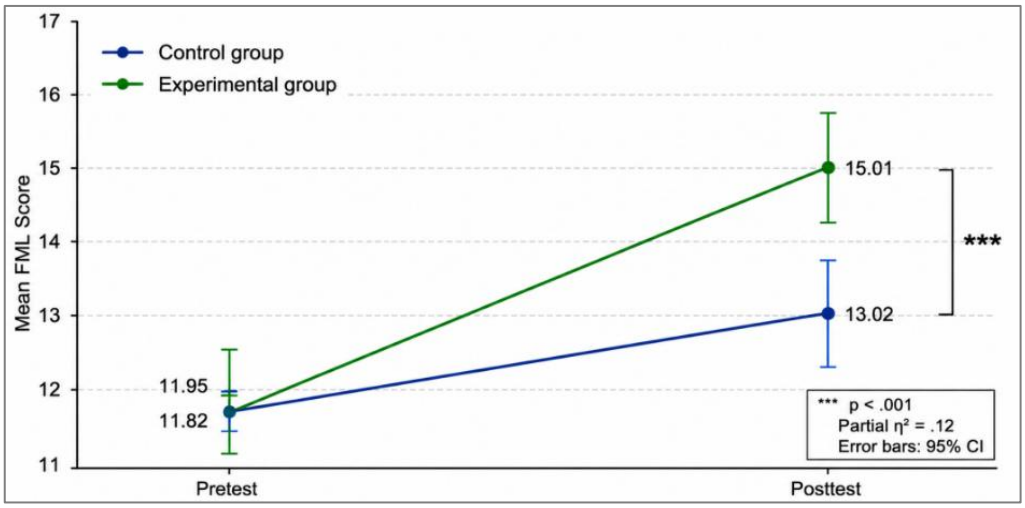


Figure 3. Changes in FML scores from pretest to posttest

Prior to the inferential analyses, the assumptions of normality and homogeneity of variance were examined, as shown in Table 5. The results indicated that FML scores were normally distributed for both the pretest and posttest ($p>0.05$) and that the assumption of homogeneity of variance was satisfied ($p=0.24$). These findings supported the use of parametric statistical analyses.

ANCOVA was conducted to examine the effect of instructional condition on posttest FML scores while controlling for pretest performance, as shown in Table 6. After adjusting for baseline differences, a significant effect of group was observed on posttest FML scores, $F(1, 136)=18.64$, $p<0.001$, partial $\eta^2=0.12$. Pretest scores also made a significant contribution to the model, $F(1, 136)=6.71$, $p=0.011$, partial $\eta^2=0.05$. These results indicate that the PCaRD intervention had a moderate effect on students' FML.

Figure 4 presents the adjusted posttest means estimated through ANCOVA analysis. After controlling for pretest scores, the EG demonstrated higher adjusted FML scores than the CG. The separation between the adjusted group means indicates differences in posttest performance after accounting for baseline variation.

Table 5. Assumption testing results for parametric analyses

Test	Variable	Statistic	*p*
Shapiro–Wilk	Pretest scores	0.98	0.11
Shapiro–Wilk	Posttest scores	0.97	0.08
Levene's test	Posttest scores	1.42	0.24

Table 6. ANCOVA results for posttest FML scores

Source	SS	*df*	MS	*F*	*p*	Partial η^2
Pretest scores (covariate)	42.18	1	42.18	6.71	0.011	0.05
Group	117.12	1	117.12	18.64	<0.001	0.12
Error	854.21	136	6.28	—	—	—

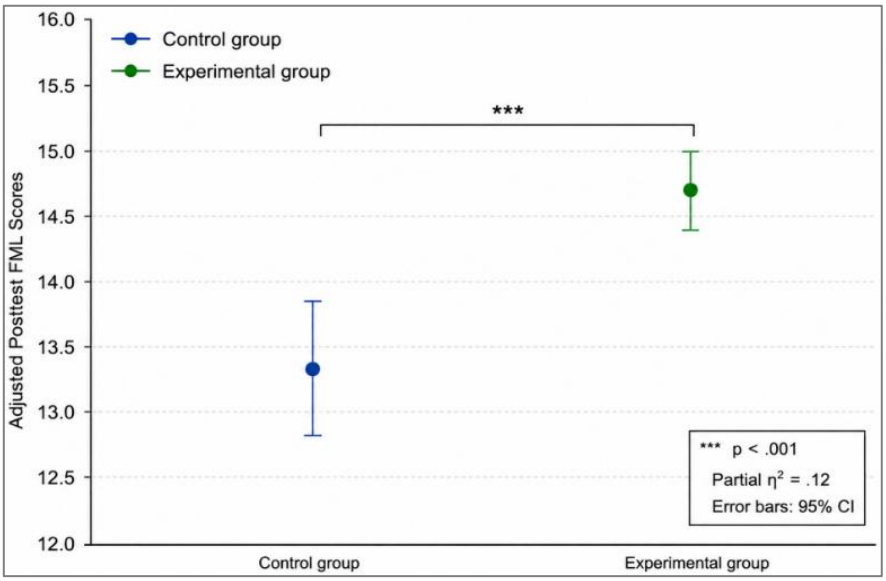


Figure 4. Adjusted posttest FML scores by group

Finally, paired-samples t-tests were conducted to examine within-group changes in FML scores from pretest to posttest, as shown in Table 7. Significant improvements were observed in both groups. The CG demonstrated a significant increase in FML scores, $t(66)=5.46$, $p<0.001$, whereas the EG showed a substantially larger improvement, $t(71)=12.97$, $p<0.001$. These findings provide further evidence of the effectiveness of the PCaRD DGBL model in improving FML compared with traditional instruction.

Table 7. Paired-samples t-test results for within-group comparisons

Group	MD	*t*	*df*	*p*	95% CI
CG	1.20	5.46	66	<0.001	[0.76, 1.64]
EG	3.06	12.97	71	<0.001	[2.59, 3.53]

5. DISCUSSION

The findings indicate that students exposed to the PCaRD model achieved significantly higher FML outcomes compared to those receiving traditional instruction, even after controlling for prior achievement levels. This suggests that structured integration of DGBL can enhance students' ability to apply mathematical knowledge in unfamiliar problem-solving contexts [31]. This effect can be explained through several complementary instructional mechanisms grounded in the theoretical framework of the present study. First, the play phase provides immediate feedback that enables students to identify and correct errors while actively exploring mathematical concepts [32]. Second, contextualized game scenarios promote contextual learning, allowing students to apply mathematical reasoning in authentic situations rather than isolated procedural exercises [33]. Third, the reflection and discussion phases encourage collaborative reflection and metacognitive regulation by requiring students to explain their reasoning, compare alternative solution strategies, and evaluate their own understanding [34]. Finally, the repeated application of mathematical concepts throughout the PCaRD instructional cycle provides cognitive scaffolding, facilitating knowledge construction and transfer to unfamiliar mathematical situations.

These instructional processes collectively promote deeper conceptual understanding by encouraging learners to externalize reasoning, evaluate alternative solution strategies, and refine their mathematical thinking through social interaction [35]. These mechanisms are directly aligned with the development of FML, which requires both conceptual understanding and transfer of knowledge to non-routine contexts [36].

These results are consistent with previous research demonstrating that DGBL is most effective when digital games are embedded within structured pedagogical scaffolds rather than used as standalone tools [37]. The present findings are consistent with international studies conducted across diverse educational contexts, which similarly reported that structured DGBL improves higher-order mathematical reasoning and problem-solving skills [38]. However, unlike many previous studies that primarily examined students' motivation, engagement, or general mathematics achievement, the present study specifically investigated FML as the primary educational outcome [39].

In addition, the study contributes empirical evidence from a primary education context in Central Asia, where research on structured DGBL implementation remains limited [40], [41]. Teachers should therefore integrate digital learning environments within guided instructional cycles that promote reasoning, explanation, and collaborative knowledge construction [42]. At the curriculum level, the PCaRD model provides a structured bridge between procedural mathematics instruction and the development of transferable problem-solving competencies required for real-world application.

In the context of Kazakhstan's ongoing educational reforms, which emphasize competency-based learning and digital transformation of classroom practices, the findings are particularly relevant for primary mathematics education [43], [44]. The integration of PCaRD aligns with national priorities aimed at developing students' FML as part of the updated curriculum standards. Therefore, the results provide evidence that structured DGBL can support the implementation of these national educational goals in real classroom settings.

From a practical perspective, the findings have implications for multiple educational stakeholders. For teachers, the results suggest that digital mathematics games should be integrated within structured instructional cycles that explicitly connect gameplay with curricular activities, guided reflection, and collaborative discussion rather than being used as isolated motivational tools. For school leaders, successful implementation of structured DGBL requires adequate digital infrastructure, institutional support, and opportunities for continuous professional development. For curriculum developers, the findings indicate that pedagogical frameworks such as PCaRD can be incorporated into mathematics curricula to strengthen FML through authentic problem-solving activities. For educational policymakers, the results provide empirical support for initiatives promoting competency-based mathematics education and the meaningful integration of digital technologies into primary classrooms. For teacher education programs, the findings highlight the importance of preparing future teachers to design and implement structured DGBL environments. Finally, for digital learning designers, the study emphasizes that educational games should be developed not only to increase student engagement but also to support reflection, collaborative discussion, and the transfer of mathematical knowledge to authentic real-world contexts. Overall, the study demonstrates that the educational effectiveness of DGBL depends primarily on sound pedagogical design rather than on technology itself.

Despite the findings, several limitations should be acknowledged when interpreting the results of this study. The sample was drawn from only two public schools located in one district of Almaty, Kazakhstan, and included only grade 4 students. Although this ensured curricular and contextual consistency, it limits the generalizability of the findings to other grade levels, regions, school types, or educational systems. In addition, the study employed a quasi-experimental design without random assignment of participants, which is common in educational research conducted in authentic school settings but may introduce selection bias despite the use of baseline equivalence testing and ANCOVA. Furthermore, students and teachers were aware of their participation in the intervention, and therefore a Hawthorne effect cannot be completely excluded, as increased attention and participation may have influenced students' performance independently of the instructional model.

Moreover, the intervention duration of six weeks may be considered relatively short for examining long-term effects of the PCaRD model on FML, leaving the sustainability of learning gains uncertain. The study also focused exclusively on cognitive outcomes (FML), without examining affective or behavioral variables such as motivation, engagement, or attitudes toward mathematics, which are important dimensions of DGBL. Although implementation fidelity was monitored, some variation in teacher delivery and classroom dynamics may still have influenced the consistency of the intervention across groups. Finally, the absence of a delayed posttest (follow-up assessment) prevents evaluation of the long-term retention and transfer of FML skills. Overall, these limitations should be considered when interpreting the findings. Nevertheless, the present study provides robust initial evidence for the effectiveness of the PCaRD model in improving FML among primary school students. Future research should employ randomized or multi-site designs, include students from different grade levels and geographical regions, and incorporate delayed posttests to examine the long-term sustainability of FML outcomes.

6. CONCLUSION

This study examined the effectiveness of the PCaRD DGBL model in enhancing FML among primary school students in Kazakhstan. The findings demonstrated that students who learned through the PCaRD model achieved significantly higher FML outcomes than those receiving traditional instruction. These results suggest that integrating DGBL within a structured pedagogical cycle of play, curricular activity, reflection, and discussion effectively enhances students' ability to apply mathematical knowledge in authentic problem-solving contexts. Theoretically, this study extends the literature on DGBL by demonstrating that improvements in FML can be explained through structured pedagogical processes rather than digital technology alone. By integrating constructivist learning theory, experiential learning theory, cognitive load theory, self-determination theory, and situated learning theory, the study provides a comprehensive theoretical explanation of how the PCaRD model facilitates knowledge construction, knowledge transfer, and the development of FML.

Practically, the findings suggest that teachers should integrate digital games within structured instructional cycles that combine gameplay with curricular activities, reflection, and collaborative discussion. Furthermore, school leaders, curriculum developers, teacher educators, and educational policymakers may use the PCaRD framework to support competency-based mathematics education and the effective integration of digital technologies into primary classrooms. The findings suggest that the effectiveness of DGBL may depend more on the pedagogical structure through which meaningful mathematical reasoning is fostered, knowledge is transferred, and FML is developed than on the technology itself. Although this study was conducted in Kazakhstan, the pedagogical principles underpinning the PCaRD model may be applicable beyond a single national context. By integrating DGBL with structured reflection and collaborative discussion, the model provides a transferable instructional framework that may assist mathematics educators in diverse educational settings. These findings may therefore inform curriculum design, teacher professional development, and mathematics instruction in education systems seeking to strengthen students' FML through evidence-based digital game-based pedagogy.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The corresponding author may provide study data upon reasonable request.

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