Development of a Game-based Augmented Reality System on Geometric Concepts in Elementary School

Meng-Hsien Cheng [1], Yi-Chun Lin [2], and Yen-Ting Lin [3,*]

[1] Department of Computer Science and Artificial Intelligence, College of Computer Science, National Pingtung University, Pingtung City, Taiwan
[2] College of Mount Dawu, National Pingtung University, Pingtung City, Taiwan
[3] Department of Computer Science and Artificial Intelligence, College of Computer Science, National Pingtung University, Pingtung City, Taiwan
Email: samsam3843@gmail.com (M.H.C.); jellyplum@gmail.com (Y.C.L.); ricky014@gmail.com (Y.T.L.)
*Corresponding author
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***Abstract*—Geometric concepts and spatial reasoning are fundamental components of early mathematics education. However, young learners often experience difficulties in understanding abstract spatial and shape relationships through conventional instruction alone. Although Augmented Reality (AR) and game-based learning have been increasingly applied in mathematics education, relatively limited attention has been paid to integrating AR, image recognition, and real-world object exploration into game-based learning activities for lower-grade elementary students. To address this gap, this study developed a game-based AR learning system with image recognition functions to support first-grade students in learning geometric concepts. The system enables learners to identify geometric shapes from everyday objects, visualize corresponding three-dimensional models through AR, and apply the recognized shapes in interactive game-based matching tasks. A one-group pretest-posttest study was conducted with 31 first-grade students from an elementary school in Taiwan. Data were collected through a mathematics achievement test, a learning motivation questionnaire, and a flow experience questionnaire. Paired-samples *t*-tests, independent-samples *t*-tests, one-sample *t*-tests, and Analysis of Covariance (ANCOVA) were used to examine students' learning achievement, motivation, and flow experience. The results indicated that the system supported students' learning of geometric concepts, particularly among students with low prior knowledge after controlling for prior achievement. Students also reported a significantly high level of flow experience during the learning activity. However, no significant difference was found between pretest and posttest learning motivation, possibly because students' initial motivation was already high. These findings suggest that the proposed game-based AR system may serve as a promising instructional support tool for elementary geometric concept learning. Nevertheless, because this study was conducted with a small sample and without a control group, the findings should be interpreted with caution. Future studies should include larger and more diverse samples, delayed posttests, and comparison groups to further examine the long-term learning effects of AR- and image recognition-supported game-based learning.**

***Keywords*—augmented reality, game-based learning, image recognition, geometric concepts, elementary mathematics education, quality education**

I. Introduction

Learning spatial and geometric concepts plays a crucial role in enhancing students' abilities in logical reasoning, spatial thinking, and problem solving. It also helps bridge mathematical knowledge with everyday life while fostering abstract thinking. According to Verdine *et al*. [1], early mathematics education—particularly instruction in spatial and shape concepts—significantly improves students' spatial reasoning skills and is strongly associated with later academic achievement in mathematics and other subjects. Strengthening spatial and geometric understanding in the early stages of learning thus benefits not only mathematics education but also learning across disciplines. Similarly, Wai *et al*. [2] emphasized that early training in spatial skills can substantially improve students' mathematical performance, with particularly pronounced effects during the elementary school years. Therefore, elementary education presents a critical window for cultivating spatial and shape skills. In addition to academic benefits, learning spatial and geometric concepts can help students build self-confidence and support their holistic development.

Traditional mathematics instruction in elementary schools tends to rely heavily on lecture-based approaches. However, Simms [3] noted that such traditional instruction often results in only superficial understanding of mathematical concepts, lacking deeper cognitive engagement and limiting students' capacity for independent learning and creativity. This issue is especially evident in the instruction of spatial and geometric concepts, which inherently require hands-on manipulation and visual experiences to be fully understood. High-quality mathematics curricula should incorporate rich visual and manipulative activities to foster spatial reasoning and geometric comprehension [4]. Unfortunately, conventional textbooks often emphasize theoretical explanations and procedural exercises. While physical teaching aids included in textbooks may be used during instruction, their use tends to be one-off and limited, which fails to sustain student interest or promote intuitive understanding of spatial and geometric relationships. As a result, students may lose motivation and disengage from learning. Moreover, in traditional classroom settings, instruction is typically delivered one-to-many, making it difficult for teachers to attend to every student's learning needs. Consequently, some students may fall behind or lose interest in learning spatial and shape concepts. Teachers' professional competencies in spatial and geometry education also directly affect instructional quality. As Irshid *et al*. [5] suggested, professional development can significantly enhance teaching effectiveness in this domain.

With advances in educational technology, instructional approaches have become increasingly diverse. Teachers can now integrate digital tools with traditional materials to guide students through hands-on activities, thereby deepening their understanding of geometric properties. Research by

Hirsch-Pasek *et al*. [6] demonstrated that experiential learning through hands-on activities can significantly improve students' spatial reasoning and geometric understanding. Similarly, Sarama and Clements [7] found that using digital manipulatives significantly enhances spatial and geometric learning compared to traditional methods. Game-based learning, in particular, has been shown to increase students' enthusiasm and engagement [8]. In elementary mathematics education, using games to teach spatial and shape concepts not only captures students' attention but also encourages active learning. Game-based environments promote deeper understanding and facilitate students' grasp of abstract mathematical concepts [9]. Through repeated interaction and experimentation in games, students can reinforce their knowledge and improve their problem-solving skills.

Augmented Reality (AR) technology also offers unique advantages for enhancing spatial and geometric understanding. As Billinghurst *et al*. [10] reported, AR enables students to visualize and interact with three-dimensional geometric models, thereby strengthening their understanding of spatial structures. The interactive nature of AR promotes student motivation and engagement [11], transforming the learning process into a more immersive experience. Through AR, students can use touch, drag, and rotation gestures to explore geometric properties, encouraging active participation and improving learning outcomes. Since learning spatial and shape concepts requires abstract thinking, AR's ability to concretize mathematical ideas makes it especially valuable for elementary learners whose abstract reasoning skills are still developing. Combining game-based learning with AR can create immersive environments that enhance student concentration and engagement throughout the learning process.

Despite the growing use of AR and game-based learning in mathematics education, several research gaps remain [12]. First, many existing AR-supported mathematics learning studies have focused primarily on presenting virtual geometric models or predefined learning materials, while relatively fewer systems enable young learners to actively explore geometric shapes from real-world objects in their immediate environment [13]. Second, although game-based learning can enhance engagement and motivation, its educational value depends on whether game mechanics are closely aligned with specific learning objectives [14]. For first-grade students, geometric concepts should not be presented only as abstract definitions or visual symbols; instead, learners need opportunities to observe, manipulate, compare, and connect shapes with familiar objects from daily life [15]. Third, empirical evidence remains limited regarding how an AR system that integrates image recognition and game-based learning may support elementary students with different levels of prior knowledge in learning geometric concepts [16].

To address these gaps, this study developed a game-based augmented reality system with image recognition functions for learning geometric concepts in elementary school. The novelty of the system lies in its integration of real-world object recognition, AR-based three-dimensional visualization, and game-based shape-matching tasks. Through the system, students can identify geometric shapes from everyday objects, visualize corresponding virtual models, and apply the recognized shapes to complete interactive game tasks. This design aims to reduce the abstractness of geometric concepts, provide concrete and visual learning support, and enhance students' engagement during the learning process [17].

Accordingly, this study aimed to develop and preliminarily evaluate a game-based AR system for first-grade students' learning of geometric concepts. Specifically, the study examined students' learning achievement after using the system, explored whether the system supported students with different levels of prior knowledge, and investigated students' learning motivation and flow experience during the learning activity. The findings are expected to provide preliminary evidence for the design and implementation of AR- and image recognition-supported game-based learning in elementary geometric concept instruction.

II. Literature Review

A. Geometric Concepts and Spatial Learning in Elementary Mathematics

With the ongoing reforms in education and the rapid development of digital technologies, research in elementary mathematics education has become increasingly diverse. A key focus in both academic and practical contexts is how to leverage innovative teaching strategies and technology integration to enhance learning outcomes. Modern approaches in mathematics education—such as multimedia instruction, interactive teaching tools, and game-based learning—have demonstrated the ability to foster flow experiences, thereby increasing students' motivation and interest, and supporting autonomous and diversified learning [18]. Anderson *et al*. [19] found that interactive instruction significantly improves students' learning performance. Strategies such as group discussions, problem-based learning, and cooperative learning encourage peer interaction, stimulate critical thinking and creativity, and build learners' confidence.

Despite ongoing innovations in curriculum design and teaching methods, practical implementation still faces several challenges. Traditional mathematics instruction often involves one-way knowledge transmission, with teachers dominating the classroom and students remaining passive recipients. This dynamic leads to low student engagement and a widening gap in comprehension. Tomlinson [20] emphasized that personalized teaching strategies can greatly improve learning outcomes, recommending instructional design that addresses students' individual needs and proficiency levels. Pan and Ke [21] highlighted the benefits of using multimedia tools—such as mathematical games and simulation software—to help students intuitively grasp mathematical concepts. Current educational reform efforts in mathematics therefore emphasize the use of emerging technologies to strengthen students' mathematical application abilities and creative thinking, ultimately fostering self-directed learning and the practical application of knowledge across various contexts.

While the foundational principles of mathematics instruction remain constant, teaching methods must evolve

alongside students' psychological development and the sociocultural landscape [22]. Employing diverse teaching strategies allows educators to more effectively deliver mathematical knowledge and better meet learners' needs. Enhancing students' mathematical literacy is a critical aspect of mathematics education. Research by Artigue *et al*. [23] showed that inquiry-based learning promotes active exploration of mathematical problems and improves students' mathematical thinking and creativity. Context-based teaching, which applies mathematical concepts to real-life situations, enables students to better understand the practical relevance of mathematics. Similarly, Selvianiresa and Prabawanto [24] found that when students can connect mathematical ideas to their everyday experiences, they are better able to bridge new concepts with prior knowledge. Both inquiry-based learning and context-based instruction have been shown to effectively improve mathematical literacy and the ability to make mathematical connections.

Clements and Sarama [4] analyzed the current arrangement of geometry and spatial content in elementary curricula and recommended incorporating more hands-on activities and practical experiences to enhance students' understanding. Cheng and Mix [25] investigated the effects of different instructional strategies—ranging from traditional lecture-based methods to technology-enhanced interactive instruction—on elementary students' spatial perception abilities. Their findings showed that virtual reality-based instruction was more effective than traditional methods in enhancing students' spatial awareness and learning interest. These findings suggest that integrating modern technologies into instruction can make learning more accessible, intuitive, and effective.

Nevertheless, the integration of virtual and physical learning environments remains constrained by external factors such as classroom space, available equipment, and teaching aids. The high cost of virtual technology equipment makes widespread adoption difficult. Without consistent access to sensors or compatible instructional materials, the effectiveness of mixed-reality learning environments may be limited. Addressing how to minimize the impact of physical constraints—such as classroom settings and hardware availability—on virtual learning integration is an essential challenge in promoting the practical and widespread use of educational technology.

Taken together, previous studies suggest that geometric concept learning in the early elementary years should emphasize concrete representation, visual exploration, and connections to everyday objects [26]. For first-grade students, geometric concepts such as circles, squares, triangles, cylinders, cones, and spheres are not merely formal mathematical terms; they are closely related to how children observe, classify, and describe objects in their surrounding environment [27]. Therefore, instructional approaches that provide opportunities for learners to manipulate shapes, compare object features, and connect geometric forms with real-life contexts may better support conceptual understanding than approaches based only on verbal explanation or static textbook images [28]. This perspective provides the pedagogical foundation for developing a learning system that connects geometric concepts with students' everyday experiences.

B. Game-based Learning in Elementary Mathematics

Game-Based Learning (GBL) refers to the integration of educational content into game design and mechanics, transforming conventional learning into an engaging and enjoyable experience. According to Plass *et al*. [29], GBL can enhance students' motivation and academic performance. Hamari *et al*. [8] also emphasized that challenges, rewards, and immediate feedback embedded in games significantly boost learners' motivation and encourage active participation. Furthermore, well-defined goals and achievements in games help learners clarify their thinking and set meaningful personal learning objectives. In addition to promoting motivation, GBL fosters self-directed learning, as students are often required to explore virtual environments, discover objectives, and solve problems independently. This process stimulates curiosity and creativity while cultivating critical thinking and problem-solving skills. Narrative elements within games also increase interaction and engagement, while visual and auditory stimuli can reinforce memory retention.

Pappas [30] pointed out that while GBL is effective in increasing learners' interest and motivation, the ultimate priority must remain on learning objectives. All game mechanics must align with the intended educational goals. Without clearly defined learning targets, GBL risks diverting students' attention away from meaningful learning outcomes. Effective game design requires careful consideration of difficulty levels, feedback mechanisms, and reward systems. These elements not only boost learners' motivation but also help sustain their engagement throughout the learning process. Plass *et al*. [29] emphasized that an effective educational game should incorporate progressive difficulty and provide timely, constructive feedback to ensure that learners are continually challenged and supported. Johnson *et al*. [31] highlighted the importance of integrating educational content seamlessly into game environments through contextual tasks and challenges that allow learners to apply knowledge naturally while solving in-game problems.

In elementary mathematics education, game-based learning is particularly valuable when game tasks are designed to correspond directly to mathematical concepts and problem-solving processes [32]. Prior studies have indicated that game-based learning can increase students' motivation, engagement, and perceived flow, but its effectiveness depends on whether the game mechanics support meaningful learning rather than merely providing entertainment [33]. For example, clear goals, progressive challenges, immediate feedback, and opportunities for repeated practice can help learners maintain attention and refine their understanding of mathematical ideas [34]. In the context of geometric concept learning, game-based tasks can encourage students to identify, compare, and match shapes through active exploration [35]. However, if game elements are not closely connected to the intended learning objectives, students may focus on completing the game rather than understanding the mathematical meaning of the tasks.

Accordingly, the present study adopted game-based learning not simply to increase enjoyment, but to structure students' learning of geometric concepts through

shape-matching tasks, immediate feedback, level progression, and repeated interaction. The design of the game mechanics was aligned with the learning objective of helping first-grade students recognize and apply basic geometric concepts. This alignment is important because the educational value of game-based learning depends on the integration of instructional goals, task design, and feedback mechanisms [36].

C. Augmented Reality and Image Recognition for Geometry Learning

AR is a technology that integrates virtual elements with the real-world environment by superimposing digital information—such as images, sounds, and sensory inputs—onto a user's view of the physical world. Through the use of various technological devices, including smartphones, sensors, cameras, displays, and computing platforms, AR allows virtual content to be presented in real time within the user's physical environment. AR systems are characterized by the integration of virtual and real environments, real-time interaction, and 3D visualization capabilities [10].

With rapid advancements in digital technology and the increasing accessibility of mobile devices, AR has been increasingly applied in educational contexts [37]. Unlike conventional instructional media that rely mainly on verbal explanations or static images, AR can overlay digital information onto the physical environment and provide real-time interaction with virtual objects [38]. These features make AR particularly useful for learning topics that require visualization, manipulation, and the connection of abstract concepts with concrete experiences [39].

AR has shown promise as an innovative and effective teaching tool across various subjects in foundational education. Bulut and Ferri [40] reported that AR technologies help elementary students solve complex applied mathematics problems more effectively, particularly by supporting comprehension and problem decomposition. When properly implemented, AR can reduce the cognitive complexity of mathematical instruction and concretize abstract ideas. Cevikbas *et al*. [41] reviewed both AR and Virtual Reality (VR) applications in mathematics education, concluding that these immersive technologies are especially beneficial for students with learning difficulties or disabilities, as they enhance accessibility, engagement, and academic performance. Cai *et al*. [42] also demonstrated that incorporating AR into mathematics instruction significantly improved students' learning engagement, attitudes, and outcomes, with learners expressing positive feedback toward AR-based applications. Apriza *et al*. [43] argued that traditional mathematics instruction often fails to sustain student interest and foster deep understanding, while AR offers a promising alternative by making abstract concepts more tangible. Their study recommended the integration of AR into elementary mathematics curricula, supported by comprehensive teacher training and infrastructure investment.

In elementary mathematics, the topic of spatial and shape concepts is particularly well suited for AR-enhanced learning. Hands-on manipulation and physical models are commonly used to help students build intuitive understanding and retain geometric knowledge. Increasingly, studies have explored how modern technologies, including AR, can enhance instructional practices in this area. Demitriadou *et al*. [44] compared traditional instruction with AR-based virtual learning for geometry and found that the AR group demonstrated significantly higher levels of interactivity and interest. A growing body of research supports the efficacy of AR in spatial and geometric learning. Su *et al*. [45] evaluated a VR-based immersive mathematics learning system and found that it positively influenced students' learning motivation, and academic performance. The results suggest that such systems can lead to improved learning outcomes by increasing engagement and deepening understanding of complex geometric concepts.

AR is particularly relevant to geometry learning because it can support spatial visualization, object manipulation, and the connection between abstract concepts and concrete representations [46]. For young learners, geometric concepts often involve mental transformation, perspective taking, and the recognition of spatial relationships [47]. AR can reduce the difficulty of these processes by presenting virtual three-dimensional objects in ways that students can observe and interact with directly [48]. This visual and interactive support may help learners build stronger links between geometric vocabulary, object features, and spatial properties [49].

In addition to AR visualization, image recognition can further strengthen the connection between mathematics learning and real-world experiences [50]. Instead of relying only on predesigned digital objects, image recognition allows students to search for and identify geometric forms in their surrounding environment. This process encourages students to observe daily objects mathematically, such as recognizing cylinders in bottles, cones in traffic cones, or spheres in balls. From a learning perspective, this function may support knowledge transfer by helping students apply geometric concepts beyond the textbook or screen-based environment [51]. However, previous AR-based mathematics studies have relatively rarely integrated real-world object recognition with game-based learning tasks for lower-grade elementary students [52]. This gap suggests the need for a system that not only visualizes geometric concepts but also encourages learners to discover them in everyday contexts.

D. Synthesis of the Literature and Research Gap

The reviewed literature suggests that elementary geometric concept learning benefits from concrete, visual, interactive, and contextualized learning experiences. Studies on early geometry and spatial learning emphasize that young learners need opportunities to manipulate shapes, observe object features, and connect geometric concepts with familiar objects in everyday life [4, 15, 17, 26–28]. Game-based learning can support motivation, engagement, feedback, challenge, and repeated practice when game mechanics are meaningfully aligned with instructional goals [8, 18, 21, 29, 32–36]. AR-based learning further supports geometry learning by enhancing spatial visualization, interaction with three-dimensional representations, and the connection between abstract concepts and concrete visual experiences [10, 16, 40–49, 53].

In addition, image recognition and authentic-context AR applications can extend geometry learning beyond predefined digital models by helping learners identify geometric forms from real-world objects and connect mathematical concepts with everyday environments [50, 51, 54].

However, a critical comparison of previous studies also reveals several unresolved issues. First, many AR-supported mathematics and geometry learning studies have focused mainly on virtual visualization, three-dimensional manipulation, or predefined instructional materials [40–49, 55–58]. Although these studies demonstrate the potential of AR for supporting spatial visualization and geometric understanding, fewer systems provide young learners with opportunities to actively discover geometric shapes in their own physical environment. Second, game-based mathematics learning studies have shown positive effects on motivation, engagement, and learning performance [18, 21, 29, 32–36], but fewer studies have examined how game mechanics can be integrated with AR visualization and real-world object recognition to support specific geometric learning objectives for lower-grade elementary students. Third, although previous research has discussed AR in elementary mathematics education and geometry learning [16, 40, 41, 52, 58], empirical evidence remains limited regarding how an AR system integrating image recognition and game-based tasks may support learners with different levels of prior knowledge or promote flow experience during geometry-related learning activities.

To further clarify the research gap and substantiate the novelty of the proposed system, Table 1 compares the main features of previous studies with those of the present study. The comparison shows that although prior studies have examined AR-supported mathematics learning, geometry visualization, game-based mathematics learning, and authentic-context AR applications, relatively few have integrated real-world object recognition, AR-based three-dimensional visualization, and game-based shape-matching tasks for lower-grade elementary geometric concept learning.

Table 1. Comparison between previous studies and the proposed system

Research focus	Main features in previous studies	Remaining limitations	Features of the proposed system
AR-supported mathematics learning	Previous studies and reviews have shown that AR can enhance students' engagement, attitudes, and learning outcomes in mathematics education [40–43, 52, 58].	Many studies discuss AR broadly in mathematics education, but fewer focus specifically on lower-grade elementary geometric concept learning with real-world object recognition.	The proposed system focuses on first-grade students' geometric concept learning and integrates AR with image recognition and game-based learning tasks.
AR for geometry and spatial learning	Prior studies have shown that AR and immersive technologies can support spatial visualization, spatial reasoning, and three-dimensional geometry learning [16, 44–49, 53-56].	Many systems emphasize virtual visualization or manipulation of predefined geometric models.	The proposed system allows students to identify geometric forms from everyday objects and visualize corresponding three-dimensional representations through AR.
Game-based mathematics learning	Game-based learning can support motivation, engagement, feedback, challenge, and repeated practice in mathematics learning [8, 18, 21, 29, 32–36].	Game mechanics may not always be closely aligned with specific mathematical learning objectives.	The proposed system aligns game mechanics with geometric concept learning through shape-matching tasks, immediate feedback, level progression, and repeated practice.
Real-world and contextualized geometry learning	Prior studies emphasize the importance of manipulatives, everyday-life connections, and hands-on experiences in geometry learning [15, 26–28].	Real-world contextual learning is often separated from AR-based visualization or digital game tasks.	The proposed system connects real-world object exploration, AR visualization, and game-based shape application within one learning environment.
Image recognition and authentic-context AR	Authentic-context AR studies suggest that AR can support geometry learning and connect mathematical concepts with real-world contexts [50, 51, 54].	Relatively few systems combine image recognition, AR visualization, and game-based tasks for lower-grade elementary students.	The proposed system enables students to recognize objects, store identified shapes, and apply the recognized shapes in game-based matching tasks.
Support for learners with different prior knowledge	Prior research suggests that AR and interactive technologies may benefit learners with different needs or learning difficulties [41], and spatial visualization may support mathematical learning [59].	Limited empirical evidence exists on whether AR- and image-recognition-supported game-based learning may support students with different prior knowledge levels.	The present study preliminarily examines whether the system supports students with different levels of prior knowledge in geometric concept learning.

As shown in Table 1, the proposed system differs from many previous studies by integrating image recognition, real-world object exploration, AR visualization, and game-based learning tasks within one learning environment. This integration is intended to help young learners connect geometric concepts with everyday objects, visualize corresponding three-dimensional representations, and apply the recognized shapes through interactive game-based activities. Therefore, this study addresses the identified research gap by developing and preliminarily evaluating a game-based AR system for elementary geometric concept learning.

Therefore, this study developed a game-based AR system that integrates image recognition, real-world object exploration, AR-based three-dimensional visualization, and shape-matching game tasks for elementary geometric concept learning. By connecting students' everyday environments with AR visualization and interactive game mechanisms, this study aims to provide preliminary evidence for the design and implementation of technology-supported geometry learning activities in elementary school contexts.

III. Materials and Methods

A. System Design and Development

This study developed a game-based learning system that integrates image recognition and Augmented Reality (AR), aiming to allow learners to freely explore common basic geometric shapes in their everyday environments. Through the system's shape-matching game, students are expected to strengthen their understanding of fundamental shapes and enhance their interest in learning spatial and geometric

concepts in mathematics.

The system design was guided by the learning objective of helping first-grade students recognize, compare, and apply basic geometric concepts through concrete and visual experiences [60]. Rather than presenting geometric shapes only as isolated symbols or definitions, the system was designed to connect geometric concepts with familiar objects in students' daily environments [27]. The core learning mechanism consists of three stages: first, students observe and identify geometric features in real-world objects; second, the system presents corresponding visual and three-dimensional representations through AR; third, students apply the recognized shapes to complete game-based matching tasks. This design was intended to support geometric concept learning through observation, visualization, manipulation, and repeated practice [26].

The development process consisted of four stages. In the first stage, the learning content was selected based on the first-grade mathematics curriculum, focusing on basic geometric concepts and shape recognition. In the second stage, 3D models and composite objects were created using Blender 4.0 and then imported into Unity for game development. In the third stage, the image recognition function was trained using Google Teachable Machine to identify common geometric forms from real-world objects. In the fourth stage, the AR visualization and game interaction functions were integrated into the Android-based application, allowing students to recognize objects, store identified shapes, and use them in the shape-matching game.

In terms of AR use, students were not required to wear head-mounted displays or use virtual reality equipment. Instead, the AR function was implemented through Android tablet cameras, enabling students to scan physical objects and view corresponding digital geometric representations on the tablet screen. The system required Android tablet devices equipped with a camera and sufficient processing capability to run Unity-based AR functions and image recognition tasks. During implementation, stable lighting conditions and clear object boundaries were also important to improve recognition accuracy [61]. These hardware and environmental requirements should be considered when schools plan to implement similar systems.

The architecture of the AR-based game learning system integrated with image recognition is illustrated in Fig. 1. The system was designed for use by first-grade elementary school students and implemented on Android-based tablet devices. The game application was developed using the Unity game engine, and the 3D composite objects used in the game were modeled with Blender 4.0. These composite objects consist of simple items constructed from basic geometric shapes—such as houses, pencils, and snowmen—allowing students to improve their memory of fundamental shapes during the shape-matching process. The image recognition component was trained using Google's Teachable Machine.

The shape-matching game consists of 10 levels, each containing three tasks. In the level selection interface, three stars are displayed beneath each level, indicating task completion status. A level is considered complete when all three stars are illuminated. The game's home screen is shown in Fig. 2, the level selection screen in Fig. 3, and the gameplay interfaces for levels one through ten in Fig. 4. The game incorporates five common geometric shapes: sphere, square, cone, cylinder, and triangle.

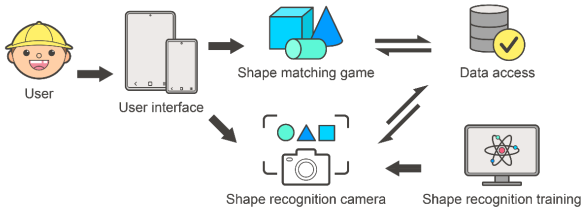


Fig. 1. System architecture.

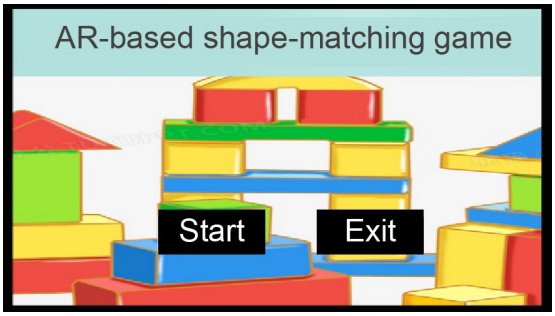


Fig. 2. Initial game interface.

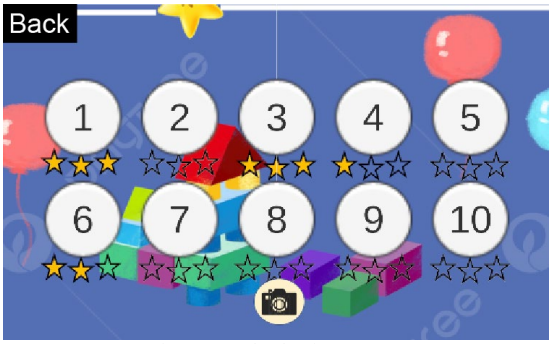


Fig. 3. Level selection screen.

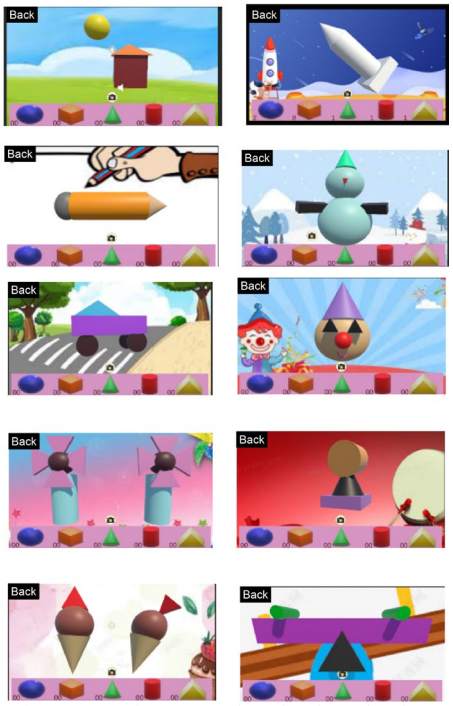


Fig. 4. Gameplay screens from level 1 to level 10.

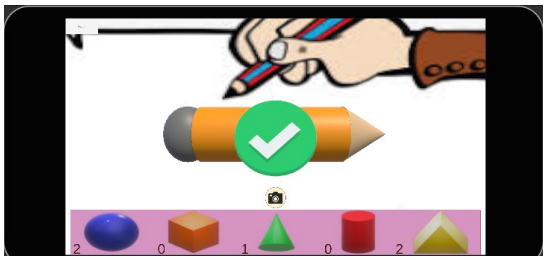
When the game starts, students are provided with a virtual backpack containing the five geometric shapes. The goal is to match the correct shapes to uncolored parts of the composite

object shown on the screen. Players do so by selecting a shape from the backpack and dragging it to the corresponding target area. When a shape is selected, the system plays a voice prompt pronouncing its name in Chinese. If the match is correct, the target shape becomes colored; if incorrect, one of the available shape items in the backpack is deducted.

When the quantity of a specific shape in the backpack reaches zero, players can use the image recognition camera, as shown in Fig. 5, to explore and photograph objects in their real-life environment that correspond to the required shapes. A key design constraint is that the same shape cannot be stored consecutively. For example, after storing a circle, the player must store a different shape before being allowed to store another circle. This restriction is intended to prevent players from rapidly progressing through the game by repeatedly capturing the same object. All captured shapes can be reviewed in the backpack and used during gameplay. Once all uncolored shapes in a level are correctly matched, a success message is automatically triggered, indicating the level has been completed (see Fig. 6).



Fig. 5. Image recognition interface.


Fig. 6. Level completion screen.

B. Research Model and Experimental Procedure

This study adopted a preliminary research model to examine how a game-based AR system with image recognition may support elementary students' learning of geometric concepts. The model assumes that the integration of real-world object recognition, AR-based visualization, and game-based shape-matching tasks can provide concrete and interactive learning experiences [62]. These experiences may help students connect geometric concepts with everyday objects, support learning achievement, sustain learning motivation, and promote flow experience during the learning activity [57]. Based on this model, learning achievement, learning motivation, and flow experience were selected as the major outcome variables.

This study developed an interactive game-based learning system that integrates image recognition and AR technologies to support first-grade elementary school students in learning mathematical concepts related to spatial and shape recognition. The system enables students to learn geometric features using common objects from their daily lives and apply this knowledge during gameplay. The research adopted a one-group pretest-posttest design, in which the same group of participants was assessed before and after the intervention to analyze the differences resulting from the experimental treatment.

The one-group pretest–posttest design was adopted because the present study was positioned as a preliminary evaluation of a newly developed instructional system. The main purpose was to examine the feasibility of implementing the system in an authentic elementary classroom and to obtain initial evidence regarding students' learning achievement, motivation, and flow experience. Because the study was conducted in a real school setting with intact first-grade classes, random assignment and the establishment of a separate control group were not feasible at this stage. Therefore, the findings should be interpreted as preliminary rather than conclusive causal evidence [63]. Future studies should adopt a quasi-experimental design with comparison groups, such as traditional instruction groups or non-AR digital game groups, to more rigorously examine the specific effects of AR and image recognition components [64].

Data collection was conducted through questionnaires. Prior to using the system, students completed a survey measuring their motivation for learning mathematics. After the intervention, students completed additional questionnaires measuring their learning motivation, flow experience, and learning outcomes. These pre- and post-intervention responses were analyzed to examine changes in the measured constructs, as well as the potential influence of different learner backgrounds.

The participants in this study were first-grade students from an elementary school in Pingtung County, Taiwan, during the 2023 academic year. These students had already acquired basic knowledge of two-dimensional geometric figures, such as circles, squares, and triangles, as well as the distinguishing features of shapes and forms. However, they had not yet been introduced to the concept of three-dimensional shapes and had no prior experience with the game-based learning system developed in this study. A total of 31 students participated, including 14 boys and 17 girls.

Although the sample size was limited, it reflected the size of an intact first-grade classroom in the participating school. The purpose of the present study was not to provide definitive evidence of causal effectiveness, but to conduct a preliminary and feasibility-oriented evaluation of a newly developed instructional system in an authentic elementary classroom. For this purpose, the sample size was considered acceptable for examining classroom implementation feasibility, collecting initial learning outcome data, and identifying potential trends in students' learning achievement, motivation, and flow experience. Nevertheless, the small sample size and single-school context limit the statistical power and generalizability of the findings [65]. Therefore, the results should be interpreted cautiously, and future research should involve larger and more diverse samples across different schools, grade levels, and educational contexts [41].

The experimental procedure is illustrated in Fig. 7. Students' most recent mathematics test scores were used as

pretest achievement data. The total duration of the instructional experiment was 150 min. The 150-min duration was designed to fit within the practical constraints of elementary classroom instruction while allowing students to experience the complete instructional sequence, including traditional concept introduction, system orientation, AR-supported game-based learning, and posttest assessment. Because first-grade students may have limited attention spans during technology-based activities, the system use session was limited to 30 min to maintain engagement and reduce fatigue [66]. Nevertheless, the short intervention duration is a methodological limitation. The 30-min system use session may have been sufficient for students to experience the core functions of the system and generate immediate engagement or flow experience, but it may not have been long enough to produce stable changes in learning motivation or long-term conceptual development. Learning achievement measured immediately after the activity should therefore be interpreted as short-term learning performance rather than long-term retention. Similarly, the non-significant change in learning motivation may partly reflect the limited exposure time, because motivational change often requires repeated learning experiences over a longer period. Future studies should extend the intervention duration, include repeated sessions, and administer delayed posttests to examine whether the observed learning outcomes and flow experience can be sustained over time [67].

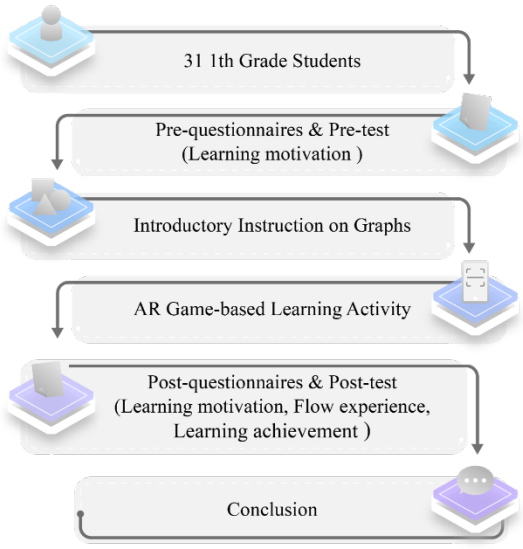


Fig. 7. Experimental procedure.

At the beginning of the session, students were asked to complete the pretest questionnaire assessing mathematics learning motivation, with instructions and completion time totaling 10 min. The first phase of the intervention involved a 60-min session of traditional instruction, during which the teacher introduced foundational concepts of spatial and geometric shapes. This was followed by a 10-min explanation of the game-based learning system developed for this study, including the game rules and interface usage. Students then used the system for 30 min to engage in learning activities related to spatial and shape concepts through interactive gameplay. Upon completing the game session, students were asked to complete a posttest questionnaire and a learning achievement test. The posttest instruments included items related to mathematics learning motivation, flow experience, perceived usefulness and ease of use of the technology, with a completion time of approximately 20 min. The session concluded with a 20-min paper-based test to assess students' learning achievement.

C. Research Instruments

This study employed multiple research instruments, including a demographic questionnaire, a mathematics achievement test on shapes and solids, a student learning motivation questionnaire, and a flow experience questionnaire.

To ensure content validity, the mathematics achievement test was developed according to the learning objectives of the first-grade "Shapes and Solids" unit and was reviewed with reference to textbooks, workbooks, worksheets, and school assessment materials using the same curriculum version [68]. The questionnaire items for learning motivation and flow experience were adapted from previously validated instruments [69]. Minor wording adjustments were made to ensure that the items were understandable for first-grade students. Before formal administration, the instruments were reviewed by the classroom teacher to confirm their appropriateness for the students' reading level and learning context.

To evaluate whether the interactive game-based system developed in this study effectively supports learning of geometric features, a mathematics achievement test was constructed. The test was designed with reference to first-grade mathematics textbooks, workbooks, handouts, and midterm exam papers from various schools using the same curriculum version. The test aligned with the learning objectives of the "Shapes and Solids" unit in the elementary mathematics curriculum. The assessment consisted of 10 items, each worth 10 points, for a total of 100 points. No penalty was applied for incorrect responses. Because the achievement test consisted of dichotomously scored items, with each item scored as either correct or incorrect, KR-20 reliability was calculated to examine the internal consistency of the test. Based on the valid achievement test responses, the KR-20 coefficient was 0.776, indicating acceptable internal consistency for a preliminary classroom-based assessment. Item difficulty indices, calculated as the proportion of students who answered each item correctly, ranged from 0.59 to 0.93. Item discrimination indices, calculated using the upper and lower 27% groups, ranged from 0.13 to 0.88. These results suggest that the test generally provided acceptable measurement quality for preliminary evaluation.

To examine whether the system enhances students' learning motivation and flow experience, as well as to explore any gender-based differences, pretest and posttest questionnaires were administered. The learning motivation questionnaire was adapted from Lin [70], who based the design on the Motivated Strategies for Learning Questionnaire (MSLQ). Nine items were selected, and the original 7-point Likert scale was modified to a 5-point Likert scale. This instrument was used in both pretest and posttest phases. The reliability of the pretest version was Cronbach's $\alpha = 0.777$, and the posttest version showed higher internal consistency with Cronbach's $\alpha = 0.841$.

The flow experience questionnaire was adapted from Pearce *et al*. [71], which outlined key components of flow experience. The instrument included eight items, rated on a 5-point Likert scale, and was administered only as a posttest. It aimed to assess the degree of immersion students experienced while using the system. The overall reliability of the flow questionnaire was Cronbach's $\alpha = 0.883$.

IV. Analysis and Discussion

In addition to significance testing, effect sizes were calculated to provide a more complete interpretation of the magnitude of the observed differences [72]. For independent-samples *t*-tests, Cohen's d was estimated based on group means and standard deviations [73]. For paired-samples *t*-tests, Cohen's *dz* was calculated by dividing the *t* value by the square root of the sample size [74]. For ANCOVA, partial eta squared (ηp^2) was reported to indicate the proportion of variance explained by the group effect after controlling for the covariate [75]. Because the present study was conducted with a relatively small sample, the effect sizes should be interpreted cautiously and used as supplementary indicators rather than definitive evidence [65].

A. Analysis of Gender Differences and Learning Achievement

This study implemented an image recognition and augmented reality-based shape-matching game as an instructional tool. The participants were 31 first-grade students from an elementary school in Pingtung County, Taiwan, during the 2023 academic year. A total of 29 valid posttest achievement tests were collected for data analysis.

The results of the gender-based analysis showed that the average posttest mathematics score for male students was 79.77 (SD = 21.24), while the average for female students was 76.96 (SD = 15.69). An independent samples *t*-test was conducted to examine differences in learning achievement between male and female students. The results revealed no significant difference between the two groups, $t = 0.409$, $p = 0.685$, Cohen's $d = 0.15$, as shown in Table 2. The small effect size indicates that the difference in posttest learning achievement between male and female students was minimal. This suggests that the game-based AR learning activity was similarly accessible to both male and female students in this sample. However, given the small sample size, this finding should be interpreted cautiously and should be further examined in future studies with larger and more balanced gender groups.

Table 2. Independent samples *t*-test of learning achievement by gender

Gender	*N*	Mean	*SD*	*t*	*p*
Male	12	79.77	21.24	0.409	0.685
Female	17	76.96	15.69		

To further explore the role of prior knowledge, students were divided into two groups based on their most recent mathematics test scores. Because this study was exploratory and involved an intact classroom with a small number of participants, a median-split approach was used to form high and low prior knowledge groups for descriptive subgroup comparison. The top 15 students were classified as the high prior knowledge group, and the remaining 14 students were classified as the low prior knowledge group. This grouping allowed the study to preliminarily examine whether students with different initial achievement levels showed different post-intervention performance patterns. However, dichotomizing a continuous variable may reduce statistical information, lower analytical precision, and oversimplify individual differences. Therefore, the subgroup findings should be interpreted cautiously. Future studies with larger samples should use more robust analytical approaches, such as regression-based moderation analysis, to examine the role of prior knowledge without converting continuous scores into categorical groups. An independent samples *t*-test was conducted to compare the academic performance between these two groups. As shown in Table 3, the difference was statistically significant, $t = 5.914$, $p < 0.001$, Cohen's $d = 2.20$, indicating that students with high prior knowledge achieved significantly higher scores than those with low prior knowledge on the recent mathematics test. The large effect size shows that there was a substantial initial achievement gap between the two groups before the intervention. This result supports the need to control for prior achievement when examining students' post-intervention learning performance.

Table 3. Independent samples *t*-test of academic performance by prior knowledge level

Variable	Group	*N*	Mean	*SD*	*t*	*p*
Math Score	High Prior Knowledge	15	91.06	3.70	5.914	0.000***
	Low Prior Knowledge	14	64.26	16.57		

***$p < 0.001$

To evaluate the impact of the instructional intervention on student learning achievement, a one-way Analysis of Covariance (ANCOVA) was conducted. The posttest achievement scores served as the dependent variable, the most recent mathematics test scores were used as the covariate, and prior knowledge level (high vs. low) was the fixed factor. The interaction effect between prior knowledge and the covariate was not significant ($F = 2.511$, $p = 0.126 > 0.05$), indicating that the assumption of homogeneity of regression slopes was met and ANCOVA could be appropriately applied. Although there was a substantial difference in prior achievement between the two groups before the intervention, the ANCOVA results (Table 4) showed that there was no statistically significant difference between the high and low prior knowledge groups in posttest scores after controlling for prior mathematics achievement, $F = 2.569$, $p = 0.121$, $\eta p^2 = 0.09$. The effect size suggests a moderate group effect after adjusting for the covariate, but the result did not reach statistical significance. Therefore, this finding should be interpreted cautiously. The adjusted mean of the low prior knowledge group was higher than that of the high prior knowledge group; however, this difference should be understood only as a descriptive tendency rather than evidence of differential effectiveness. One possible explanation for this tendency is that AR visualization, real-world object recognition, and repeated shape-matching tasks may have provided concrete representations and immediate feedback, which could be helpful for learners who need more visual and contextualized support [54]. Nevertheless, because the ANCOVA result was not statistically significant and this study did not include a control group, the result cannot be interpreted as evidence that the system was more effective for students with lower

prior knowledge. Future studies should compare the proposed system with traditional instruction and non-AR digital games to further examine the specific contribution of AR-supported image recognition.

Table 4. ANCOVA results: Posttest achievement scores by prior knowledge level

Prior Knowledge	*N*	Mean	*SD*	Adjusted Mean	*SE*	*F*	*p*
High	15	90.00	13.09	73.47	4.39	2.569	0.121
Low	14	67.86	25.17	85.56	4.60		

B. Pretest–Posttest Analysis of Learning Motivation

This study employed both pretest and posttest versions of the learning motivation questionnaire, with 30 valid responses collected. To assess whether students' learning motivation differed significantly before and after the learning activity, a paired-samples *t*-test was conducted. As shown in Table 5, the results revealed no statistically significant difference between pretest and posttest motivation scores, $t = -0.498$, $p = 0.622$, Cohen's $dz = -0.09$. The small effect size indicates that the change in learning motivation was minimal. One possible explanation is that students' initial motivation was already high before the intervention, as reflected in the pretest mean score of 4.56 on a 5-point scale. This may have created a ceiling effect, leaving limited room for further measurable improvement after a short-term learning activity [76]. Therefore, although the system did not significantly increase students' learning motivation, it may have helped maintain students' already positive disposition toward mathematics learning.

Table 5. Paired samples *t*-test of learning motivation before and after the activity

Group	*N*	Mean	*SD*	*t*	*p*
Motivation Pretest	30	4.56	0.53	−0.498	0.622
Motivation Posttest	30	4.63	0.44		

Based on the pretest mean score of 4.56, students were divided into high and low learning motivation groups, and an independent samples *t*-test was conducted to analyze group differences (Table 6). The results indicated a significant difference between the high and low motivation groups, $t = 5.701$, $p < 0.001$, Cohen's $d = 2.10$, suggesting that students with higher initial motivation showed substantially greater interest and enthusiasm in learning mathematics compared with those with lower motivation. This large effect size confirms that students' motivational profiles were clearly differentiated before the intervention.

Table 6. Independent samples *t*-test based on pretest learning motivation

Group	*N*	Mean	*SD*	*t*	*p*
High Motivation	17	4.90	0.14	5.701	0.000***
Low Motivation	13	4.13	0.53		

***$p < 0.001$

Similarly, using the posttest mean score of 4.63, students were again categorized into high and low learning motivation groups. As shown in Table 7, a significant difference was observed between the high and low posttest motivation groups, $t = 10.136$, $p < 0.001$, Cohen's $d = 3.93$. Although the overall pretest–posttest change in motivation was not statistically significant, the number of students classified in the high motivation group increased from 17 to 20, and their average score approached the upper end of the scale. However, this subgroup change should be interpreted only as an exploratory descriptive observation rather than evidence of motivational improvement. Because the paired-samples t-test showed no significant overall change in learning motivation, the results suggest that the system may have maintained students' already high motivation levels, but they do not provide sufficient evidence that the intervention significantly increased motivation.

Table 7. Independent samples *t*-test based on posttest learning motivation

Group	*N*	Mean	*SD*	*t*	*p*
High Motivation	20	4.90	0.14	10.136	0.000***
Low Motivation	10	4.09	0.30		

***$p < 0.001$

To explore whether gender played a role in changes in learning motivation, paired-samples *t*-tests were conducted separately for male and female students, as shown in Table 8. The results indicated no significant differences in motivation scores before and after the activity for either male students, $t = -0.719$, $p = 0.485$, Cohen's $dz = -0.19$, or female students, $t = 0.187$, $p = 0.854$, Cohen's $dz = 0.05$. These small effect sizes suggest that the intervention did not produce meaningful gender-specific changes in learning motivation. Importantly, both male and female students maintained motivation levels above the scale midpoint, indicating generally positive motivation toward mathematics learning throughout the activity. This suggests that the intervention had no differential effect on motivation by gender. Importantly, both male and female students maintained motivation levels above the midpoint of 3, indicating consistently high motivation toward learning mathematics across the experimental period.

Table 8. Paired samples *t*-test of learning motivation by gender

Group	*N*	Mean	*SD*	*t*	*p*
Male Motivation Pretest	14	4.46	0.67	−0.719	0.485
Male Motivation Posttest	14	4.64	0.49		
Female Motivation Pretest	16	4.65	0.36	0.187	0.854
Female Motivation Posttest	16	4.62	0.41		

C. Analysis of Flow Experience

This study utilized a flow experience questionnaire to assess students' levels of engagement during the learning activity, covering dimensions such as concentration, perceived difficulty, emotional state, and the subjective passage of time. All items were rated on a 5-point Likert scale, and a total of 30 valid responses were collected.

To determine whether students experienced a significantly high level of flow during the activity, a one-sample *t*-test was conducted, using a test value of 4 ("agree"). As shown in Table 9, students' overall flow experience was significantly higher than the test value of 4, $t = 3.305$, $p = 0.003$, Cohen's $d = 0.60$. This medium effect size suggests that students reported a meaningfully positive flow experience during the learning activity. This result indicates that the game-based AR system may have supported students' concentration, enjoyment, and engagement. The shape-matching tasks, immediate feedback, level progression, and AR-supported object exploration may have helped students maintain attention and become immersed in the learning process [54]. From a pedagogical perspective,

this finding suggests that the system not only supported cognitive learning of geometric concepts but also provided an engaging learning experience [16].

Table 9. One-sample *t*-test of students' flow experience during the activity

Category	Test Value = 4			
	Mean	*SD*	*t*	*p*
Flow Experience	4.45	0.74	3.305	0.003**

**$p < 0.01$

To examine whether gender influenced students' flow experience, an independent samples t-test was conducted to compare posttest scores between male and female students. As shown in Table 10, there was no significant difference in flow experience based on gender, $t = -0.240$, $p = 0.812$, Cohen's $d = -0.09$. The small effect size indicates that male and female students reported similar levels of flow experience. This suggests that the game-based AR learning activity was engaging for students regardless of gender in this sample. Both male and female students had average scores above the midpoint of 3, indicating that regardless of gender, students generally reported a positive and engaging learning experience.

Table 10. Independent samples *t*-test of flow experience by gender

Gender	*N*	Mean	*SD*	*t*	*p*
Male	14	4.41	0.84	−0.240	0.812
Female	16	4.48	0.66		

Based on the overall mean flow score of 4.45, students were categorized into high and low flow experience groups. An independent samples *t*-test was conducted to analyze differences between these groups. As presented in Table 11, the difference between the high and low flow experience groups was statistically significant, $t = 8.058$, $p < 0.001$, Cohen's $d = 3.05$. This large effect size indicates a substantial difference in students' subjective learning experience. While both groups scored above the midpoint of 3, students in the high-flow group reported particularly strong engagement and positive experiential responses. This finding highlights an important intangible aspect of the game-based AR learning system: beyond measurable achievement outcomes, the system may contribute to learners' sense of involvement, enjoyment, and sustained attention [77]. These experiential factors are important in elementary mathematics education because positive engagement may encourage young learners to participate more actively in repeated practice and exploration of geometric concepts [78].

Table 11. Independent samples *t*-test of high vs. low flow experience

Group	*N*	Mean	*SD*	*t*	*p*
High Flow	19	4.91	0.16	8.058	0.000***
Low Flow	11	3.65	0.66		

***$p < 0.001$

D. Theoretical Interpretation and Pedagogical Implications

The findings can be interpreted through several theoretical perspectives related to geometry learning, visual representation, embodied abstraction, and game-based learning. From the perspective of early mathematics learning, young learners develop geometric understanding more effectively when they are provided with concrete experiences, manipulatives, and opportunities to connect mathematical concepts with real-world objects [4, 26–28]. In the present study, the integration of real-world object recognition and AR-based visualization allowed students to identify geometric forms from familiar objects and observe corresponding three-dimensional representations. This design is consistent with the idea that concrete and contextualized experiences can support students' construction of geometric understanding.

The findings also align with the perspective of embodied abstraction in primary geometry education. Boonstra *et al*. [15] suggested that young learners' interaction with physical and spatial experiences can support the development of abstract geometric concepts. In this study, students were not only shown geometric forms on a screen; instead, they were encouraged to observe, recognize, and apply shapes from their surrounding environment. Such interaction may help students connect geometric vocabulary with object features and spatial relationships. Similarly, the role of visual representations in geometry learning has been emphasized because visual support can help learners transform abstract concepts into more accessible and meaningful representations [17]. The AR-based three-dimensional visualization in the proposed system may therefore have provided an additional representational bridge between concrete objects and formal geometric concepts.

From the perspective of spatial learning and transfer, the use of AR and image recognition may also support students' spatial visualization and application of geometric concepts beyond textbook-based learning. Prior research has indicated that AR can support geometry learning by enhancing spatial visualization and interaction with three-dimensional objects [16, 46–49], while spatial visualization may contribute to mathematical learning through mechanisms of spatial transfer [59]. In the present study, the adjusted mean difference between prior knowledge groups did not reach statistical significance and should be interpreted only as a descriptive tendency. Nevertheless, the system's combination of AR visualization, real-world object recognition, and repeated shape-matching tasks may provide a possible instructional pathway for supporting learners who need more concrete and visual assistance.

Finally, the high level of flow experience can be interpreted from the perspective of game-based learning. Previous studies have suggested that game-based learning can support engagement, flow, challenge, feedback, and repeated practice when game mechanics are aligned with learning objectives [8, 21, 29]. In this study, the shape-matching tasks, immediate feedback, level progression, and AR-supported object exploration were designed to align with the learning objective of recognizing and applying basic geometric concepts. Therefore, the reported flow experience suggests that the system may have provided an engaging learning environment rather than merely adding entertainment elements. For teachers and instructional designers, these findings imply that AR- and image-recognition-supported games should be designed around clear learning objectives, concrete representations, and meaningful interaction with real-world contexts.

E. Summary of Findings

Overall, the results provide preliminary evidence that the

game-based AR system may support elementary students' learning of geometric concepts, particularly for students with lower prior knowledge. Although students with high prior knowledge had substantially higher mathematics achievement before the intervention, the post-intervention ANCOVA results showed no significant difference between the high and low prior knowledge groups after controlling for prior achievement. This pattern suggests that the system may have offered concrete and visual learning support that was especially beneficial for students who initially had weaker mathematics performance [78].

In terms of learning motivation, the results did not show a significant pretest–posttest difference. However, students' motivation scores were already high before the intervention and remained high after the activity. This suggests that the system may have helped sustain students' positive motivation toward mathematics learning rather than producing a measurable increase within a short intervention period.

With regard to flow experience, students reported a significantly high level of engagement during the learning activity. This result suggests that the integration of game-based tasks, AR visualization, image recognition, and real-world object exploration may provide an engaging and immersive learning experience for young learners [12]. Taken together, the findings indicate that the proposed system has potential as an instructional support tool for elementary geometric concept learning, but the results should be interpreted as preliminary due to the small sample size, short intervention duration, and lack of a control group.

V. Conclusion

This study developed a game-based augmented reality system with image recognition functions to support first-grade students' learning of geometric concepts. By integrating real-world object recognition, AR-based three-dimensional visualization, and game-based shape-matching tasks, the system was designed to help students connect abstract geometric concepts with familiar objects in their everyday environment. The preliminary evaluation suggests that the system has potential as an instructional support tool for elementary geometric concept learning, particularly by providing concrete visual representations, immediate feedback, and interactive practice.

The study offers both system development and pedagogical contributions. From a system development perspective, it demonstrates a feasible approach to integrating image recognition, AR visualization, and game-based learning within one elementary mathematics learning environment. From a pedagogical perspective, the findings suggest that geometric concept learning may benefit from activities that connect formal mathematical vocabulary with real-world objects, visual exploration, and repeated interactive practice. For educators, such systems may be used as supplementary tools to support students' observation, comparison, and application of geometric forms. For instructional designers, the results highlight the importance of aligning game mechanics, AR functions, and learning objectives rather than using digital technologies only for novelty or entertainment.

Several limitations should be acknowledged. First, this study involved a relatively small sample of first-grade students from a single elementary school in Taiwan, which limits the generalizability of the findings. Second, the one-group pretest–posttest design did not include a control group; therefore, the observed outcomes cannot be attributed solely to the AR and image recognition components. Third, the intervention was conducted over a short period, and no delayed posttest was administered. As a result, this study could not examine long-term retention of geometric concepts. Fourth, classroom implementation may be influenced by hardware performance, camera quality, lighting conditions, and object recognition accuracy.

Future research should involve larger and more diverse samples and adopt quasi-experimental or controlled research designs. In particular, future studies should compare the proposed system with traditional instruction and non-AR digital games to examine the specific contribution of AR visualization and image recognition to learning outcomes. Delayed posttests should also be included to investigate long-term retention. In addition, future research may further examine cognitive mechanisms such as spatial reasoning, visualization, knowledge transfer, and the role of concrete representations in supporting young learners' understanding of geometry.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Y.-T.L. and C.-M.H. conducted the research; Y.-T.L. and C.-M.H. analyzed the data; Y.-T.L., C.-M.H. and Y.-C.L. wrote the paper; Y.-T.L. and Y.-C.L. revised and edited the paper; All authors have read and approved the final manuscript.

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