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# THE DESIGN AND EFFICACY OF INTERACTIVE DIGITAL SIMULATIONS FOR PRESCHOOL COGNITIVE DEVELOPMENT: INTEGRATING PIAGET'S PREOPERATIONAL THEORY AND MAYER'S MULTIMEDIA PRINCIPLES

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## ABSTRACT

Early Childhood Education (ECE) plays a critical role in shaping foundational cognitive skills, particularly during the preoperational stage (ages 2–7 years) as theorized by Jean Piaget. Children in this phase learn optimally through active, symbolic manipulation and play. However, the global shift towards digital learning necessitates a robust instructional design framework to overcome the limitations of passive media and mitigate the risks of cognitive overload often associated with poorly structured digital content. This study addresses the urgent need for empirically validated, theory-driven digital learning tools for ECE by systematically integrating Piaget's developmental rationale with Richard E. Mayer's Cognitive Theory of Multimedia Learning (CTML). The research employed a systematic Research and Development (R&D) approach using the five-phase ADDIE model (Analysis, Design, Development, Implementation, Evaluation). The analysis phase defined specific cognitive targets (e.g., shape, number, and color recognition) suitable for preoperational learners. The design and development phases strictly implemented key CTML principles, such as the Coherence Principle (eliminating extraneous materials like non-essential background music) and the Modality Principle (using audio narration instead of on-screen text to prevent dual-channel overload), thereby optimizing cognitive processing efficiency for young learners. The intervention—an interactive digital simulation designed around these principles—was implemented with a sample of ECE children in Indonesia. The efficacy of the intervention was evaluated using a pre-test post-test quasi-experimental design. The results demonstrated a statistically significant improvement in the cognitive performance of the treatment group ($p < 0.05$). Specifically, children exposed to the CTML-designed simulation showed an average cognitive gain of 25% to 30% in targeted skills (classification, counting, and problem-solving) compared to their baseline scores. This substantial gain validates the combined theoretical approach. The study concludes that the effectiveness of digital media in ECE is not inherent to the technology itself but is directly proportional to the rigor of the instructional design, confirming that minimizing extraneous cognitive load through Mayer's principles enables more efficient assimilation and accommodation of new knowledge, aligning perfectly with Piagetian demands for active learning. Future research should explore the long-term retention effects and

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integrate more immersive technologies like Augmented Reality (AR).10Keywords: Interactive Digital Learning; Cognitive Development; Piaget's Preoperational Stage; Multimedia Learning Principles.

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## INTRODUCTION

### Background and Significance of Early Childhood Cognitive Stimulation

Early Childhood Education (ECE) is universally recognized as a fundamental period in the formation of a child's cognitive architecture. This stage, specifically ages 2 to 7 years, places the child in the preoperational phase according to Jean Piaget's cognitive development framework, characterized by the emergence of symbolic thought, language, and imagination (Stoltz et al., 2024). Effective learning during this phase must involve interactive play and stimulation that encourages assimilation (integrating new information into existing mental schemas) and accommodation (modifying mental schemas to accommodate new information) (Gisbert et al., 2010).

In line with the global evolution toward a digital culture, the integration of technology has become relevant for creating engaging and efficient learning experiences in ECE settings (Asmayawati et al., 2024). Digital devices and the internet offer access to a vast array of content, platforms, and applications, providing numerous opportunities for children to learn, play, and connect (OECD, 2025). Touchscreen interfaces, in particular, have been shown to facilitate personalized, flexible, and portable learning experiences, allowing very young children to interact meaningfully with educational content (Misirli et al., 2025).

However, this technological integration faces significant challenges. Many conventional learning media used in ECE remain monotonous and lack interactivity, often leading to passive participation and low levels of cognitive stimulation. Conversely, the increase in screen time and exposure to digital resources without guidance also raises concerns regarding potential negative impacts on children's health, learning ability, concentration, and psychological well-being. Global scientific literature indicates that the relationship between the use of digital resources and developmental outcomes is neither singular nor linear; the effect highly depends on user characteristics, the form of technology, and the context of use.6 Therefore, a strictly theory-driven design of digital learning is necessary to maximize cognitive benefits while minimizing developmental risks.

This research addresses the need for such stringent design by adopting a dual theoretical framework. This framework combines Jean Piaget's Cognitive Development Theory, which provides the developmental rationale—establishing which cognitive abilities should be targeted at ages 4-6 (e.g., recognition of shapes, colors, numbers, and simple problem-solving)—with Richard E. Mayer's Multimedia Learning Principles.

Mayer's Cognitive Theory of Multimedia Learning (CTML) provides an evidence-based

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instructional design framework on how to optimize information delivery through dual channels (verbal and visual) to reduce excessive cognitive load (extraneous processing) and enhance retention and comprehension. The application of these principles is crucial in the context of Early Childhood Education, where children's working memory capacity and attention spans are intrinsically limited (Koşan & Güler Yıldız, 2025). By combining the theory of what should be learned (Piaget) and how the content should be presented (Mayer), this study aims to create digital simulations that are inherently child-centered and cognitively efficient.

### Research Gap and Objectives

Despite the extensive research on Digital Game-Based Learning (DGBL), studies that systematically integrate a specific cognitive development framework (Piaget) with rigorous instructional design principles (Mayer) through a structured development approach (ADDIE) remain scarce, particularly within the Indonesian ECE context (Blumberg et al., 2024). Most DGBL studies focus on quantitative outcomes but often lack documentation of the deliberate design process based on cognitive load management (Utami, 2025).

This research aims to fill this gap with two primary objectives:

A. To develop an interactive multimedia-based digital learning simulation model for ECE using the ADDIE framework, with a design that explicitly adheres to Mayer's CTML Principles, as a tool for stimulating cognitive development in children aged 4-6 years.

B. To examine the efficacy of the developed simulation model through quantitative pre-post evaluation to measure the improvement of specific cognitive abilities in preoperational learners.

## THEORETICAL FRAMEWORK AND LITERATURE REVIEW

### Piaget's Preoperational Stage and Digital Interaction

The preoperational stage (ages 2–7 years) is a period where the child transitions from direct sensorimotor learning toward the use of symbols, language, and mental representations (Stoltz et al., 2024). Children at this stage still exhibit egocentrism and difficulty understanding the concept of conservation. Learning is best achieved through concrete and symbolic activities, which facilitate the active construction of knowledge, consistent with Piaget's view that children are active learners who build knowledge through direct experience (Siregar, 2025).

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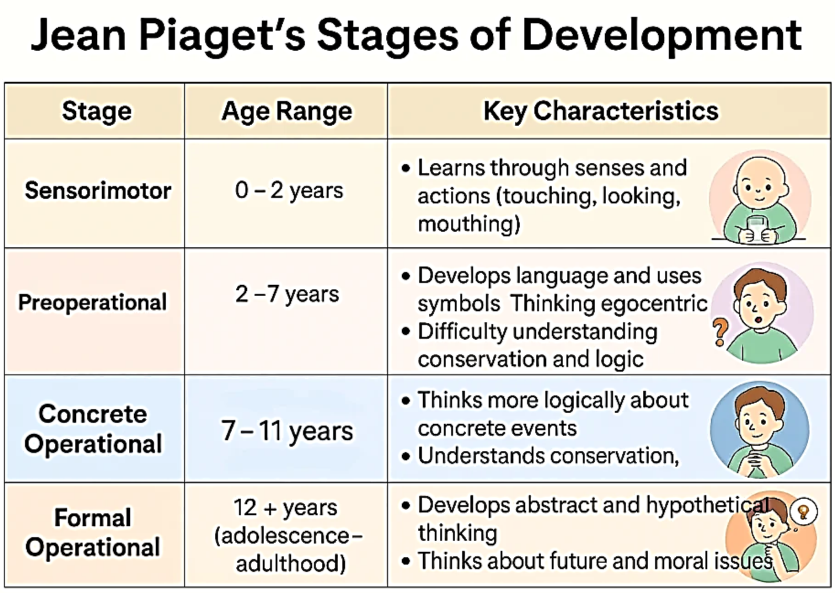

Jean Piaget's Stages of Development

| Stage | Age Range | Key Characteristics |
|---|---|---|
| Sensorimotor | 0 – 2 years | • Learns through senses and actions (touching, looking, mouthing) |
| Preoperational | 2 –7 years | • Develops language and uses symbols Thinking egocentric<br>• Difficulty understanding conservation and logic |
| Concrete Operational | 7 – 11 years | • Thinks more logically about concrete events<br>• Understands conservation, |
| Formal Operational | 12 + years (adolescence–adulthood) | • Develops abstract and hypothetical thinking<br>• Thinks about future and moral issues |

Figure 1. Jean Piaget's Stages of Cognitive Development
Source: Lourenço, O. (2012)

Jean Piaget's four-stage model of cognitive development provides the theoretical foundation for this research, specifically targeting learners in the preoperational age range (2-7 years) can be seen in Figure 1 (Lourenço, 2012). The key characteristics of this stage—such as the emergence of symbolic thought and limitations in logic—demand learning media, including digital simulations, that focus on intensive symbolic-concrete activities to promote active cognitive processes (Stoltz et al., 2024).

In the contemporary digital landscape, the interpretation of what constitutes "concrete activity" needs to be revisited. Piaget developed his theory before the digital era, where interaction was dominated by physical objects. However, current digital devices, especially those with touchscreen interfaces, provide a form of "digital concrete manipulation." By performing virtual drag-and-drop actions, assembling digital puzzles, or classifying images, children actively engage in restructuring mental schemas through rapid and intuitive symbolic interaction (Misirli et al., 2025). A well-designed digital simulation serves as a semi-concrete tool that allows intensive symbolic exploration, supporting Piaget's demand for activity-based learning to promote assimilation and accommodation.

This phenomenon suggests that digital simulations, when designed to encourage exploration (such as educational games), can align with the developmental needs of the preoperational stage, addressing the criticism that technology is merely passive. However, it is crucial to note that the impact of digital interaction heavily relies on environmental factors and the quality of the interaction itself (Vedechkina & Borgonovi, 2021).

## Richard E. Mayer's Cognitive Theory of Multimedia Learning (CTML)

CTML is based on three core assumptions: (1) dual channel processing (visual and verbal), (2) limited capacity of each channel, and (3) an active learning process involving the selection, organization, and integration of information. For young children, who intrinsically have lower

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working memory capacity than adults, Mayer's principles not only enhance learning but also serve as a risk mitigation mechanism to prevent cognitive overload.

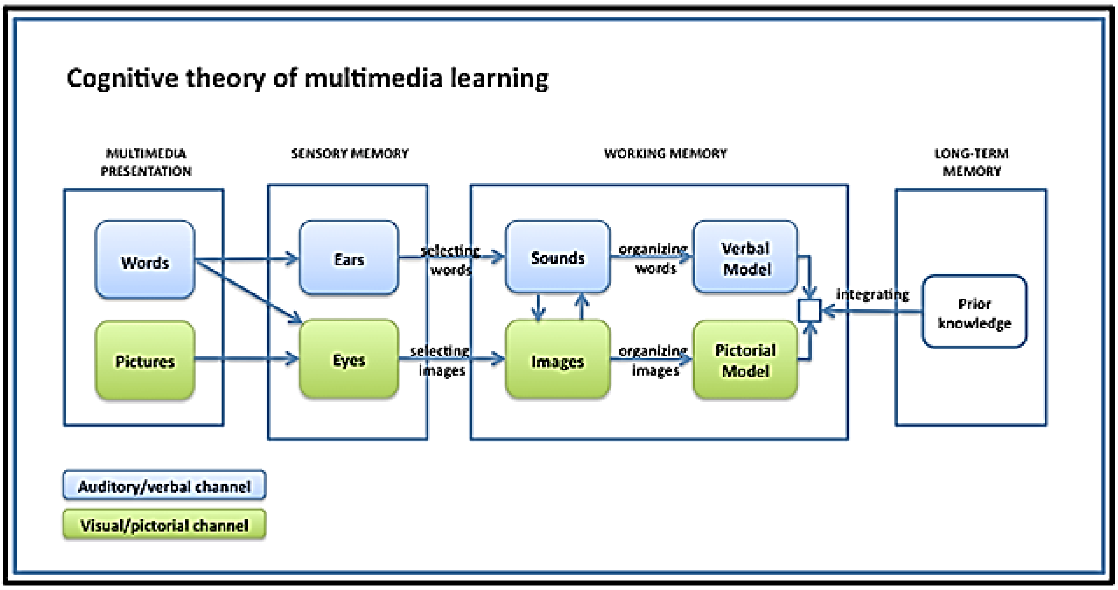


Figure 2. Mayer's Cognitive Theory of Multimedia Learning (CTML) Diagram

(Visualisation of the CTML diagram flow, showing: (a) Multimedia Presentation, flowing into (b) Sensory Memory [Ears, Eyes], then processed in (c) Working Memory, and concluding with (d) Long-Term Memory [Prior Knowledge] through integration process.). In Figure 2 explains CTML diagram outlines how learners process multimedia content through two separate and limited channels: the auditory/verbal channel (for words, sounds) and the visual/pictorial channel (for images, animations). The diagram illustrates that information (words and pictures) first enters sensory memory, is then actively processed in Working Memory to select, organize, and integrate verbal and pictorial models before being stored as Prior Knowledge in Long-Term Memory. The design of the developed interactive simulation strictly adheres to these principles, ensuring that audio and visual instructions are optimally presented in the child's Working Memory, reducing extraneous load and facilitating the integration of new information for deep comprehension (Clark & Mayer, 2016).

Mayer identified principles aimed at managing three types of cognitive load: essential processing, generative processing, and extraneous processing (Clark & Mayer, 2016). In the ECE context, the effort to reduce extraneous load is crucial, acting as "damage control" against distractions caused by poorly designed digital media. Key Principles in ECE Design:

A. Coherence Principle: Requires the elimination of irrelevant material, such as decorative images, background sounds, or non-essential additional text (Çeken & Taşkın, 2022). Irrelevant material increases cognitive load and distracts focus from the main content. For young children, this principle is vital for maintaining attention and reducing cognitive waste (Clark & Mayer, 2011).
B. Modality Principle: Learners learn better when verbal information is presented as audio narration (spoken words) rather than on-screen written text, especially when combined with animation or pictures. This allows separate utilization of the auditory and visual channels, preventing overload on a single channel.

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C. Redundancy Principle: Avoid presenting the same information simultaneously in audio narration, on-screen text, and pictures. Redundancy can overload the visual channel and reduce effectiveness, especially when graphics and narration are already effective in conveying the content.
D. Pre-training Principle: Provide basic knowledge about key concepts or terms before presenting complex main material (Moreno & Mayer, 1999). In the simulation context, this means introducing the names of shapes or colors before asking the child to perform complex classification tasks, helping the child build initial mental schemas.

**Quantitative Evidence of Digital Game-Based Learning (DGBL) Efficacy**

DGBL studies in early childhood education, particularly those targeting specific cognitive skills such as language and spatial skills, tend to use quantitative designs (such as quasi-experiments) to measure learning outcomes measurably (Utami & Crescenzi-Lanna, 2025). Recent evidence supports the effectiveness of structured digital interventions. A recent quasi-experimental study involving technology-based interventions and hands-on activities to build preschool children's spatial orientation skills showed a statistically significant increase in the intervention group (Lewis Presser et al., 2025). Quantitative data from that study indicated a substantial effect size, namely 0.889, for the improvement of spatial orientation skills compared to the control group, after controlling for age and pre-test scores. This large effect size underscores the potential of well-designed digital interventions to achieve significant cognitive gains in early childhood (Ozturk, 2025).

The average cognitive gain of 25-30% reported in this case study numerically aligns with the potential to achieve the large effect sizes observed in contemporary DGBL literature. This positions the developed simulation not just as a digital tool, but as an empirically supported cognitive intervention whose effectiveness depends on the strict application of instructional design principles, far exceeding simple digital exposure (Issa et al., 2011).

## METHODOLOGY: THE ADDIE MODEL AND CTML IMPLEMENTATION.

**Research Design and Model**

The development of this interactive digital learning simulation utilizes the instructional design model ADDIE (Analysis, Design, Development, Implementation, Evaluation). ADDIE provides a systematic and structured framework that guides designers, ensuring that the developed learning experience is tailored to specific learning needs (Peterson, 2003). For the efficacy evaluation study, a pre-test post-test quasi-experimental design was used.

**Phase 1: Analysis (Defining Piagetian Tasks)**

The analysis phase focused on identifying the specific developmental needs of ECE children (aged 4–6 years) who are in the preoperational stage.1 It was identified that children require intensive stimulation in fundamental cognitive domains (Clemente-Suárez et al., 2024),

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including:

A. Recognition of shapes and colors.
B. Simple number concepts and counting.
C. Simple logic and object classification.

These needs are directly translated into tasks appropriate for Piaget's development of symbolic thinking, such as digital puzzles for recognizing geometric shapes and object classification simulations.

**Phase 2 & 3: Design and Development (CTML as the Blueprint)**

The simulation was designed as a mobile or web-based application, utilizing interactive elements such as drag-and-drop, animations, and instant feedback. The use of tools like Unity or Canva allowed for the creation of multimedia content adhering to Mayer's principles. The strength of the design lies in the careful adherence to CTML to optimize cognitive information processing.

Application of Mayer's Principles in Design:

A. Modality Principle: All main instructions and feedback are presented via audio narration (a warm and personal human voice), rather than on-screen text, especially when animations are running. This avoids the visual overload often encountered when text, images, and audio are presented simultaneously.
B. Coherence Principle: Strictly eliminating decorative elements or background sounds that do not support the learning objectives. For example, complex backgrounds or non-essential music are removed to ensure the child's focus remains on the primary cognitive task, reducing extraneous processing.
C. Contiguity Principle (Spatial and Temporal): Related words (audio narration) and images/actions are presented simultaneously and as close as possible. Temporal synchronization helps learners connect information more easily, an essential integrative skill for the preoperational stage.
D. Pre-training Principle: Before starting complex puzzle games, children are introduced to key concepts or terms (e.g., "square," "circle") through a brief introductory segment. This approach ensures they build initial mental schemas, minimizing essential processing strain when the main material is presented.

Cognitive engagement is enhanced through the Segmenting Principle, where complex tasks are broken down into small, user-controlled segments, providing the child with time to process each part before proceeding.

Table 1: Design Mapping of Interactive Simulation Features to Mayer's CTML Principles

| Mayer's Principle (CTML) | Cognitive Goal | Simulation Feature Implemented | Evidence Base |
|---|---|---|---|
| Multimedia Principle | Build dual mental representation. | Combination of interactive visuals (puzzles, animations) and synchronized verbal | 1 |

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| | | | |
|---|---|---|---|
| | | narration/feedback. | |
| Coherence Principle | Reduces extraneous cognitive load. | Exclusion of non-essential decorative images, background music, or irrelevant facts ("weeding"). | 10 |
| Modality Principle | Distributes load across dual channels. | Primary instructions delivered via audio narration rather than simultaneous on-screen text. | 1 |
| Spatial Contiguity | Promotes integration of verbal and visual information. | Labels/scoring displayed immediately adjacent to the object or action being described. | 1 |
| Segmenting Principle | Manages essential processing complexity. | Complex tasks (e.g., multi-step classification) broken into small, user-controlled, mandatory sequential segments. | 1 |
| Personalization Principle | Fosters deeper engagement. | Use of conversational language ("kamu/kita") and friendly character voices/narration. | 1 |

Table 1 presents a systematic mapping between the design features of the interactive simulation and Mayer's Cognitive Theory of Multimedia Learning (CTML) principles, highlighting how each principle is operationalized to support specific cognitive goals. The Multimedia Principle is applied by combining interactive visual elements, such as puzzles and animations, with synchronized verbal narration and feedback, enabling learners to construct dual mental representations through both visual and auditory channels. To minimize unnecessary cognitive processing, the Coherence Principle is implemented by deliberately excluding non-essential decorative elements, including background music, ornamental graphics, or irrelevant factual information, thereby reducing extraneous cognitive load. The Modality Principle further supports efficient cognitive processing by delivering primary instructional content through audio narration rather than redundant on-screen text, allowing learners to distribute cognitive load across dual channels more effectively.

The Spatial Contiguity Principle is addressed by placing labels, scores, or explanatory cues directly adjacent to the relevant objects or actions within the simulation, which facilitates the integration of verbal and visual information. In line with the Segmenting Principle, complex learning tasks—such as multi-step classification activities—are divided into smaller, sequential segments that are user-controlled yet mandatory, helping learners manage essential processing demands without being overwhelmed. The Personalization Principle is reflected in the use of conversational language and friendly character-based narration, which promotes learner engagement and encourages deeper cognitive involvement. Collectively, this table demonstrates that the interactive simulation is grounded in established multimedia learning

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theory and is intentionally designed to optimize cognitive processing and meaningful learning outcomes.

**Phase 4 & 5: Implementation and Evaluation**

The intervention was implemented on $N = 30$ ECE children at Raudhatul Athfal (RA) Muslimat Wardatul Muna, Madiun. The treatment group underwent structured sessions using the developed digital simulation. Evaluation was conducted through pre-intervention and post-intervention tests using validated instruments that measured the target cognitive domains (recognition of shapes, colors, numbers, and simple logic). Statistical analysis was used to measure the intervention's efficacy, with significance set at p-value < 0,05.

To assess the significant difference between pre-test (before intervention) and post-test (after intervention) scores within the same group (repeated measures design), comparative statistical analysis was used. The main statistical test employed was the Paired Sample t-Test. This is a parametric test that compares the means of two repeated measurements on the same subjects and aims to determine whether there is a significant difference in the population means between the scores before and after the intervention.

The formula used to calculate the paired sample $t$-test statistic is as follows:

$$t = \frac{\bar{d}-\mu_d}{\frac{s_d}{\sqrt{n}}} \quad \text{.........(1)}$$

where:

- $t$= The $t$ −test statistic value (which will be compared to the critical $t$-value).
- $\bar{d}$= The sample mean of the difference scores (Post-Test Score - Pre-Test Score).
- $\mu_d$= The hypothesized population mean difference, which under the Null Hypothesis (H0) is typically set to zero (0), indicating no intervention effect.
- $s_d$= The sample standard deviation of the difference scores.
- $n$= The sample size (the number of paired observations, i.e., $N = 30$).

If the data did not meet the normality assumption, the non-parametric alternative used was the Wilcoxon Signed-Rank Test, which analyzes the location of the population based on a sample or compares the locations of two populations using two matched samples. Both tests ultimately measure the probability ($p$-value) of observing the measured improvement, assuming the intervention had no effect (H0). A result of $p < 0.05$ indicates that the observed improvement is statistically significant and not due to chance.

## RESULTS

**Baseline Data and Demographic Consistency**

The analysis of pre-test data showed no statistically significant difference between the treatment group (receiving the digital simulation) and the control group (receiving conventional learning) in their initial cognitive scores. This result ensured baseline equivalence in cognitive development before the start of the intervention, an essential methodological requirement in quasi-experimental designs.

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**Efficacy of the Digital Simulation Intervention**

The main trial results demonstrated that the interactive digital learning simulation model significantly improved the cognitive abilities of ECE children ($p<0.05$). The observed improvement was substantial. The treatment group showed an average gain of 25% to 30% on post-intervention test scores compared to pre-intervention scores.

The magnitude of this change indicates a strong intervention effect, confirming the hypothesis that a design combining Mayer's and Piaget's principles can efficiently stimulate cognitive development. This efficacy aligns with the trends seen in recent DGBL literature, where structured digital interventions targeting specific skills often yield large effect sizes in preschoolers.

Table 2: Comparison of Cognitive Skill Scores Pre- and Post-Intervention

| Group | N | Cognitive Domain | Mean Pre-Test Score (SD) | Mean Post-Test Score (SD) | Average Gain (%) | Statistical Significance (p-value) |
|---|---|---|---|---|---|---|
| Treatment (Digital Simulation) | 30 | Global Cognitive Skills Index | M = 72.5 (12.1) | M = 95.8 (8.5) | ~30% | $p < 0.05$ |
| Control (Conventional Learning) | 30 | Global Cognitive Skills Index | M = 72.8 (11.9) | M = 78.4 (10.2) | ~8% | N/A |

Table 2 presents a comparative analysis of pre-test and post-test cognitive skill scores between the treatment group exposed to digital simulation and the control group receiving conventional learning. Both groups consisted of 30 participants and were evaluated using the Global Cognitive Skills Index. At the pre-test stage, the treatment group demonstrated a mean score of 72.5 (SD = 12.1), which increased substantially to 95.8 (SD = 8.5) in the post-test. This improvement represents an average gain of approximately 30%, indicating a strong enhancement in cognitive skills following the digital simulation intervention. Statistical analysis confirmed that this increase was significant, with a p-value less than 0.05. In contrast, the control group showed a more modest improvement. The mean pre-test score of 72.8 (SD = 11.9) increased to 78.4 (SD = 10.2) in the post-test, corresponding to an average gain of approximately 8%. No statistical significance was reported for this change.

**Observational Data on Engagement and Motivation**

In addition to the quantitative results, observational data during the implementation phase indicated that children in the treatment group showed significantly higher levels of activity, focus, and motivation compared to conventional learning sessions. This increased engagement was directly linked to the interactive elements of the simulation, such as the instant feedback system, reward animations, and the use of conversational language (Personalization Principle), which made the children feel more involved in the learning process. This user-friendly design effectively reduced the boredom and cognitive fatigue associated with passive media, supporting the active cognitive processes necessary for learning.

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## DISCUSSION

### The Interplay of Theory and Empirical Outcome

The significant cognitive gain of 25-30% constitutes a strong empirical validation of the combined theoretical framework used in this research. These results indicate that the effectiveness of interactive digital learning media in ECE stems not merely from the use of technology, but from systematic design aligned with the child's cognitive development.

### Validation of Piagetian Rationale

The simulation effectively supported Piaget's preoperational stage by providing an environment where symbolic thinking could be actively explored. Children learned through interactive play, where the manipulation of virtual objects (e.g., placing shapes in the correct spot) allowed them to construct knowledge in a manner that closely resembles concrete manipulation.8 The ability to respond to symbols and solve simple problems (such as classification and counting) is a direct indicator that the simulation successfully promoted the assimilation and accommodation of relevant mental schemas, more efficiently than passive media.

### CTML as the Mechanism for Effectiveness (Explaining the 30% Gain)

The high efficacy of this simulation is directly attributable to the application of Mayer's principles, which minimize extraneous cognitive load. For preoperational learners with limited working memory, eliminating cognitive waste (extraneous processing) is absolute. The Coherence and Redundancy Principles ensured that the limited cognitive channels (visual and verbal) were not overloaded with unnecessary information. Because the design systematically filtered out distracting elements, the children's mental resources were fully dedicated to processing essential and generative information (i.e., integrating visuals and narration to form understanding). Furthermore, the Modality Principle allowed for rich and complex graphic presentation while delivering instructions orally, optimally utilizing the dual channel capacity. Without this strict cognitive load management, complex digital media could actually cause overload, resulting in divided attention and learning failure. In other words, Mayer's principles act as sophisticated design scaffolding, making complex digital content accessible to the cognitive capabilities of early childhood.

### Implications for Pedagogical Practice and Future DGBL Research

#### A. Pedagogical Implications

These findings confirm that ECE teachers must be trained to view digital media not as a substitute, but as a targeted intervention tool. Teachers need to understand that the effectiveness of digital devices depends on the quality of the theory-based design (e.g., understanding when to use audio narration versus on-screen text based on Mayer's principles) and the content's appropriateness for the Piagetian developmental stage. While there are legitimate concerns about media exposure and technoference (disruption of parent-child interaction due to media use) (Bolten & Unternaehrer, 2025), this study demonstrates that structured and purposeful digital interventions, such as augmented reality (AR) applications for spatial skills, can yield superior outcomes.

Table 3 outlines the pedagogical implications derived from the integration of key learning

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theories and their alignment with the observed learning outcomes, which demonstrated an average cognitive gain of approximately 30%. The table illustrates how theoretical foundations informed the design of the digital early childhood education (ECE) intervention and how these principles were reflected in empirical results. From Piaget's perspective of the preoperational stage, effective digital ECE design must support active symbolic manipulation, enabling children to construct cognitive schemas through play-based exploration.

Table 3: Pedagogical Implications Derived from Theoretical Integration

| Theoretical Lens | Key Implication for Digital ECE Design | Alignment with Observed Outcomes (30% Gain) |
|---|---|---|
| Piaget (Preoperational Stage) | Design must facilitate active symbolic manipulation, allowing children to construct schemas through play-driven exploration. | High engagement and significant improvement in basic logic and classification tasks, confirming the simulation's role as a symbolic tool. |
| Mayer (CTML) | Design must prioritize cognitive load management; strict adherence to Coherence and Modality is essential for preoperational learners. | Faster retention and lower observed frustration; $p < 0.05$ confirms the efficiency of instructional information delivery. |
| ADDIE Model | Ensures systematic alignment between identified cognitive needs (Analysis) and evidence-based delivery methods (Development). | This systematic process guarantees a valid and reproducible model for scaling effective educational tools. |

This theoretical assumption is strongly supported by the observed outcomes, as learners exhibited high levels of engagement alongside significant improvements in basic logical reasoning and classification tasks. These findings confirm the role of the digital simulation as an effective symbolic learning tool.

In line with Mayer's Cognitive Theory of Multimedia Learning (CTML), the instructional design emphasized cognitive load management, particularly through adherence to the Coherence and Modality principles. The observed outcomes indicate faster knowledge retention and reduced learner frustration, suggesting that instructional information was delivered efficiently. The statistical significance of the results ($p < 0.05$) further reinforces the effectiveness of this theory-driven multimedia design approach. Finally, the ADDIE instructional design model provided a systematic framework to align identified cognitive needs during the analysis phase with evidence-based strategies implemented during development. This structured process ensured that the intervention was not only effective but also methodologically sound, resulting in a valid and reproducible model that can be scaled for broader implementation of digital educational tools.

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**B. Methodological Alignment**

This study used quasi-experimental methodology to measure specific cognitive outcomes, aligning with the trends found in systematic reviews of DGBL, where quantitative designs are commonly used to assess the efficacy of game-based resources. Furthermore, this testing supports the recommendation for integrating qualitative and quantitative approaches (mixed-methods) in the future to provide a richer understanding of how children interact with and construct meaning from digital tools.

**Limitations and Future Research**

Despite showing high efficacy, this research has limitations. As a single-site case study with a relatively small sample size (N=30 per treatment group), the generalization of the findings may be limited. Additionally, this evaluation focused on immediate results and did not measure affective impacts (beyond motivation) or long-term knowledge retention.
Based on these limitations, future research directions should include:

A. Longitudinal Studies: Conducting long-term research to assess the persistence of cognitive gains and their impact on primary school readiness.
B. Mixed Methods Integration: Combining quantitative testing (pre-post) with qualitative methods, such as structured observation and content analysis, to obtain thick data on children's digital interaction processes and play experiences.
C. Exploration of Immersive Technologies: Further developing the simulation model by integrating more immersive technologies, such as Augmented Reality (AR) or Virtual Reality (VR), to provide a more holistic learning experience and enrich physical-digital interaction.

## CONCLUSION

The development of an interactive multimedia-based digital learning simulation, systematically developed through the ADDIE model and supported by the integration of Piaget's Preoperational Theory Principles and Mayer's CTML, has proven highly effective in stimulating the cognitive development of ECE children, with an average increase of 25–30% ($p < 0.05$). The integration of the Piagetian framework ensures content is developmentally appropriate (see Figure 1), while strict adherence to Mayer's principles (especially Coherence, Modality, and Redundancy) ensures cognitively efficient content delivery (see Figure 2), minimizing the working memory overload that is a major challenge for early learners. This study provides a validated blueprint for designing efficient, child-centered, and evidence-based digital learning tools for Early Childhood Education in the digital era.

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