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# Understanding the Role of Simulation-Based Mathematics Learning Media in Developing Early Childhood Cognitive Abilities

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## Abstract

This study aims to understand the role of simulation-based mathematics learning media in developing the cognitive abilities of early childhood. This media is an interactive approach that utilizes a digital or virtual environment to represent mathematical concepts in a concrete and engaging manner for children. Through simulation, children can explore, manipulate, and solve mathematical problems directly, thereby encouraging active engagement and meaningful learning. Recent studies have shown that the use of simulation media can improve conceptual understanding, critical thinking skills, and problem-solving abilities in early childhood. Simulation also provides an adaptive learning experience that can be tailored to the needs and learning styles of each child, effectively accommodating the diversity of cognitive abilities in the classroom. In addition, simulation media supports cognitive development in accordance with Piaget's and Vygotsky's theories, where children learn through active interaction with the environment and guidance from adults. This study highlights the importance of selecting and developing simulation media that are appropriate to the cognitive developmental stage of early childhood, as well as the need to evaluate the effectiveness of these media through valid and reliable measuring instruments. Thus, simulation-based mathematics learning media has the potential to be an innovative solution in improving the quality of mathematics learning and supporting the optimal cognitive development of early childhood.

Keywords: Learning media, cognitive abilities, early childhood

## INTRODUCTION

Early childhood education is a crucial foundation for developing children's cognitive, social, and emotional abilities (Guiney, Chou, Vianna, & ..., 2005; Tare, Chiong, Ganea, & DeLoache, 2010; Wilkinson, 2020). One crucial aspect of children is the development of cognitive abilities (Rittle-Johnson, 2020), particularly in mathematics (Egara, 2024; Marshall & Swan, 2008; Wankerl, 2023). However, learning mathematics in early childhood often faces various challenges (Rahayu, Meilani, & ..., 2019), both in terms of the child's developmental characteristics and the learning methods used.

Cognitively, early childhood is in the preoperational stage according to Jean Piaget's theory (Rohimah, 2024), where they begin to use symbols and language, but still struggle to understand abstract concepts and concrete logic (Erath, 2021; Khasawneh, 2023; Setiawan, 2022). This often causes children to struggle to grasp abstract mathematical concepts, such as numbers, shapes, and arithmetic operations (Christou, 2024; Marsigit, 2020; Yang, 2022). Furthermore, conventional learning methods, such as practice problems and lectures, tend to be ineffective because they don't align with children's learning characteristics, which require concrete experiences, exploration, and direct interaction (DeLoache, Sugarman, & Brown, 1985; Wilkinson, 2020; Zhang, 2020).

Other problems that often arise are children's lack of motivation and interest in mathematics (Poçan, 2023), as well as internal barriers such as learning disorders (e.g., dyscalculia) (Sheromova, 2020) and external factors such as an unsupportive learning environment(Toma, 2025). Therefore, innovations in media and learning methods are needed to accommodate the needs and characteristics of early childhood (Björklund, 2020; Qisma & Afifah, 2024; Setiawan, 2022).

The development of digital technology has opened up new opportunities in education, including in Indonesia (Fuller, 2020; Suh, Moyer, & Heo, 2005; Weng, 2023). Data from the Central Statistics Agency in 2024 shows that approximately 39.71% of young children in Indonesia use mobile phones, and 35.57% have access to the internet (Kristanto Mulyono & Yeni Apriyani, 2021). This figure has increased significantly compared to previous years, indicating that children are increasingly familiar with technology from an early age (Lee, 2024; Marsigit, 2020; Xu, 2022). This presents an opportunity for educators to utilize digital media (Lestari, Afifah, & Supriyo, 2023), including simulation-based learning media, in mathematics teaching.

Simulation-based mathematics learning media is an innovation that offers an interactive and enjoyable learning experience (Wang, 2025). Through simulations, children can explore, manipulate virtual objects, and solve problems directly in a safe and engaging digital environment (Sümmermann, 2021; von Bülow, 2023). Various types of simulation media have been developed, such as PhET Simulations, Flash-based applications, 3D simulations, and educational games that integrate mathematical elements(Codreanu, 2020; Mo, 2024; Yu, 2024).

Recent research shows that the use of simulation media in mathematics learning can improve conceptual understanding, critical thinking skills, and problem-solving abilities in early childhood (Desnita, 2022). Simulation media also provides an adaptive learning experience, can be tailored to the needs and learning styles of each child, and is effective in accommodating the diversity of cognitive abilities in the classroom. Furthermore, this media supports cognitive development in accordance with Piaget's theory which emphasizes the importance of concrete experiences and active exploration and Vygotsky's theory, which highlights the role of social interaction and scaffolding in the learning process (Robertson, 2020).

Despite the enormous potential of simulation media, several research gaps and implementation challenges remain. Research specifically addressing the use of simulation media for early childhood mathematics learning is still limited (Shabana, 2023), particularly regarding integration with the curriculum, technological infrastructure readiness, and teacher training (Christou, 2024; Takaria, 2020). Furthermore, cultural relevance and local context also need to be considered to ensure that the media developed truly meets the needs of Indonesian children.

Based on the above description, developing simulation-based mathematics learning media that are appropriate for the cognitive developmental stages of early childhood is crucial (Qurrotaini, Kusumawardani, & ..., n.d.). Furthermore, it is necessary to evaluate the effectiveness of these media using valid and reliable measuring tools to ensure that the media used truly has a positive impact on children's cognitive development. Therefore, research on the role of simulation-based mathematics learning media in developing the cognitive abilities of early childhood is highly relevant and needed. The results of this study are expected to make a tangible contribution to improving the quality of mathematics learning in early childhood education and supporting optimal children's cognitive development.

## RESEARCH METHOD

### 2.1 Research design

This study uses a quantitative approach with a quasi-experimental design, aiming to test the effectiveness of simulation-based mathematics learning media in developing the cognitive abilities of early childhood. A quasi-experimental design was chosen because in the context of early childhood education, full randomization is often difficult (Graham, 2020). The study will involve two groups: an experimental group using simulation media and a control group using conventional learning methods.

### 2.2 Research Subjects

The study subjects are early childhood children (4–6 years old) at the Melati Pancing Preschool in Pancing. Subject selection was conducted using purposive sampling, considering equitable characteristics between the experimental and control groups, such as age, gender, and socioeconomic background.

### 2.3. Research Procedures

The preparation phase involved outreach to the school and parents regarding the research objectives and procedures, as well as obtaining permits and fulfilling all ethical aspects, including informed consent from parents or guardians and assent from the children. In the pre-test phase, children's initial cognitive abilities in both groups were measured using valid and reliable instruments such as the Cognitive Assessment of Young Children (CAYC) or the Developmental Assessment on an E-Platform (DEEP), adapted to the local context. During the treatment phase, the experimental group participated in mathematics learning using interactive simulation media, such as digital simulation applications, educational math games, or computer-based simulations, while the control group participated in mathematics learning using conventional methods, such as lectures, picture books, or physical teaching aids. This treatment was administered for 4–6 weeks, 2–3 times per week. After the treatment, in the post-test phase, children's cognitive abilities were measured again using the same instruments as the pre-test.

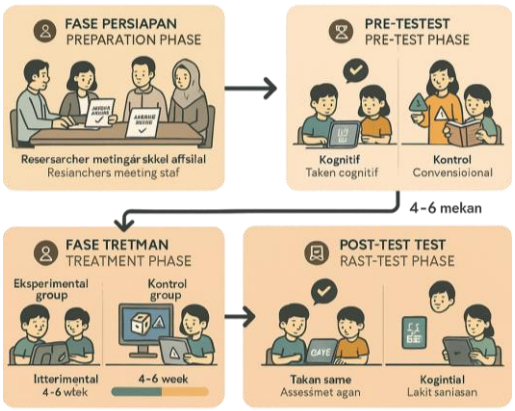


*Figure 1. Simulation Research Procedure*

### 2.4 Research Instruments

Cognitive ability measurement instruments use tools with proven validity and reliability, such as CAYC, DEEP, or AIM-ECD, to measure cognitive aspects such as mathematical concept understanding, critical thinking skills, and problem-solving (Saripah, 2023). Meanwhile, instruments to evaluate the effectiveness of simulation media use instruments such as the Simulation Learning Effectiveness Inventory (SLEI) or the Simulation Effectiveness Tool (SET), which have been adapted for early childhood contexts. These instruments aim to assess children's and teachers' perceptions of the effectiveness of simulation media.

### 2.5 Data Collection Techniques

Observations were conducted during the learning process to record children's engagement, interactions, and responses to the simulation media. Structured interviews with teachers and parents were also conducted to obtain qualitative data regarding changes in children's behavior and cognitive abilities. Documentation was also conducted by

collecting children's work, progress notes, and recordings of learning activities as supporting data.

### 2.6 Data Analysis

Quantitative analysis was conducted by analyzing pre-test and post-test data using statistical tests, such as paired t-tests or ANCOVA, to determine differences in cognitive ability improvement between the experimental and control groups. Meanwhile, qualitative analysis involved thematic analysis of observational and interview data to identify patterns of change in children's behavior and learning experiences. A mixed methods approach was used, integrating the results of quantitative and qualitative analyses using a convergent parallel design, to obtain a comprehensive picture of the effectiveness of simulation media in mathematics learning for early childhood.

## RESULTS AND DISCUSSION

Early childhood cognitive development is an important foundation for later learning. Piaget stated that children aged 4–6 are in the preoperational stage, where their understanding develops through the manipulation of symbols, images, and direct interaction with concrete objects (Weinan, 2020). At this stage, simulation-based learning media can be an effective bridge between abstract mathematical concepts and children's concrete understanding.

Simulation-based learning media for mathematics provides an interactive environment that allows children to experience learning situations as if they were real. These simulations encourage active engagement, improve focus, and strengthen logical thinking processes. This is a counting simulation for early childhood. The simulation displays an image of apples, and children can count them by clicking buttons.

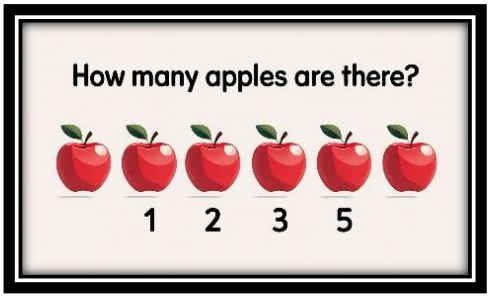


*Figure 2. simulation of mathematics learning media for preschool children*

In the image above, children will see a number of apples on the screen, and each time the program is run, the number of apples will be randomized between 1 and 5. Children can count visually while associating the sum with the number that will be given in the next stage. This program can be expanded with interactive number buttons, sounds, and animated ball sounds.

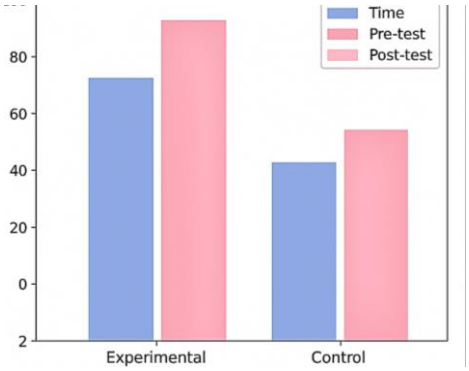


*Figure 3. Improvement in Early Childhood Cognitive Scores Before and After Using Simulation*

The visualization results in the image above show that the experimental group experienced a more significant increase in scores than the control group, supporting research findings on the effectiveness of simulation media in developing cognitive abilities in early childhood.

Thus, the results of this study not only demonstrate the positive impact of simulation-based mathematics learning media on cognitive abilities in early childhood, but are also supported by data visualizations that empirically reinforce the findings and are easily understood by various parties.

### 3.1 The Role of Simulation Media in Early Childhood Mathematics Learning

Simulation-based mathematics learning media offers an innovative approach that is highly relevant to the cognitive development needs of early childhood. Digital or virtual simulations allow children to explore, manipulate, and solve mathematical problems directly in a safe and engaging environment. This aligns with Piaget's theory (Khasawneh, 2023), which emphasizes the importance of concrete experiences and active exploration in children's learning during the preoperational stage (2–7 years) (Erath, 2021), and Vygotsky's theory, which highlights the role of social interaction and scaffolding in supporting cognitive development.

Recent studies have shown that the use of simulation media can improve understanding of mathematical concepts, critical thinking skills, and problem-solving abilities in early childhood. Simulations also provide adaptive learning experiences, tailored to the needs and learning styles of each child, effectively accommodating the diversity of cognitive abilities in the classroom.

### 3.2 Effectiveness of Simulation Media Compared to Conventional Methods

Research has shown that simulation media are not only equivalent, but in many cases superior to conventional learning methods. Digital simulations can improve knowledge retention, motivation, and children's engagement in the learning process. Meta-analyses in STEM and early childhood education show that simulation-based interventions can increase the effectiveness of mathematics learning

by 22–25% compared to traditional methods.
Furthermore, simulations allow children to learn through trial and error without real-world risks, thus developing confidence and independence in learning mathematics. Teachers and parents also report that children who use simulation media show increased interest and confidence in learning mathematics.

### 3.3 Challenges in Implementing Simulation Media

Despite its significant benefits, implementing simulation media in Early Childhood Education (PAUD) faces several challenges. The first challenge is limited infrastructure, as not all PAUD institutions have access to adequate digital devices. Furthermore, teacher readiness is also a concern, as they require special training to optimally utilize simulation media. Simulation designs must also be age-appropriate, tailored to their cognitive developmental stage, with a simple interface and relevant content. Finally, accessibility and inclusivity are crucial factors, as simulation media must be accessible to all children, including those with special needs.

### 3.4 Best Practices in Developing Simulation Media

For simulation media to be effective, developers and educators need to consider several principles, such as interactive and engaging design using age-appropriate visual elements, sound, and animation. It is also crucial to provide scaffolding in the form of prompts and feedback that help children learn gradually. Furthermore, integrating assessments with valid and reliable measurement tools, such as CAYC or DEEP, is crucial for objectively assessing children's cognitive development. Finally, simulation content should be adapted to the local cultural context to make it more relevant and understandable to children in Indonesia.

### 3.5 Implications of Piaget's and Vygotsky's theories

Simulation media plays an important role in supporting Piaget's principles by providing students with concrete experiences and exploration opportunities. Through this media, students can experience the concepts being studied for themselves, allowing them to develop a deeper and more meaningful understanding (Graham, 2020; Khasawneh, 2023; Nasution, 2020). Apart from that, simulation media also applies Vygotsky principles by offering collaborative features and digital scaffolding. This feature helps students interact and collaborate with their peers, further enriching the learning experience.
In the learning context, students can study independently or together with peers, while receiving guidance from the teacher who functions as a facilitator. The teacher's role in this situation is to provide guidance and support where necessary, while encouraging students to explore and find their own solutions. In this way, students can develop critical and creative thinking skills, as well as build confidence in their ability to learn and solve problems.

## CONCLUSION

Based on research findings on the role of simulation-based mathematics learning media in developing cognitive abilities in early childhood, it was concluded that simulation media have a significant and positive impact on children's cognitive development. The use of digital simulations allows children to explore, manipulate, and solve mathematical problems directly, encouraging active engagement and meaningful learning. Children who learn with simulation media show higher improvements in understanding mathematical concepts, critical thinking skills, and problem-solving abilities compared to conventional methods. Simulation media is adaptive to the diversity of children's learning styles, including visual, auditory, and kinesthetic, thus accommodating individual needs in heterogeneous classes. This media supports the principles of cognitive development according to Piaget and Vygotsky's theory, where children learn actively through interaction with the environment and guidance from adults. Teachers and parents also feel the benefits of simulation media in facilitating the explanation of abstract concepts and increasing children's motivation and confidence in learning mathematics. However, the implementation of simulation media faces challenges such as limited technological infrastructure, teacher readiness, and the need to adapt content to the local cultural context. Therefore, the development and evaluation of simulation media must be carried out continuously with valid and reliable measuring tools.

## RECOMMENDATIONS

Developing relevant and inclusive simulation media requires attention from developers and educators to ensure it is appropriate for early childhood cognitive development, easily accessible, and relevant to the cultural context and local needs. Simulation content needs to be designed with a simple, interactive, and engaging interface to facilitate effective and enjoyable learning. Teachers also need adequate training on the use and integration of simulation media in mathematics learning, including technical and pedagogical aspects, as well as digital classroom management strategies. Furthermore, improving infrastructure and access to technology is crucial, with governments and educational institutions needing to ensure the availability of digital devices and internet connections so that all children can access simulation media equally. Continuous evaluation and monitoring of the effectiveness of simulation media need to be conducted regularly using valid measurement tools, such as the Cognitive Assessment of Young Children (CAYC), to make improvements and ensure a positive impact on children's cognitive development. Collaboration with parents and the community is also essential in supporting simulation-based learning, by involving parents in the learning process at home and the community in providing resources. Healthy screen time management must be balanced to avoid negative impacts on children's socio-emotional and physical development, with teachers and parents needing to regulate duration and ensure digital activities are educational and interactive. Thus, simulation-based mathematics learning media not only improves mathematics learning outcomes, but also builds a strong cognitive foundation for early childhood to face future learning challenges.

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