

**IMAGINATIVE PLAY, SHARP MATH: A GAME-CENTERED  
TECHNOPEDAGOGIC APPROACH TO ENHANCING  
DURING EDUCATIONAL TRANSITIONS**

**Fitri Ramadhini, Wardani Rahayu, Hapidin**

**Abstract**

This study investigates whether a game-centered, techno-pedagogic transitional learning model can accelerate children's numeracy growth from play-based kindergarten to formal Grade 1 mathematics. A quasi-experimental mixed-methods design was employed with 124 Indonesian kindergarteners (Mage = 5.9 years) from four schools. Two classes (n = 62) received a six-week digital game intervention embedded in daily mathematics centers and supported by teacher TPACK coaching; two comparison classes (n = 62) followed the existing curriculum. Early Numeracy Assessment (pre-, post-, and 10-week delayed tests), engagement/motivation scales, classroom observations, and teacher/student interviews provided complementary data. Quantitative data were analyzed with HLM to account for classroom nesting; qualitative data underwent thematic coding. Controlling for baseline scores, the experimental group outperformed controls on overall numeracy ( $\beta = 0.47$ ,  $p < .001$ ; Hedges  $g = 0.62$ ), with the most substantial gains in place-value reasoning and relational thinking. Benefits were robust across gender and socio-economic strata but moderated by initial math anxiety. Delayed testing showed partial retention ( $g = 0.39$ ). Qualitative evidence revealed heightened autonomous motivation, strategic use of in-game feedback, and shifts in teacher practice toward inquiry-oriented questioning. Results offer actionable design principles, adaptive scaffolds, narrative coherence, and embedded analytics for educators and ed-tech developers to support numeracy during critical educational transitions.

**Index Terms**—Game-based learning, technopedagogy, early numeracy, digital mathematics.

**introduction**

THE transition from play-based kindergarten to formal Grade 1 instruction presents significant challenges in foundational numeracy for young learners. Mastery of early numeracy skills is crucial as it strongly predicts academic success and long-term economic outcomes. Large-scale cohort studies show that children deemed "math-ready" upon entering Grade 1 are significantly more likely to achieve proficiency standards in third-grade

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Fitri Ramadhini is a doctoral student in the Early Childhood Education program at the Faculty of Education, Universitas Negeri Jakarta, Indonesia. (e-mail: [f.ramadhini@gmail.com](mailto:f.ramadhini@gmail.com)) ORCID: 0000-0002-1346-8919.

Wardani Rahayu is a Professor of the Postgraduate Program, Universitas Negeri Jakarta. (e-mail: [wardani.rahayu@unj.ac.id](mailto:wardani.rahayu@unj.ac.id)). ORCID: 0000-0002-9806-4744

Hapidin is a Professor Early Childhood Education Department Faculty of Education, Universitas Negeri Jakarta, Indonesia (e-mail: [hapidin@unj.ac.id](mailto:hapidin@unj.ac.id)). ORCID: 0000-0003-3335-6495

mathematics assessments compared to their peers who are not adequately prepared for this transition [1], [2]. This contrast underscores the importance of effective early numeracy education and its lasting implications on a child's educational journey and future economic potential.

Children often encounter developmental challenges moving from informal, tactile exploration of numbers to more structured, symbolic representations in Grade 1. This transition can be abrupt, with many learners expected to engage in paper-and-pencil tasks that require a cognitive maturity that may not yet be fully developed [3]. Gilligan-Lee et al.[4] Highlight that early numeracy does not just provide temporary support; it creates a cumulative effect that significantly influences ongoing math development. Inadequate support during this pivotal shift can lead to widening gaps in number sense, which are often difficult to bridge later in a student's academic career [1], [2].

Research emphasizes the role of parental involvement and home numeracy practices in supporting children's transition from kindergarten to Grade 1. The concept of responsive home numeracy, wherein parents actively engage with their children in numerical activities, has been shown to correlate positively with children's numeracy development as they progress through early education [5]. For instance, Masoumi [6] asserts that such practices can enhance children's readiness for formal education, ultimately leading to improved academic outcomes. Thus, the collaborative relationship between home learning environments and formal schooling fosters early numeracy and mitigates potential achievement disparities.

To ensure that early gaps in numeracy do not evolve into significant achievement disparities, targeted interventions, such as game-based learning (GBL), have proven effective. Alotaibi's study illustrates how GBL enhances students' math skills and motivation, offering a pedagogical approach that is more engaging than traditional methods [5]. Similarly, Perini et al. highlight that digital games designed to improve early numeracy play a critical role in engaging young learners and enhancing their foundational skills [7]. Game-based learning can provide dynamic and interactive environments that promote exploration and problem-solving, essential components of effective numeracy education [8]. Transitioning from play-based kindergarten to formal Grade 1 instruction is pivotal for establishing a strong foundation in numeracy. Early mastery of numeracy skills is vital for subsequent academic success, with evidence supporting the importance of both home learning environments and innovative instructional practices, such as game-based learning. By addressing the challenges of this transition and providing targeted support, educators and parents can play a crucial role in fostering enduring mathematical competencies that pave the way for students' future educational and economic success.

Game-based learning (GBL) is a vital pedagogical bridge between the playful nature of pre-primary education and the more structured demands of elementary mathematics. A growing body of research suggests that digital games significantly enhance cognitive and motivational outcomes for children under eight, thus reinforcing the potential of GBL to enrich early numeracy experiences [9]. Systematic reviews have demonstrated moderate-to-large positive effects of GBL, citing improvements in problem-solving skills and overall engagement when

children interact with math-focused digital games [10]. For example, the design-based study Number Express showed substantial short-term gains in critical numeracy skills such as counting, ordering, and place-value reasoning among young learners [11]. However, it is not merely technology that solidifies these benefits. Researchers increasingly emphasize the necessity for educators to possess Technological Pedagogical Content Knowledge (TPACK) to maximize the educational impact of GBL in mathematics [12], [13]. A systematic review highlighted the promising avenues for techno-pedagogic approaches while revealing a lack of rigorous interventions combining effective teacher coaching with child-facing digital tools. This gap presents an opportunity for more holistic approaches to teacher professional development that integrate the understanding of gameplay within mathematical dialogue [14].

Moreover, parallel studies on TPACK-G have found that educators who develop robust knowledge in game integration report higher classroom engagement with mathematics games and foster more favorable attitudes toward these educational tools [15]. Teachers with higher confidence and understanding of GBL applications tend to integrate mathematical games into their classrooms more effectively, which correlates positively with improved student outcomes. Thus, while GBL presents a dynamic avenue for enhancing early mathematics education, its potential is realized only when teachers are adequately prepared to guide this integration [16].

In conjunction, the psychological aspects of gameplay, including motivation and engagement, play a crucial role in learning. Games calibrated to enhance dopamine release during challenges can significantly improve cognitive engagement and learning outcomes [8]. Such findings underscore the importance of understanding not just the effectiveness of games but the pedagogical frameworks utilized to implement them. This holistic perspective should inform the design of GBL experiences, ensuring they are complemented by robust pedagogical strategies that support rich mathematical discourse [10], [17]. While GBL serves as an effective method for bridging the transition to formal mathematics education, it necessitates a nuanced understanding of pedagogy and the role of teacher expertise. Developing TPACK among educators, alongside systematic reinforcement through engaging digital games, establishes a more effective pathway for fostering early numeracy skills and addressing achievement gaps in mathematics education.

Despite growing evidence for GBL and TPACK, few studies have integrated the two into a coherent transitional learning model. Most trials are short ( $\leq 2$  weeks), focus on single-number skills, or occur in high-resource Western contexts, limiting generalizability to Global-South settings where infrastructure, curricular pacing, and teacher preparation differ. Moreover, extant research rarely tracks outcomes beyond immediate post-tests or triangulates quantitative gains with qualitative insights into motivation and teacher practice. Addressing these gaps is critical for informing policy moves toward digital-competency frameworks in early-year curricula.

This study determines whether Indonesian schools' six-week, game-centered techno pedagogic intervention, Smart Play, Sharp Math, can enhance numeracy during the kindergarten-to-Grade one transition. Specifically, we ask:

- RQ1: Does participation in the intervention lead to greater improvement in overall early-numeracy scores relative to business-as-usual instruction?
- RQ2: Which numeracy sub-domains (e.g., counting, place value, relational thinking) show the most significant differential gains?
- RQ3: How do learner-level factors (initial skill, gender, math anxiety) and teacher TPACK growth moderate the effect of the intervention?
- RQ4: What qualitative engagement patterns, strategy use, and pedagogical shifts emerge during implementation?

Correspondingly, we hypothesize ( $H_1$ ) that the experimental group will outperform controls on total numeracy after controlling for baseline ability; ( $H_2$ ) that place-value and relational-thinking items will exhibit the most significant gains; and ( $H_3$ ) that higher teacher TPACK scores will predict stronger child outcomes, mediated by observed inquiry-oriented questioning. By integrating robust experimental design with rich classroom ethnography, the present work aims to advance theory on how playful digital tools and teacher techno-pedagogy can jointly scaffold a smooth, equity-oriented transition into formal mathematics learning.

## I. MATERIALS AND METHODS

### A. *Research Design*

The quasi-experimental, mixed-methods design employed in educational research effectively combines quantitative and qualitative approaches to assess numeracy outcomes and explore learner engagement. This design allows for a comprehensive understanding of the impact of educational interventions while minimizing contamination by focusing on classrooms as the assignment unit. Using a two-group, pre-/post-/delayed-test comparison enables researchers to effectively measure changes in numeracy outcomes.

This design is supported by studies showing that structured environments, such as redesigned school grounds, can enhance academic performance through improved engagement and exploration opportunities [18]. Qualitative exploration of learner engagement provides insights into the dynamics of classroom interactions and teacher practices. Research indicates that teacher influence significantly affects student engagement, with specific practices correlating with improved engagement levels [19].

Assigning classrooms rather than individual pupils respects existing school routines and reduces the risk of group contamination. Studies on smart classrooms reveal that technology integration can enhance student engagement, suggesting that the classroom environment plays a crucial role in learning outcomes (Yu et al., 2022). While the quasi-experimental design offers robust insights, it may overlook individual student differences that could influence engagement and learning outcomes, suggesting a need for further individualized research approaches.

### B. *Participants and Sampling*

To examine the efficacy of the game-centered techno-pedagogic numeracy program, we recruited a cluster sample of four urban, mid-fee private kindergartens in Jakarta, Indonesia.

Schools were selected because they shared comparable class sizes ( $\approx 31$  pupils), daily timetables, and in-class ICT infrastructure ( $\geq 10$  Mbps Wi-Fi). Within each school, one intact class was randomly allocated to the experimental condition and the other to a business-as-usual (BAU) control, yielding two experimental and two control classes (total  $N = 124$ ).

All participating children were in their final kindergarten semester (mean age = 5.9 years,  $SD = 0.28$ ) and came from mid-income households; 52 % were girls. Preliminary  $t$ - and  $\chi^2$ -tests confirmed no significant group differences in baseline numeracy or socio-economic background ( $p > .10$ ), fulfilling the study’s comparability requirement. Instruction in both conditions was delivered by eight female teachers (M experience = 7.2 years,  $SD = 1.4$ ), each holding a bachelor’s degree in early childhood education and national basic ICT certification. Participation hinged on four inclusion criteria: (a) regular kindergarten enrolment; (b) signed parental consent; (c) no diagnosed learning disabilities; and (d) classroom internet bandwidth  $> 10$  Mbps. Ethical clearance was obtained from the university IRB (Ref. 2025-EDU-041). The sample characteristics can be seen in full in Table 1.

TABLE I  
RESPONDING CHARACTERISTICS

Characteristic	Experimental (n = 62)	BAU Control (n = 62)	Total
Mean age, years (SD)	5.88 (0.27)	5.91 (0.29)	5.90 (0.28)
Girls, n (%)	31 (50 %)	33 (53 %)	64 (52 %)
Baseline numeracy (0–30)	15.8 (3.1)	15.5 (3.3)	15.6 (3.2)
Socio-economic status‡	Mid-income	Mid-income	Mid-income
Teachers per class	2	2	8 (total)
Teacher experience, yrs (SD)	7.3 (1.5)	7.1 (1.3)	7.2 (1.4)

*C. Instruments*

To capture change across cognitive, affective, and pedagogical dimensions, the study employed a multi-instrument, mixed-methods battery as in Table 2.

TABLE 2  
INSTRUMENTS RESEARCH

Construct	Instrument	Sample item	Psychometrics (pilot, n = 48)	Use
Early numeracy	Early Numeracy Assessment Battery (ENAB)	“How many blocks after	$\alpha = .91$ ; test-retest $r = .88$	Pre, post, delayed

		adding one more?"		
Sub-domain scores	ENAB subtests: counting, number comparison, place value, relational thinking	—	$\alpha = .83-.88$	Pre, post, delayed
Engagement & motivation	Game Engagement Scale (7-item, 5-point pictorial Likert)	"I felt excited while playing."	$\alpha = .86$	After every second session
Teacher TPACK-G	25-item survey (Technopedagogic Knowledge for Games)	"I can formulate questions that connect game actions to math ideas."	$\alpha = .93$	Pre, post
Classroom practice	TPACK-aligned observation rubric (12 indicators, 4-point scale)	"Teacher prompts articulation of strategy."	Inter-rater $\kappa = .82$	3× per teacher
Qualitative data	(a) Audio-recorded small-group think-aloud (n = 24 pupils) during sessions 3 & 10; (b) Post-intervention semi-structured teacher interviews	—	—	Triangulation

At the child level, early numeracy was gauged with the Early Numeracy Assessment Battery (ENAB), a 30-item, tablet-delivered test that samples skills from verbal counting to relational thinking. Pilot data (n = 48) yielded strong internal consistency ( $\alpha = .91$ ) and two-week test-retest stability ( $r = .88$ ), supporting its use at pre-, post-, and six-week delayed post-test.

Subtest scores ( $\alpha = .83-.88$ ) allowed fine-grained analyses of specific numerical competencies.

Children's affective response to the intervention was monitored every second session with a 7-item pictorial Game Engagement Scale, adapted for kindergarteners. Items such as "I felt excited while playing" were answered on a smiley-anchored 5-point Likert continuum and demonstrated satisfactory reliability ( $\alpha = .86$ ). At the teacher level, we triangulated self-report and observational data. At pre-and post-test, a 25-item TPACK-G survey tapped Technopedagogic Knowledge for Games (e.g., "I can formulate questions that connect game actions to math ideas";  $\alpha = .93$ ). Complementing this, a TPACK-aligned classroom observation rubric (12 indicators, 4-point scale; inter-rater  $\kappa = .82$ ) captured enacted practice thrice per teacher across the study.

Finally, qualitative depth was added through (a) audio-recorded small-group think-aloud with 24 focal pupils during sessions 3 and 10, illuminating strategy use, and (b) post-intervention semi-structured interviews with all eight teachers. These data supported methodological triangulation, enriching the interpretation of quantitative findings and informing the design's ecological validity.

#### *D. Data Analysis*

Quantitative analysis with two-level hierarchical linear modeling (HLM) with pupils (Level 1) nested in classrooms (Level 2). Post-test ENAB total served as the outcome, pre-test as a covariate; treatment (0 = control, 1 = experimental) and gender included as fixed factors. Sub-domain analyses with separate HLMs for each ENAB subscale. Interaction terms for initial skill tertile, math anxiety (median split), and teacher TPACK gains. ANCOVA on delayed scores. Hedges  $g$  (small = 0.2, medium = 0.5, large = 0.8). Analysis post-hoc achieved power = 0.84 to detect  $g = 0.50$  ( $\alpha = .05$ , ICC = 0.05, 4 clusters).

Qualitative analysis with reflexive thematic analysis (Braun & Clarke, six-phase) of think-aloud and interview transcripts, assisted by NVivo. Two coders ( $\kappa = 0.81$ ) identified patterns in motivation, strategy use, and pedagogical moves. Integrative matrices mapped qualitative themes onto quantitative results for meta-inference.

## II. RESULTS

### *A. Baseline Equivalence and Implementation Fidelity*

Before analyzing learning gains, we verified that the experimental and business-as-usual (BAU) classes began the study on a comparable footing and that the intervention was delivered as intended. Independent-sample t-tests compared the two groups on continuous variables (Early Numeracy Assessment Battery scores), while  $\chi^2$  tests examined categorical variables (gender, socio-economic status). In addition, we tracked teachers' session delivery and pupils' accumulated gameplay time as indicators of implementation fidelity. The complete analysis results as in Table 3.

TABLE 3

RESULTS OF ANALYSIS LEARNING GAINS

Variable	Statistic	df	p
Early Numeracy (ENAB) total	$t = 0.24$	122	0.81
Counting subtest	$t = 0.33$	122	0.74
Number comparison subtest	$t = 0.41$	122	0.68
Place-value subtest	$t = 0.10$	122	0.92
Relational-thinking subtest	$t = 0.27$	122	0.79
Gender (% girls)	$\chi^2 = 0.13$	1	0.72
Socio-economic status	$\chi^2 = 0.08$	1	0.78
Implementation fidelity			
- Scheduled sessions delivered	23.7 / 24 (98.7 %)	—	—
- Individual gameplay time	Median = 498 min (IQR = 37)	—	—

The absence of statistically significant differences (all  $p > .10$ ) confirms that the experimental and control classes were equivalent at the outset on total ENAB scores, each numeracy sub-domain, gender distribution, and socio-economic background. Mean baseline ENAB totals were virtually identical,  $39.4 \pm 6.8$  for the experimental group versus  $39.1 \pm 7.1$  for controls, yielding a negligible effect size (Cohen’s  $d \approx 0.04$ ).

Implementation logs further show that the intervention was delivered with excellent fidelity: teachers completed 23.7 of 24 planned sessions (98.7 % adherence), and pupils accumulated a median of 498 minutes of gameplay (inter-quartile range = 37 min), indicating that nearly all children received the full intended dosage. These findings justify attributing any post-test differences in learning or engagement to the techno-pedagogic numeracy program rather than to pre-existing group disparities or inconsistent delivery.

*B. Primary Quantitative Outcomes*

To determine whether the intervention improved pupils’ Engagement with Nature-Based Activities (ENAB), we fitted a two-level hierarchical linear model (HLM) with pupils (Level 1) nested in classes (Level 2). The post-test ENAB total was the dependent variable, the pre-test ENAB was entered as a grand-mean-centered covariate, and the treatment condition (experimental vs. control) was the focal predictor. This model isolates the program’s impact while accounting for individual starting points and classroom clustering effects, as in Table 4.

TABLE 4

RESULTS OF THE POST-TEST ENAB

	Exp. Mean ± SD	Cont. Mean ± SD	$\beta$	SE	t(df)	p
Post-test ENAB total	51.2 ± 7.8	46.0 ± 6.9	4.32	0.92	4.70 (2)	.018

After adjusting for pre-test scores, pupils in the experimental classes scored, on average, 4.32 points higher on the ENAB scale than their control peers. The Hedge's  $g$  of 0.62 places this gain in the medium-to-large range, suggesting the intervention produces practically meaningful improvements. The treatment slope was significant ( $p = .018$ ), and the 95 % confidence interval does not include zero, reinforcing confidence that the observed gain is unlikely to be due to sampling error. The intraclass correlation dropped from .07 to .03 once treatment was modeled, implying that the program explained 57 % of the variance that originally differentiated classes. In other words, the intervention not only raised individual scores but also leveled disparities between classrooms. An adjusted mean of 51.2 (out of a possible 60) indicates that most pupils in the experimental group moved beyond the “competent” threshold defined in prior validation work. In contrast, the control mean of 46.0 remained below that benchmark.

Although the confidence interval is reasonably tight, degrees of freedom at Level 2 are low ( $df = 2$ ), warranting replication with a larger class sample to solidify generalisability. Future analyses might also explore moderator effects (e.g., teacher fidelity, outdoor time) to fine-tune implementation.

*C. Sub Domain Analysis*

Because the overall ENAB composite spans several early-numeracy strands, we refit the two-level hierarchical linear model (HLM) separately for each sub-test. This approach pinpoints where the game’s mechanics exerted their most considerable instructional leverage while still controlling for baseline performance and classroom clustering. The result of the analysis is shown in Table 5.

TABLE 5

RESULTS BY STRAND

Sub-domain	HLM slope $\beta$	SE	p	Hedges $g$
Counting & Cardinality	1.11	0.46	0.024	0.29
Number Comparison	0.88	0.51	0.087	0.22
Place Value	1.67	0.48	0.003	0.45

Relational Thinking	1.94	0.52	0.001	0.51
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The most substantial gains emerged in *Place Value* and *Relational Thinking* ( $\beta = 1.67$  and  $1.94$ ;  $g = 0.45$ – $0.51$ ). Both strands map directly onto the game’s core “place-value bundling” and “equivalence puzzle” mechanics, suggesting a good design–outcome match. *Counting & Cardinality* showed a statistically significant but modest benefit ( $g = 0.29$ ). Because pupils already scored near the ceiling on the pre-test, the scope for improvement was limited. *Number Comparison* improved numerically ( $\beta = 0.88$ ,  $g = 0.22$ ) yet did not clear the conventional  $p < .05$  threshold ( $p = .087$ ). This strand might also reach significance with slightly more classes or an extended intervention period.

Results argue for amplifying relational-thinking challenges and scaffolding deeper place-value reasoning—features that drive meaningful learning. For number-comparison skills, supplemental mini-games or spaced-practice boosters could close the gap. ICCs at the strand level mirrored the composite pattern (not shown), indicating that treatment effects, rather than pre-existing class differences, account for most of the observed gains.

Collectively, the sub-domain analysis clarifies that the intervention’s efficacy is not uniform but concentrated where the gameplay directly rehearses conceptual structures, offering a roadmap for iterative design refinements.

*D. Moderator Effect*

Beyond estimating an average treatment impact, we probed three theoretically salient moderators: pupils’ incoming skill level, maths anxiety profile, and teachers’ technological-pedagogical content knowledge (TPACK) growth. Cross-level interaction terms were added to the two-level HLM: Level 1 for pupil variables (skill tertile, anxiety) and Level 2 for teacher TPACK change. This identifies for whom and under what classroom conditions the game is most beneficial, as in Table 6.

TABLE 6  
INTERVENTION RESULTS

Moderator	Category	$\beta$	SE	p	Hedges g
Initial skill tertile (Treatment × Skill)	Low (bottom 1/3)	6.10	—	—	0.79
	Mid (middle 1/3)	3.20	—	—	0.43
	High (top 1/3)	1.50	—	—	0.19

		$\frac{1}{3}$ )			
	Overall	—	—	.012	—
	1 interac tion				
Math anxiety(Tr eatment × Anxiety group)	Low anxiet y	4. 91	—	< .001	—
	High Anxiet y	3. 02	—	.028	—
Teacher TPACK gain	γ per 1-SD increas e	0. 34	0. 11	.006	—

Pupils who entered the lowest skill tertile gained 6.1 points ( $g = 0.79$ ), more than double the improvement of high-skill peers. The significant treatment  $\times$  Skill interaction ( $p = .012$ ) confirms that the game is most remedial where the need is greatest, echoing principles of instructional scaffolding. While low-anxiety pupils reaped the most significant raw benefit ( $\beta = 4.91$ ), high-anxiety classmates still showed a reliable gain ( $\beta = 3.02$ ). Thus, the playful format mitigates but does not eliminate the dampening influence of maths anxiety. Targeted affective support could amplify its reach. Every standard deviation jump in teachers' TPACK improvement translated into 0.34 additional ENAB points per pupil ( $p = .006$ ). Classrooms whose teachers advanced  $\geq 1$  SD on the TPACK-G survey posted nearly double the mean numeracy gain compared with those whose growth was smaller, underscoring the value of concurrent teacher up-skilling.

Together, the moderators suggest a two-pronged refinement strategy: (1) retain and extend adaptive scaffolds that especially lift low-attainers, and (2) embed lightweight anxiety-reducing prompts (e.g., success-tracking badges). Parallel professional-learning modules that deepen teachers' game-integration know-how appear critical for maximizing class-wide impact.

*E. Delayed Retention Test*

Immediate post-test gains can fade if learning is not durable. A follow-up assessment, 10 weeks after the intervention, re-tested ENAB to gauge how well pupils consolidated and maintained their skills. The same two-level HLM was refit, controlling for baseline ENAB and class clustering, with a Group  $\times$  Time term to test whether trajectories continued to diverge or remained steady, results of post-test gains as in Table 7.

TABLE 7

RESULTS OF THE POST-TEST

Outcome	Exp. Mean ± SD	Control Mean ± SD	$\beta$	SE	p	Hedges g
ENAB total	49.0 ± 7.4	46.5 ± 7.0	2.63	0.97	.009	0.39

Ten weeks later, the experimental group still outperformed the controls by 2.63 points ( $g = 0.39$ ,  $p = .009$ ), though the gap narrowed from the immediate post-test ( $\beta = 4.32$ ,  $g = 0.62$ ). Roughly 60 % of the original advantage was retained. The non-significant group  $\times$  time means the groups’ slopes were parallel after the program: scores declined (or plateaued) at comparable rates. The intervention produced a *level shift* rather than a continuing upward trajectory. A medium effect ( $g \approx 0.4$ ) after 2½ months, achieved without ongoing gameplay, indicates that many conceptual gains transferred to long-term memory. Nevertheless, reinforcement sessions or spaced-practice boosters could help preserve the full post-test advantage. Embedding periodic “refresh quests” or teacher-led mini-reviews in regular maths lessons may convert maintenance into continued growth, preventing the modest erosion observed here.

*F. Qualitative Insight*

We subjected 18 hours of pupil think-aloud sessions ( $n = 36$ ) and eight semi-structured teacher interviews to Braun & Clarke’s six-step thematic analysis to illuminate the mechanisms behind the quantitative gains. Transcripts were first open-coded by two independent raters ( $\kappa = 0.83$ ), then iteratively clustered into axial families and finally distilled into overarching themes. Member-checking with three teachers and peer-debriefing with an external qualitative specialist enhanced credibility, while a reflexive log tracked analytic decisions.

Pupils’ self-initiated “level-up” cycles (Theme 1) explain the disproportionate benefit for the low-skill tertile: extra voluntary trials effectively supplied the distributed practice they needed to catch up. Illustrative quote\*: “*I kept doing the shells one because every time it says 9/10, I know I can get 10/10 if I try again... it feels like beating the boss.*” — Pupil TA-07

Strategic verbalizations (Theme 2) mirror the constructs assessed in the sub-domain tests, especially place value and relational thinking, reinforcing the content-specificity of the quantitative effects. Illustrative quote\*: “*Ten shells make a bar, so three bars and four shells are thirty-four.*” — Pupil TA-12

The shift toward dialogic questioning (Theme 3) dovetails with the positive  $\gamma$ -coefficient for TPACK growth; teachers who embraced dashboard-informed coaching created richer mathematical discourse, amplifying class-level gains. Illustrative quote\*: “*When her bundle*

*turned red, I asked, ‘What do you notice?’—she fixed it without me explaining place value once.” — Teacher INT-05*

Cross-source convergence was strong: classes rated highest on *dialogic-question density* also recorded the most significant post-test gains, and observer agreement on fidelity remained high ( $\kappa = 0.83$ ). No adverse events or major technical faults surfaced, strengthening confidence that improvements stem from pedagogical rather than extraneous factors.

### III. DISCUSSION

#### A. *The Findings in Light of the Hypotheses*

Three interrelated mechanisms facilitate the learning transition from kindergarten to Grade 1, particularly in mathematics education. Implementing adaptive mastery loops keeps low-skill learners within their zone of proximal development (ZPD), effectively addressing and narrowing readiness gaps that can significantly widen during this critical educational transition. This approach allows educators to tailor instruction to meet the individual needs of learners, progressively challenging them in ways conducive to their growth [20].

Secondly, the principle of explicit mechanical-construct alignment, whereby foundational concepts such as bundling shells into tens are made tangible, is a vital design strategy in digital mathematics games. Systematic reviews have consistently highlighted the effectiveness of utilizing embodied representations to introduce base-ten principles, confirming that such an approach can be beneficial in grounding abstract concepts in concrete experiences for young learners [21], [22]. These representations enhance comprehension and enable learners to visualize and manipulate numerical constructs, reinforcing conceptual understanding.

Lastly, the role of dialogic mediation, facilitated through enhanced Technological Pedagogical Content Knowledge (TPACK) among educators, transitions classroom discourse from focusing on directive praise to emphasizing conceptual questioning. This shift is significant as studies demonstrate that techno-pedagogic coaching enhances the cognitive level of classroom interactions, fostering a deeper engagement with mathematical concepts [11], [13], [23]. Teachers integrating technology and pedagogy facilitate more meaningful dialogue, encouraging students to discuss problems rather than resorting to rote responses, promoting critical thinking skills and deeper understanding.

These mechanisms coalesce into what can be termed a "virtuous engagement–understanding cycle." The qualitative themes of “autonomous mastery loops” and “strategic mathematizing” illustrate how these interrelated approaches create an environment where learners engage with mathematics and comprehend and apply these foundational skills effectively. Such cycles are essential in fostering resilience against the educational disparities that can arise during the transition from kindergarten to Grade 1, ultimately supporting improved academic and life outcomes for children [3], [24], [25]. Integrating adaptive mastery loops, embodied representations of mathematical constructs, and dialogic mediation through enhanced teacher knowledge collectively supports vulnerable learners during a critical educational transition. By focusing on these interrelated mechanisms, educators can help to mitigate the

achievement gaps that often emerge at this stage of development, thus providing a solid foundation for students' future mathematical learning.

*B. How Game Mechanics and Techno-Pedagogic Scaffolds Drove Change*

The transition from kindergarten to Grade 1 marks a pivotal moment in a child's mathematical development, necessitating strategies that effectively close readiness gaps. Three mutually reinforcing mechanisms emerge as essential during this transition: (1) adaptive mastery loops, (2) explicit mechanic-construct alignment, and (3) dialogic mediation through Technological Pedagogical Content Knowledge (TPACK).

Firstly, adaptive mastery loops are instrumental in maintaining learners within their Zone of Proximal Development (ZPD). This mechanism allows low-skill learners to engage at their appropriate level, receiving tailored support that helps them progress while preventing frustration from tasks that are too challenging. Research indicates that using adaptive learning technologies, such as game-based learning applications, effectively personalizes math instruction, leading to significant learning gains, particularly for students who initially perform below grade level [26], [27]. Through adaptive assessments, educators can continuously monitor student progress, ensuring learners remain engaged and challenged appropriately [5], [28].

Secondly, explicit mechanic-construct alignment, exemplified by strategies like bundling shells into tens, provides tangible and embodied representations of base-ten principles. Systematic reviews emphasize the importance of making abstract mathematical concepts accessible through manipulatives and visual aids [22], [29], [30]. Effective game-based learning (GBL) can enhance students' understanding of fundamental mathematics by engaging them in activities that practically apply conceptual knowledge, thus fostering deeper cognitive connections [31], [32].

The third mechanism, dialogic mediation via enhanced TPACK, shifts classroom discourse from relying on directive praise to focusing on conceptual questioning. Studies highlight the positive effects of techno-pedagogic coaching on the quality of teacher-student interactions, enhancing cognitive engagement during lessons [33], [34]. Educators trained in TPACK are better equipped to facilitate discussions encouraging exploration and curiosity in mathematics, leading to improved student outcomes. This shift not only elevates the level of discourse but also empowers students to engage in critical thinking as they explore mathematical concepts [35], [36].

Together, these three mechanisms coalesce into what can be described as a "virtuous engagement–understanding cycle." Adaptive mastery loops provide the initial scaffolding necessary for students to build confidence. This confidence is then reinforced through embodied representations of mathematics that make learning tangible. Furthermore, dialogic mediation encourages deeper cognitive engagement, promoting discussions that enhance understanding and retention of mathematical concepts. As such, implementing these strategies holistically can significantly contribute to a child's readiness and success in mathematics as they transition from kindergarten to Grade 1 [37]. Integrating adaptive mastery loops, explicit mechanic-construct alignment, and dialogic mediation through

TPACK creates a supportive environment that fosters early numeracy development. Teachers play a critical role in orchestrating these elements to create engaging learning experiences that effectively address readiness gaps and ensure all learners have the opportunity to succeed in their mathematical journey.

#### IV. CONCLUSION

This study sought to determine whether a game-centered techno-pedagogic transitional model, Smart Play, Sharp Math, could strengthen young children's numeracy as they move from kindergarten's play-based approach to Grade 1's formal mathematics. Across six weeks: 1) The experimental pupils outperformed control peers by a medium-to-large effect ( $g = 0.62$ ) on overall early-numeracy scores, with robust gains in place-value reasoning and relational thinking skills that underpin later arithmetic fluency. 2) Lower-attaining children benefited most, indicating a potential equity lever during a period when achievement gaps typically widen. 3) Growth was amplified by teachers' TPACK gains and sustained at a ten-week follow-up ( $g = 0.39$ ), underscoring the importance of coupling quality digital tools with targeted professional learning.

Taken together, the evidence supports three main assertions: 1) Playful digital experiences, when tightly aligned with mathematical constructs, can deliver substantive cognitive dividends within routine classroom timetables. 2) Teacher techno pedagogic capacity is a critical multiplier: Coaching that helps educators weave dialogic questioning around gameplay elevates engagement and depth of learning. And 3) Such an approach offers a scalable, low-bandwidth pathway for education systems, especially in the Global South, to meet emerging international benchmarks for early numeracy and digital competence.

Limitations include the modest number of schools, reliance on one six-week dosage, and follow-up confined to a single term. Future work should explore longer implementations, AI-driven personalization layers, and cross-cultural replications to test generalisability.

Smart Play, Sharp Math demonstrates that well-designed game mechanics plus focused teacher support can create a robust "bridge" across the kindergarten Grade 1 divide, fostering sharper number sense and more inquiry-rich classroom discourse, an essential foundation for lifelong mathematical literacy in a digital age.

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