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Research Paper

Numeracy-on-a-Budget: A Design-Based Study of Low-Cost Embodied Numeracy Using Recycled Manipulatives in Early Childhood

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Abstract

This study investigates how a low-cost, embodied numeracy intervention using recycled manipulatives supports early mathematical learning in a preschool classroom. Employing a design-based research (DBR) approach, the study examines an initial design iteration integrating three theoretical principles: embodied cognition, guided play, and scaffolded instruction through a least-to-most prompting hierarchy. The intervention was implemented over two weeks with four children aged 4–5 years, comparing a baseline worksheet-based phase with a play-based bottle-cap activity. Findings indicate consistent improvements across two key indicators, matching quantity to numerals and numeral recognition, with mean scores increasing from 1.50 to 2.75. Beyond outcome gains, process-level analysis revealed the emergence of touch-based counting, increased engagement, and early peer interaction. Mechanism-level findings suggest that embodied interaction, structured prompting, and the use of concrete manipulatives jointly supported the stabilization of one-to-one correspondence and the integration of symbolic and non-symbolic representations.The study contributes to early childhood numeracy research by demonstrating how low-cost, recyclable materials can function as cognitively meaningful tools when embedded within a theoretically informed design. The resulting design principles offer a scalable and contextually adaptable framework for numeracy instruction in resource-constrained settings. While findings remain exploratory, they provide initial evidence for the potential of design-informed, embodied learning approaches to enhance early mathematical development.

Keywords: *early numeracy; embodied learning; recycled manipulatives; design-based research; preschool education*

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INTRODUCTION

Foundational early numeracy, encompassing number recognition, one-to-one correspondence, counting principles, and ordinality, has been consistently identified as a robust predictor of later mathematics achievement and broader academic trajectories (Daucourt et al., 2021; ten Braak et al., 2022). Meta-analytic and longitudinal evidence demonstrates that early mathematical competencies are not only stable over time but also strongly associated with subsequent learning outcomes across domains, including literacy and executive function development (Daucourt et al., 2021; Schneider et al., 2018). Despite this well-established predictive role, a persistent challenge remains: translating foundational numeracy constructs into pedagogically effective, scalable, and context-sensitive classroom practices, particularly in resource-constrained early childhood education (ECE) settings (Aunio et al., 2021; Dietrichson et al., 2022).

A growing body of research has emphasized the effectiveness of play-based and game-based pedagogies in supporting early mathematical learning. Large-scale randomized controlled trials and meta-analyses indicate that guided play, when aligned with explicit learning goals, can yield moderate to large gains in cognitive and socio-emotional outcomes (Skene et al., 2022; Størksen et al., 2023). In parallel, mechanism-focused studies highlight the role of embodied cognition, suggesting that physical interaction with manipulatives can strengthen numerical understanding by grounding abstract concepts in sensorimotor experience (Gilligan-Lee et al., 2023; Skulmowski & Rey, 2018). Guided play, which combines child-led exploration with intentional instructional goals, has been shown to support both engagement and learning outcomes in early childhood settings (Weisberg et al., 2016). These findings collectively underscore the importance of integrating engagement, embodiment, and instructional intentionality in early numeracy interventions.

However, three critical gaps remain insufficiently addressed in the current literature. First, while the benefits of manipulatives are well documented, most studies rely on commercially produced or digitally mediated materials, limiting applicability in low-resource contexts where access to such tools is constrained (Byrne et al., 2023). Second, although embodied and play-based approaches are often studied independently, there is limited empirical work examining how low-cost, physically embodied activities, designed and implemented within authentic classroom routines, activate specific learning mechanisms such as one-to-one correspondence stabilization or error-reduction in counting processes (Orrantia et al., 2022; Eason & Ramani, 2020). Third, existing research tends to prioritize large-scale interventions, leaving a gap in practice-proximal, classroom-embedded evidence that captures how instructional micro-strategies (e.g., prompting sequences, touch-counting routines) operate in real-world teaching environments (Murtagh et al., 2022; Williams et al., 2022).

Addressing these gaps, the present study investigates a teacher-designed, low-cost numeracy intervention using recycled bottle caps as manipulatives within routine preschool instruction. Rather than testing effectiveness in a controlled experimental sense, this study adopts a practice-embedded, descriptive design to document how a structured, embodied, and resource-efficient activity can support key numeracy processes. Importantly, the intervention integrates a least-to-most prompting hierarchy with a "count-while-touching" routine, enabling examination of how embodied interaction and instructional scaffolding jointly contribute to learning progression. This study makes three contributions to the field. First, it extends the literature on embodied numeracy learning by demonstrating how recycled, low-cost manipulatives can function as cognitively meaningful tools, not merely as substitutes for commercial materials (Byrne et al., 2023; Gilligan-Lee et al., 2023). Second, it provides mechanism-oriented insights into how specific instructional routines—particularly touch-based counting and structured prompting—may stabilize one-to-one correspondence and enhance symbolic–nonsymbolic mapping (Orrantia et al., 2022; Skene et al., 2022). Third, it contributes practice-proximal evidence that bridges the gap between theory and implementation, offering a scalable, sustainable, and contextually adaptable model for early numeracy instruction in resource-limited settings (Aunio et al., 2021; Dietrichson et al., 2022). This study addresses the following question: how do low-cost embodied manipulatives, combined with structured prompting, support early numeracy development in authentic classroom settings?

LITERATURE REVIEW

Early numeracy, encompassing number recognition, one-to-one correspondence, counting principles, ordinality, and simple comparison—is a well-established predictor of later mathematics achievement and broader school readiness. Meta-analytic and longitudinal evidence shows that children's math-specific experiences, including the quality of the home math environment, are reliably associated with mathematics outcomes from preschool into the early grades (Daucourt et al., 2021; Napoli & Purpura, 2018). Translating these foundations into everyday practice is especially important for early childhood programs serving diverse and resource-constrained contexts, where teachers need feasible ways to keep mathematical ideas salient within developmentally appropriate, play-rich instruction.

A growing body of experimental and quasi-experimental research indicates that play-based and game-based pedagogies strengthen preschoolers' learning when activities embed explicit mathematics goals in engaging routines. A large randomized controlled trial of a Playful Learning Curriculum reported gains in school-readiness skills within play-oriented ECEC settings (Størksen et al., 2023), and a recent systematic review and meta-analysis concluded that game-based learning in early childhood yields moderate-to-large effects across cognitive and socio-emotional domains (Alotaibi, 2024). These results support the design of low-tech, high-engagement tasks that sustain children's interest without diluting the instructional focus on numeracy concepts.

Mechanism-focused studies further highlight the value of concrete, hands-on materials. Work on embodied and spatially grounded learning shows that physical manipulatives can produce larger and more consistent gains in spatial and mathematical outcomes than non-embodied alternatives (Gilligan-Lee et al., 2023). Comparative findings also suggest that, depending on the task and context, physical and virtual supports scaffold learning differently, underscoring the enduring importance of tangible objects for young learners. In many classrooms, however, limited budgets restrict access to commercial manipulatives. Sustainability-oriented ECE research argues that repurposed or recycled materials can function as effective learning media while nurturing environmental awareness and responsible consumption from an early age (Ohlsson, 2024). Evidence from early numeracy interventions in lower-resource settings likewise indicates that structured, small-group activities can improve number competencies among at-risk learners, pointing to the feasibility of scalable, low-cost designs (Aunio et al., 2021).

Against this backdrop, "numeracy-on-a-budget" approaches that employ recycled manipulatives, such as bottle caps used for matching quantities to numerals or ordering simple sequences, offer a promising, practice-proximal strategy. They align with the predictive importance of early numeracy, leverage the demonstrated benefits of play-based pedagogy and embodied materials, and meet practical constraints around affordability and availability. The present classroom study of recycled manipulatives in early childhood education is therefore positioned to contribute actionable evidence for practitioners seeking sustainable, engaging, and cost-effective ways to strengthen foundational number skills.

RESEARCH METHOD

This study adopts a design-based research (DBR) approach to explore how a low-cost, embodied numeracy activity can support early mathematical learning in authentic classroom settings. DBR is particularly suited for investigating educational innovations in real-world contexts, as it emphasizes iterative design, implementation, and refinement while generating practice-relevant theoretical insights (Brown, 1992). This study aims to generate preliminary design principles rather than establish causal effectiveness.

In this study, we report findings from an initial design iteration, focusing on the enactment and evaluation of a teacher-designed intervention using recycled bottle caps as manipulatives. The design was informed by three theoretical principles: (1) embodied cognition, which emphasizes physical interaction in learning, (2) guided play, which integrates child-led engagement with instructional goals and (3) scaffolded instruction through a least-to-most prompting hierarch. The overall research design is illustrated in Figure 1.

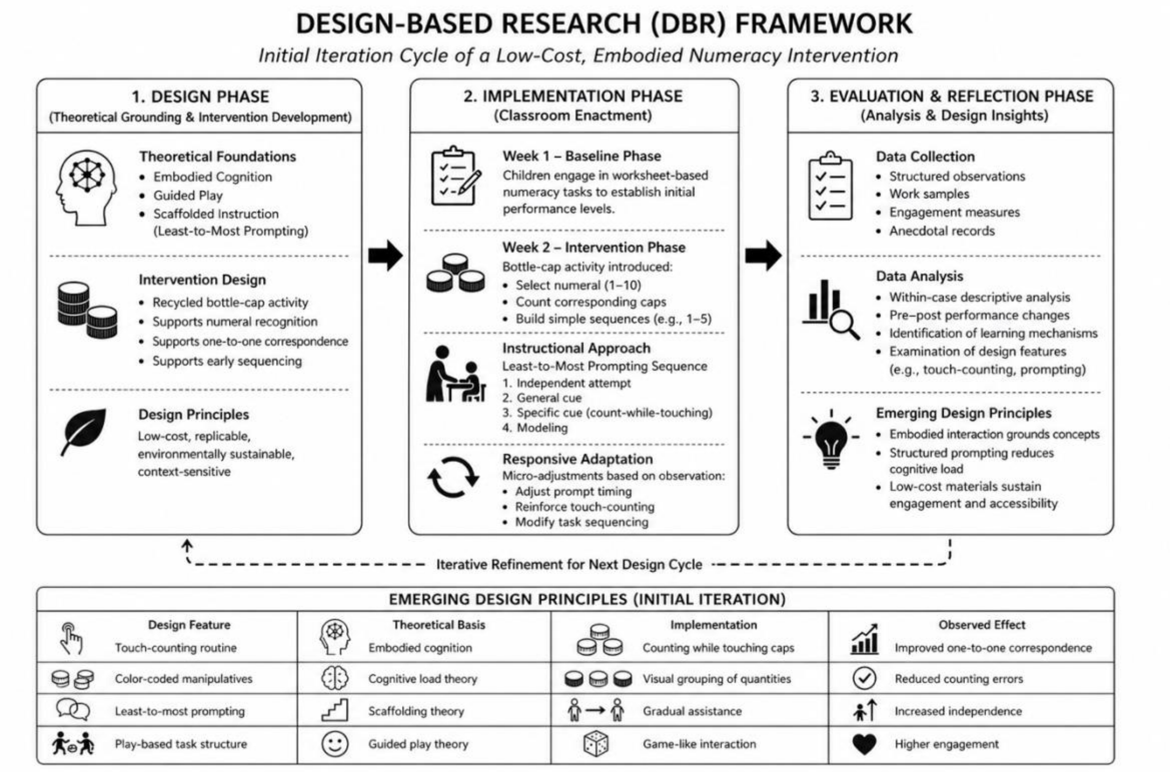

Figure 1. Design-Based Research (DBR) Framework of the Study

Setting and Participants

The research was conducted in a Group-A kindergarten classroom (ages 4–5) in Pati Regency, Central Java, Indonesia. Four children (two girls, two boys), all members of the same class, participated during regular lessons. Inclusion criteria were straightforward, enrolment in the class and attendance on observation days, and no exclusion criteria were applied. The unit of analysis was the child-session (i.e., each child observed within each session). Data were collected through structured observations, work samples, and engagement measures. Key indicators included numeral recognition, one-to-one correspondence, and task engagement, all coded using a four-level developmental rubric.

Materials

The core manipulative set comprised 60 recycled polypropylene bottle caps sourced from mixed brands. Each cap was washed with mild soap, air-dried, and then color-coded by target quantity, for example, a green set for numerals 1–5 and a blue set for 6–10, to support quick visual matching during counting tasks. Caps measured 28–33 mm in diameter and weighed 1.9–3.1 g each, ensuring they were light enough for preschoolers to handle yet substantial enough to remain stable on the work surface. Numerals were presented on a laminated A3 “caterpillar” display, featuring a cartoon head and interchangeable 1–10 cards printed in 48-point sans-serif type; Velcro™ dots allowed rapid replacement so the teacher could vary targets and sequences across trials.

During the baseline week, children completed paper-and-pencil tasks using two A4 worksheets per session: one page assessed numeral recognition (10 items) and a second page assessed quantity-to-numeral matching (10 items). These sheets were printed in black and white with 12-point font to keep visual demands low and item formatting consistent. For data capture, observers used standardized recording templates consisting of (a) a structured anecdotal record form, with fields for time, task, prompt level, correctness, and brief notes, and (b) an event-sampling tally for target behaviors. Both templates followed established classroom observation formats with minor, study-specific adaptations to the field labels and coding order (see Ayres, Ledford, & Gast, 2019). All printable materials, numeral cards, the caterpillar strip, and the recording sheets, can be produced with any standard printer on 160–220 gsm cardstock, enabling straightforward replication in comparable early-childhood classrooms.

Instrument

This study employed multiple observation-based instruments to document preschoolers' numeracy behaviors, engagement, and instructional fidelity during the two-week classroom implementation. All instruments (see Table 1) were designed for transparency and replicability, drawing on validated classroom observation and behavioral measurement methods (Bakeman & Quera, 2011; O'Brien et al., 2014; Wolery et al., 1992).

Table 1. Instruments

Component	Construct & Operational Definition	Items/Behaviors & Administration
A1 Numeral Recognition (NR)	Child correctly names an Arabic numeral (1–10) within 5 s, unprompted	Present cards 1–10 during baseline and play; record Correct/Incorrect and **Prompt Level (0–3)** on every attempt
A2 One-to-One Correspondence (OOC)	Touch-counting caps so final count equals target numeral; one touch per cap, one count word per touch	In play week, ask child to “build” an *n*-cap body; record Correct/Incorrect + Prompt Level
A3 Ordering/Sequencing (ORD)	Independently constructs ascending sequence length 3–5	In play week, give mixed numerals/caps (e.g., 1–5); record Correct/Incorrect
B Engagement (MTS)	On-task behavior: eyes on materials/teacher, manipulating caps/worksheet, appropriate responses	Momentary Time Sampling every 30 s across full 25–30 min session
C Prompt Hierarchy	Least-to-most assistance to support independent responding	0 Independent → 1 General cue (“Check your count.”) → 2 Specific cue (“Touch each cap as you say the number.”) → 3 Modeling
D Instructional Fidelity (7 items)	Consistency of delivery and materials	Check: (1) numerals visible; (2) caps clean/color-coded; (3) prompt order 0→3; (4) independent attempt first; (5) OOC via touch-counting; (6) ordering offered; (7) session 25–30 min

E Worksheet/Work-Sample Rubric (baseline)	Paper-pencil performance aligned to play tasks	Two A4 sheets/session: (a) NR 10 items; (b) Qty→Numeral 10 items; record misidentifications
F Reliability Audit	Agreement on scoring/coding	Double-code ≥25% attempts from photos/work samples by independent rater

Design Phase (Theoretical Grounding)

The study was conducted over two consecutive weeks in a preschool classroom. The first week served as a baseline phase, during which children engaged in worksheet-based numeracy tasks. The second week constituted the design implementation phase, where the bottle-cap activity was introduced and refined in situ. While the intervention was not formally redesigned across multiple cycles, observational feedback during sessions informed micro-adjustments in prompting strategies and task sequencing, consistent with DBR's emphasis on responsive adaptation (McKenney & Reeves, 2019; Anderson & Shattuck, 2012).

Implementation Phase (Classroom Enactment)

Observations spanned two consecutive weeks (four sessions total; two per week; 25–30 minutes per session).

Week 1: Baseline (Worksheets)

Each session comprised a 3-minute warm-up, 15–20 minutes of worksheet activities, and a 5–7 minute closing. Children completed numeral recognition and quantity-matching tasks individually at tables.

Week 2: Play-Based (Bottle-Cap Game)

Sessions followed the same timing but replaced worksheets with manipulative play. The teacher introduced a "caterpillar" activity: children selected a target numeral (1–10), counted out the corresponding number of caps, and aligned them to "build the caterpillar's body." Children were then invited to construct and order short sequences (e.g., 1→5) by arranging adjacent rows. Instructional support used a least-to-most prompt hierarchy: independent attempt → general cue ("Check your count") → specific cue ("Count aloud while touching each cap") → modeling. This hierarchy reflects standard response-prompting practice; our adaptation adds the "count-while-touching" cue to emphasize one-to-one correspondence. The classroom teacher led all instruction; a single observer recorded behaviors.

Evaluation and Reflection Phase (Analysis and Design Insights)

The evaluation phase focused on examining both learning outcomes and the underlying design mechanisms of the intervention. Data were collected through multiple sources, including structured observations, performance assessments using a four-level developmental rubric (BB–BSB scale), engagement measures, and anecdotal records. This multi-source approach enabled a comprehensive understanding of children's learning processes as well as the functioning of key design elements within the classroom context. Data analysis followed a within-case descriptive approach, emphasizing changes in children's numeracy performance across the baseline and intervention phases. In addition to pre–post comparisons, the analysis explored the emergence of learning behaviors and the extent to which specific design features contributed to observable improvements. This approach allowed the study to move beyond outcome description toward identifying how and why learning gains occurred.

Particular attention was directed toward mechanism-level effects associated with the intervention. These included the stabilization of one-to-one correspondence through touch-based counting routines, the reduction of counting errors during task performance, and increased independence as a result of scaffolded prompting. Such findings highlight the interaction between embodied engagement and instructional support in facilitating early numeracy development. The reflection phase synthesized these findings to generate preliminary design principles. These include the critical role of embodied interaction in grounding abstract numerical concepts, the effectiveness of structured prompting in reducing cognitive load and supporting progressive independence, and the value of low-cost, recycled materials in sustaining both engagement and accessibility. Collectively, these insights provide a foundation for refining the intervention in future DBR cycles and for informing scalable practices in resource-constrained early childhood education settings.

Data Collection

Per session, the observer recorded (a) counts of correct/incorrect NR, OOC, and ORD attempts with prompt levels; (b) MTS tallies at 30-s intervals; (c) brief anecdotal notes on salient strategies, errors, or peer interactions; and (d) work samples plus 3–5 photos of end-of-task layouts (faces excluded). All behaviors were coded live and verified against photos/work samples within 24 hours. The use of structured observation and repeated measurement aligns with established practices in single-case and classroom-based research designs (Ledford & Gast, 2018).

Coding, Quality Assurance, and Reliability

To estimate reliability, an independent rater (blinded to week) double-coded 25% of attempts from photos. Agreement was summarized using Cohen's κ for categorical variables and percent agreement for MTS tallies (Cohen, 1960; Bakeman & Quera, 2011). Discrepancies >10 percentage points triggered discussion and consensus, with an audit trail. If replication teams lack a second coder, we recommend re-coding from photos/videos after a 7-day delay to reduce recall bias.

Instructional Fidelity

Fidelity was monitored with a seven-item checklist: (1) materials prepared as specified; (2) numeral cards visible; (3) prompt hierarchy followed; (4) independent attempts offered; (5) touch-counting emphasized for OOC; (6) ordering task included; and (7) session duration 25–30 minutes. Scores ranged 0–7 (Yes/No per item); ≥6 indicated acceptable delivery.

Data Analysis

Data analysis followed a descriptive and within-case logic, examining changes in performance across phases and identifying emergent learning mechanisms. Particular attention was given to how design features, such as touch-counting routines and prompt hierarchies, mediated learning processes (Gilligan-Lee et al., 2023; Orrantia et al., 2022). Although this study represents an early-stage DBR cycle, it contributes design-relevant insights into how low-cost, embodied learning tools can be structured to support numeracy development in resource-constrained classrooms. Future iterations will extend this work through larger samples, multiple cycles, and systematic refinement of design principles.

Ethical Considerations

All activities were embedded in routine instruction with safe, non-identifiable documentation. Caregivers were informed of classroom documentation practices; no personal data were collected, and images excluded faces. The site and participants are anonymized, and procedures align with minimal-risk standards for educational observation.

FINDINGS AND DISCUSSION

Result (DBR-Aligned Version)

Learning Outcomes: Changes in Early Numeracy Performance

Across the two-week implementation, children demonstrated consistent improvements in both target indicators—matching quantity to numerals and numeral recognition. Using a four-point developmental rubric (BB = 1, MB = 2, BSH = 3, BSB = 4), mean performance increased from 1.50 during the baseline week to 2.75 in the intervention week for both indicators, representing an average gain of +1.25 levels. At the individual level, all four children showed improvement with no observed regression. The proportion of children reaching at least an independent level (≥ BSH) increased from 0% (0/4) at baseline to 50% (2/4) following the intervention. One child advanced two levels (MB → BSB), while the remaining children improved by one level each. These results indicate a uniform upward shift from "emerging" toward "independent" performance within a short instructional window.

To provide a visual summary of the changes in children's numeracy performance across the baseline and intervention phases, mean scores for both indicators are presented in Figure 2. The figure illustrates pre–post comparisons for matching quantity to numerals and numeral recognition using a four-point developmental scale.

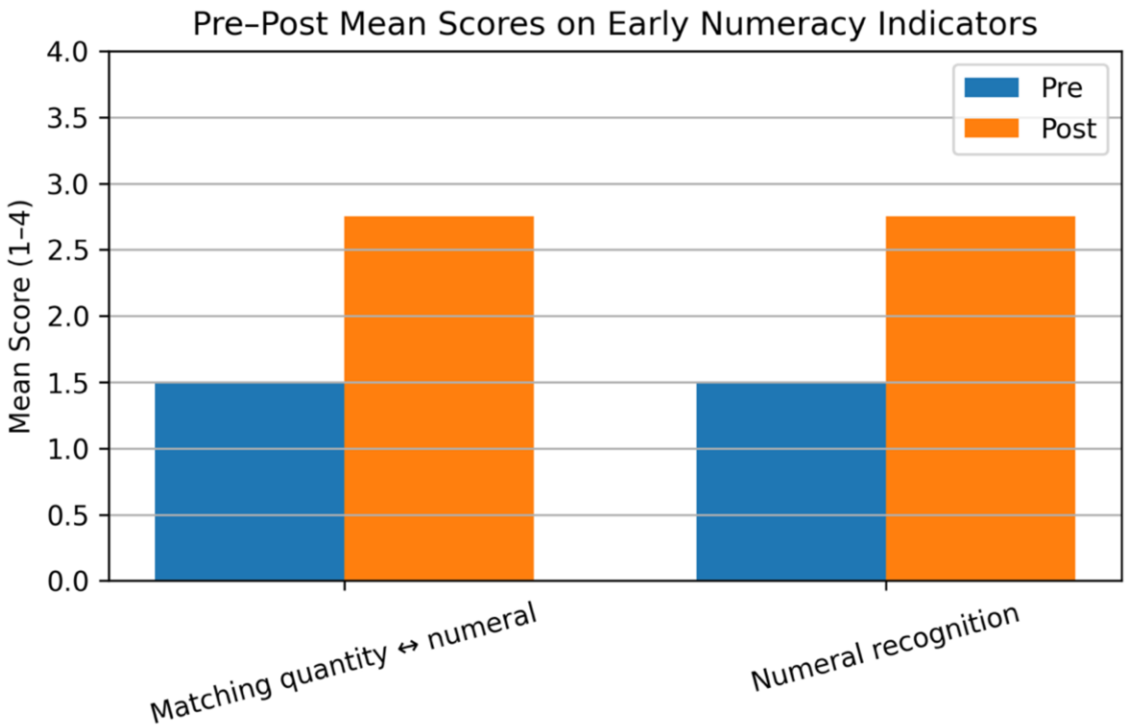

Figure 2. Pre–Post Mean Scores on Early Numeracy Indicators

As shown in Figure 2, mean scores increased from 1.50 to 2.75 across both indicators, representing a consistent improvement of +1.25 levels. This parallel upward trend from the baseline to the intervention phase indicates a generalized enhancement of early numeracy skills rather than a task-specific effect. The magnitude and consistency of these gains suggest that the intervention effectively supported children's transition from emerging to more independent performance within a relatively short instructional period.

Table 2 summarizes individual progress across the same two indicators, matching quantity to numeral and numeral recognition, using a four-point developmental rubric (BB = not yet developed, MB = emerging, BSH = independent, BSB = very well developed). For each child, the table presents the pre–post shift, level change, and a concise interpretation of likely learning mechanisms, including touch-counting and peer scaffolding.

Table 2. Individual Changes in Early Numeracy Performance

Child	Sex/Age	Matching Quantity ↔ Numeral (Pre → Post)	Numeral Recognition (Pre → Post)	Level Change	Interpretation
C1	Male, 5	MB → BSH	MB → BSH	+1	Progressed from *emerging* to *independent*; improved consistency through touch-counting.
C2	Female, 5	BB → MB	BB → MB	+1	Shifted from full dependence to partial independence; reduced initial barriers in accuracy and confidence.
C3	Female, 5	MB → BSB	MB → BSB	+2	Advanced to *very well developed*; demonstrated peer scaffolding and stable understanding.
C4	Male, 5	BB → MB	BB → MB	+1	Gradual improvement toward self-directed responses with minimal prompting.

Learning Processes: Emergence of Numeracy Behaviors

Beyond outcome gains, the intervention was associated with observable changes in children's learning behaviors. During the play-based phase, children increasingly engaged in touch-based counting, physically contacting each bottle cap while verbalizing number sequences. This behavior was rarely observed during the worksheet-based baseline but became progressively consistent across sessions. In addition, children demonstrated increased task persistence and engagement, as reflected in momentary time sampling records and observational notes. Participation shifted from passive completion of worksheets to active manipulation of materials, often accompanied by verbal counting and peer interaction. These behavioral changes suggest that the play-based, embodied design not only supported performance but also altered the nature of engagement with numeracy tasks.

To further examine how learning occurred during the intervention, Table 3 presents changes in children's observable learning behaviors across the baseline and intervention phases. These behaviors provide process-level evidence that complements the outcome data by illustrating how children engaged with tasks and developed numeracy-related strategies during classroom activities.

Table 3. Emergent Learning Behaviors Across Baseline and Intervention Phases

Behavior	Baseline (Week 1)	Intervention (Week 2)	Change
Touch-based counting	Rare / inconsistent	Frequent / consistent	↑ Strong increase
Verbal counting	Limited	More frequent and accurate	↑ Increase
Task engagement	Moderate (worksheet-based)	High (active manipulation)	↑ Increase
Peer interaction	Minimal	Occasional collaboration	↑ Emergent

As shown in Table 3, all observed behaviors demonstrate a clear positive shift from the baseline to the intervention phase. Touch-based counting, initially rare and inconsistent, became frequent and systematically applied, indicating the emergence of more structured counting strategies. Verbal counting also increased in both frequency and accuracy, suggesting improved coordination between verbal and motor processes. Furthermore, children's engagement shifted from moderate participation in worksheet-based tasks to high levels of active involvement during manipulative play, reflecting greater cognitive and behavioral investment. The emergence of peer interaction, although still occasional, indicates the beginning of collaborative learning dynamics within the classroom. Taken together, these findings suggest that the intervention not only improved performance outcomes but also transformed the nature of children's engagement and learning processes. This provides process-level support for the role of embodied interaction and play-based task structures in facilitating early numeracy development.

Mechanism-Level Findings: How the Intervention Supported Learning

Analysis of classroom interactions and performance patterns points to several mechanism-level explanations for the observed improvements. First, the touch-counting routine appears to have played a central role in stabilizing one-to-one correspondence. By requiring children to coordinate physical touch with verbal counting, the activity reduced common counting errors such as omissions and double-counting, leading to more accurate quantity–numeral mapping. Second, the least-to-most prompting hierarchy facilitated a gradual shift toward independence. Children who initially relied on specific cues or modeling began to respond to general prompts or complete tasks independently. This pattern suggests that structured scaffolding reduced cognitive load while maintaining task clarity, enabling children to internalize counting procedures more effectively. Third, the use of concrete, manipulable materials provided a stable referent for abstract numerical concepts. The bottle caps allowed children to visually and physically organize quantities, supporting both symbolic (numeral recognition) and non-symbolic (quantity representation) understanding in a coordinated manner. Taken together, these findings indicate that the effectiveness of the intervention was not solely attributable to increased engagement, but to the interaction between embodied interaction, structured prompting, and task design.

To explain why the observed improvements occurred, Table 4 summarizes mechanism-level interpretations that link key design features to children's behaviors and learning outcomes. This analysis connects the intervention's design elements with underlying cognitive and pedagogical mechanisms, providing explanatory depth beyond descriptive results.

Table 4. Mechanism-Level Findings

Design Feature	Observed Behavior	Mechanism	Outcome
Touch-counting routine	Children touch each cap while counting aloud	Embodied cognition (sensorimotor grounding)	Improved one-to-one correspondence; fewer omissions/double counts
Least-to-most prompting	Gradual reduction in reliance on teacher cues	Scaffolding; cognitive load reduction	Increased independence; more consistent task completion
Bottle-cap manipulatives	Physical grouping and alignment of quantities	Symbolic–non-symbolic mapping	Reduced counting errors; clearer quantity–numeral links
Play-based task structure	Active manipulation, verbalization, and sustained attention	Guided play; motivated engagement	Higher engagement; longer on-task behavior
Color-coded sets (optional)	Faster grouping and visual discrimination	Perceptual organization; attention support	Quicker quantity identification; reduced confusion across sets

As shown in Table 4, the intervention's effectiveness can be understood through the interaction between design features and learning mechanisms. The touch-counting routine grounded numerical concepts in sensorimotor experience, supporting more stable one-to-one correspondence. The least-to-most prompting hierarchy reduced cognitive load while enabling a gradual transition toward independent performance. In parallel, the use of concrete manipulatives facilitated clearer mapping between quantities and symbols, reducing common counting errors.

Importantly, the play-based structure amplified these effects by sustaining engagement and encouraging active participation, while visual supports such as color-coded sets further streamlined perceptual organization during counting tasks. Taken together, these findings indicate that learning gains were not solely a function of increased activity, but emerged from the coordinated influence of embodied interaction, structured scaffolding, and purposeful task design.

Design Implications: Emerging Principles from the Initial Iteration

Consistent with a design-based research approach, the results were further interpreted to generate preliminary design principles for early numeracy instruction in resource-constrained settings. First, embodied interaction is critical for grounding abstract numerical concepts. The integration of touch-based counting supported more stable and accurate one-to-one correspondence. Second, structured prompting reduces cognitive load and supports progressive independence. The least-to-most hierarchy enabled children to transition from supported to autonomous performance without disrupting task flow. Third, low-cost, recycled materials can effectively sustain engagement and accessibility. The use of bottle caps demonstrated that meaningful mathematical learning does not require specialized or expensive resources. Finally, play-based task structures enhance both engagement and learning efficiency. Embedding numeracy tasks within a game-like format promoted active participation and sustained attention across sessions. These design insights provide a foundation for subsequent DBR cycles, where the intervention can be refined, scaled, and tested across broader contexts.

Building on the mechanism-level findings, the results were synthesized to derive a set of preliminary design principles. Table 5 presents these principles as actionable insights that connect theoretical foundations, specific design features, and observed learning effects. These principles aim to inform the refinement and scalability of low-cost numeracy interventions in early childhood settings.

Table 5. Emerging Design Principles (Initial Iteration)

Design Principle	Theoretical Basis	Implementation Feature	Observed Effect	Design Implication
Embodied interaction grounds numerical concepts	Embodied cognition	Touch-based counting (count-while-touching)	More stable one-to-one correspondence; fewer counting errors	Integrate coordinated motor–verbal actions in early counting tasks
Structured prompting supports progressive independence	Scaffolding theory; cognitive load theory	Least-to-most prompting hierarchy (independent → cue → specific cue → model)	Reduced reliance on teacher support; increased independent performance	Use adaptive prompting to balance guidance and autonomy
Concrete manipulatives strengthen symbolic–non-symbolic mapping	Representational alignment; dual coding	Bottle-cap sets aligned with numerals	Clearer quantity–numeral links; reduced confusion	Provide tangible, countable units that map directly to symbols
Play-based structure sustains engagement and learning efficiency	Guided play; motivation theory	Game-like tasks (e.g., “build the caterpillar,” short sequences)	Higher engagement; longer on-task behavior	Embed explicit goals within playful, meaningful activities

Low-cost, replicable materials enable scalability and equity	Equity & access; sustainability in ECE	Recycled bottle caps; printable number cards	Consistent participation across learners; feasible classroom adoption	Design interventions using accessible, low-cost resources for broad implementation
Perceptual supports streamline counting processes (optional)	Perceptual organization; attention support	Color-coded sets and spatial alignment	Faster grouping; reduced visual confusion	Use simple visual cues to support attention and grouping

As shown in Table 5, the intervention yields a coherent set of design principles that link theory, implementation, and observed outcomes. These principles highlight that effective early numeracy learning in resource-constrained settings can be achieved through the integration of embodied interaction, structured scaffolding, and purposeful play-based design. Importantly, the use of low-cost, recyclable materials demonstrates that instructional quality does not depend on specialized resources, but on how learning experiences are structured and enacted. From a design-based research perspective, these principles represent transferable design knowledge that can guide future iterations, adaptations, and scaling efforts. While derived from an initial cycle, they offer a practical and theoretically grounded framework for developing accessible, engaging, and effective numeracy interventions in early childhood education.

Discussion

The pattern of results presented in Figure 2, particularly the parallel increase in mean scores across both indicators from 1.50 to 2.75—should not be read merely as descriptive evidence of short-term improvement. Rather, the consist, ncy of improvement across matching quantity to numerals and numeral recognition suggests that the intervention supported a more integrated form of early numeracy development. In early mathematics learning, children do not only need to recognize number symbols; they also need to connect those symbols with corresponding quantities. Therefore, the symmetry of gains across both indicators implies that the recycled bottle-cap activity may have strengthened the coordination between symbolic representations, such as written numerals, and non-symbolic representations, such as concrete quantities. This representational alignment is important because children's ability to map quantities onto symbols forms a foundational pathway toward later mathematical competence (Schneider et al., 2018; ten Braak et al., 2022; Purpura et al., 2020).

From a mechanism perspective, the observed gains can be interpreted through embodied cognition. The intervention did not present numerals as abstract visual symbols alone, but embedded them within physical action. Children were required to select, touch, count, and arrange bottle caps while coordinating verbal number words with concrete objects. This sequence of action likely helped children stabilize one-to-one correspondence because each number word was anchored to a specific physical touch. In this sense, the learning process was not simply cognitive in a narrow sense, but sensorimotor: children learned number relationships through repeated coordination of seeing, touching, saying, and arranging. Such embodied interaction may explain why improvements appeared in both quantity matching and numeral recognition, as physical manipulation created a bridge between concrete quantities and abstract symbols (Gilligan-Lee et al., 2023; Skulmowski & Rey, 2018; Mix et al., 2022).

The role of touch-based counting is especially important. In early numeracy, errors often emerge when children count too quickly, skip objects, double-count objects, or fail to connect the final count word with the total quantity. The "count-while-touching" routine helped make the counting sequence visible and controllable. By physically touching each cap while verbalizing the number sequence, children were supported to monitor their own counting actions and reduce mismatches between spoken number words and counted objects. This suggests that the intervention strengthened not only performance outcomes but also procedural stability. The increase shown in Figure 2 can therefore be interpreted as evidence of conceptual consolidation: children were not merely guessing more accurately, but increasingly coordinating quantity, symbol, and counting procedure in a more stable way.

In addition, the least-to-most prompting hierarchy appears to have supported children's gradual movement from dependence toward independence. Rather than immediately providing direct modeling, the teacher first allowed independent attempts, followed by general cues, specific cues, and modeling only when necessary. This structure matters pedagogically because it preserved children's opportunities for autonomous problem solving while still providing sufficient support when breakdowns occurred. The upward movement toward higher rubric levels therefore suggests that children were not only performing better because they received help, but because the form of help was calibrated to their current level of need. This aligns with cognitive load theory, which argues that well-designed instructional support can reduce unnecessary cognitive burden while maintaining attention on the essential structure of the task (Sweller et al., 2019; Paas & van Merriënboer, 2020).

The combination of embodied activity and scaffolded prompting also helps explain why the intervention functioned as a coherent learning system rather than a single isolated technique. Bottle caps provided tangible units for counting; the caterpillar display made the numeral target visually salient; touch-counting linked body movement with number words; and the prompting hierarchy regulated the level of adult support. Each component addressed a different aspect of the learning process, but together they created a structured environment in which children could develop accuracy, fluency, and independence simultaneously. This is consistent with a design-based research perspective, where the focus is not only whether an intervention works, but how specific design features interact with classroom processes to produce learning (McKenney & Reeves, 2019; Anderson & Shattuck, 2012).

The findings also have an important equity and implementation implication. The improvement shown in Figure 2 demonstrates that meaningful early numeracy support does not necessarily require expensive commercial manipulatives or sophisticated digital tools. Instead, low-cost recyclable materials can become cognitively powerful learning resources when they are embedded in a theoretically informed design. In this study, the pedagogical value of the bottle caps did not come from the material itself, but from how the material was structured: it was paired with visible numerals, guided play, touch-based counting, and adaptive prompting. This distinction is important because it shifts the conversation from "what resources are available" to "how available resources are pedagogically designed" (Byrne et al., 2023; Aunio et al., 2021).

Taken together, the figure-based evidence of consistent gains supports the argument that instructional quality is not determined solely by the sophistication of learning materials, but by the alignment between theoretical principles and classroom enactment. The intervention's strength lies in its integration of embodied cognition, scaffolded instruction, and play-based engagement within an accessible classroom routine. Although the findings remain descriptive and should not be interpreted as causal proof, they provide a strong initial indication that low-cost, design-informed interventions can generate meaningful learning opportunities in resource-constrained early childhood settings. This extends existing literature by showing how recycled manipulatives can function not merely as inexpensive substitutes, but as part of a coherent pedagogical design capable of supporting early numeracy development (Størksen et al., 2023; Skene et al., 2022).

CONCLUSIONS

This study demonstrates that a low-cost, embodied numeracy intervention using recycled manipulatives can support meaningful improvements in early numeracy development within authentic classroom settings. The consistent gains observed across both matching quantity to numerals and numeral recognition indicate that the intervention facilitated not only discrete skill acquisition, but also the integration of symbolic and non-symbolic numerical representations. From a design perspective, the findings highlight the importance of aligning instructional strategies with underlying learning mechanisms. The integration of touch-based counting, structured prompting, and play-based engagement created a coherent learning system that supported the development of accuracy, procedural stability, and independence. These results suggest that effective early numeracy instruction does not depend primarily on material sophistication, but on how learning experiences are structured to support embodied interaction and cognitive processing. Importantly, this study contributes to the literature by providing practice-proximal, mechanism-oriented insights into how low-cost materials can function as cognitively meaningful learning tools. The emerging design principles derived from this initial DBR iteration offer a transferable framework for developing scalable and contextually adaptable numeracy interventions in resource-constrained early childhood education settings.

LIMITATION & FURTHER RESEARCH

Despite its contributions, this study has several limitations that should be considered when interpreting the findings. First, the study involved a very small sample (four children) within a single classroom context, which limits the generalizability of the results. The findings should therefore be understood as exploratory and illustrative rather than representative of broader populations. Second, the study employed a short-term, two-week implementation without multiple iterative DBR cycles. Although micro-adjustments were made during the intervention, the absence of extended design refinement limits the ability to fully validate and stabilize the proposed design principles. Future research should incorporate multiple iterative cycles to examine how design features can be systematically improved over time. Third, the study relied primarily on observational and descriptive data without formal statistical testing or control conditions. While this aligns with the exploratory nature of early-stage DBR, it limits causal inference regarding the effectiveness of the intervention. Future studies may adopt mixed-method or quasi-experimental designs to strengthen the evidence base and examine the robustness of the observed mechanisms. Fourth, although mechanism-level interpretations were grounded in theory, they remain inferential. Future research should incorporate more fine-grained process data, such as video analysis or sequential coding, to better capture how embodied interaction and prompting strategies unfold in real time.

Building on these limitations, future research should explore the scalability of low-cost embodied interventions across diverse educational contexts, including larger and more heterogeneous samples. Comparative studies examining different types of manipulatives (e.g., recycled vs. commercial vs. digital) would also provide valuable insights into the role of material design in early numeracy learning. Additionally, longitudinal research is needed to examine whether the observed improvements translate into sustained mathematical competence over time

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