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# Enhancing kindergarten students' basic spatial and mathematical skills through digital games: A case study

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**Abstract**

Digital educational games (DEGs) have been utilized for some time across various learning domains. In light of the ongoing debate concerning their impact on skills and knowledge, particularly among very young learners, a study was undertaken to assess their effectiveness compared to conventional educational materials. The study involved 81 kindergarten students and followed a between-subjects design. This research focused on basic spatial and mathematical skills, specifically directional concepts (such as "up-down," "left-right," "in front-behind," and "above-below"), as well as students' abilities to organize and compare numbers and quantities up to ten. Evaluation tests and a questionnaire were employed to gather data on students' knowledge acquisition, motivation, enjoyment, and ease of use. The findings indicated that, compared to conventional materials, DEGs significantly enhanced the skills that were examined. Although DEGs were rated higher in terms of enjoyment and motivation, they were perceived as less easy to use. Furthermore, enjoyment emerged as the sole factor having a significant influence on learning outcomes with DEGs. The study calls for further exploration to optimize the usability and efficacy of DEGs and may assist educators in integrating them into their daily practice.

**Keywords:** Arrangement of quantities and numbers, Digital educational games, Kindergarten students, Makey-Makey, Spatial skills

## Introduction

Kindergarten education serves as a critical transition period from home to formal schooling. It is designed to lay the foundation for future academic success by fostering physical, cognitive, emotional, and social growth, thus, shaping the early stages of a child's personality and skills. Given that, it prioritizes the acquisition of skills and knowledge in language and mathematics, together with the development of physical, emotional, and social competencies

Spatial skills have been increasingly recognized as a critical component of young children's education, with potentially wide-ranging effects on their future learning (Newcombe & Frick, 2010). For instance, they can serve as predictors of later mathematical achievements (e.g., Crollen & Noël, 2015). The integration of Information and Communication Technologies (ICTs) can be helpful in fostering these skills (e.g., Kerckaert et al., 2015). Yet, although research indicated that ICTs could enhance children's motivation, interest, and engagement in learning (Shuker & Terrini, 2013), there is still a lack of research on their use to boost preschool children's spatial skills.

Knowledge of numbers and operations is fundamental to mathematics education in early childhood (Clements & Sarama, 2007). From a young age, children possess mathematical ideas and apply them to understand their everyday experiences. Of special interest is how children compare and arrange numbers and quantities. It is a multifaceted area of study that involves understanding how young children perceive, compare, and organize numerical information. What is important to note is that traditional teaching methods may not address the diverse needs of young learners, leading to inconsistent strategies in handling numerical tasks (Sharpe, 1999). In this respect, as with spatial skills, ICTs can provide an interesting alternative.

There is a contrast between learning in preschool and learning in primary school. Preschool education is less prescriptive and focuses more on learning through play and less on formal instruction. Consequently, integrating ICTs necessitates a different approach; they are mostly incorporated into playful activities to align with the developmental needs of young learners. This is where digital game-based learning (DGBL) comes into play. DGBL represents an educational framework that integrates digital educational games (DEGs) into the learning experience. DEGs are versatile tools, adaptable to various educational levels and subjects (e.g., Huang, 2023; Situmorang et al., 2024). By utilizing their interactive and playful characteristics, DEGs foster a dynamic learning environment that often surpasses the effectiveness of traditional teaching approaches.

Taking these considerations into account, a study was designed and executed to investigate the effects of DEGs on kindergarten students' spatial skills and their understanding of numerical concepts and quantities. For reasons elaborated in the coming sections, the study targeted directional concepts (such as "up-down," "left-right," "in front-behind," and "above-below"), as well as the ability to organize and compare numbers and quantities up to ten. The effectiveness of DEGs was evaluated against conventional educational materials. Additionally, students' views and attitudes were comparatively examined. Detailed information on the study's design, methodology, and findings is presented in the subsequent sections.

## Background

### Spatial skills and very young children

According to Piaget (2013), spatial abilities develop in three stages, with the initial stage occurring between the ages of three and five. During this period, children acquire topological concepts, which are primarily two-dimensional, and become capable of recognizing objects' mutual proximity, their ranking within a group, and their integration into the broader environment. While the term "spatial ability" refers to an innate ability with predetermined levels, the term "spatial skills" encompasses skills that can be enhanced through exercises and training (Sorby, 2009).

However, research demonstrated that young children frequently struggle with directional concepts (Kónya, 2006). These challenges can largely be attributed to their developmental stage and are often rooted in cognitive, perceptual, and linguistic factors. For example, age-related issues are evident. Children under the age of eight to nine commonly confuse left-right mirror images, while those around four years old experience the most noticeable difficulties. Interestingly, such confusion occurs less frequently with up-down images, indicating a developmental progression in spatial orientation skills (Uehara, 2013). Furthermore, research demonstrated that children develop the ability to distinguish and recognize left and right before they can verbally label these directions. This ability evolves significantly as children mature, with improvements observed between the ages of seven and nine (Rigal, 1994). Additionally, research consistently pointed to sex differences in spatial abilities (Vogel et al., 2003), with boys often outperforming girls (e.g., Newcombe & Frick, 2010). These discrepancies typically arise during the preschool years or upon entering first grade (Crollen & Noël, 2015).

External factors such as language (Miller et al., 2016) and motor activities (Newcombe & Frick, 2010) also play a role. Language provides relevant verbal instructions during spatial tasks that can significantly enhance children's performance (e.g., Miller et al., 2016; Pruden et al., 2011). For instance, when children use terms like "left," "right," "up," and "down," it correlates positively with improved performance in spatial tasks involving these concepts (Pruden et al., 2011). Children with language difficulties encounter additional challenges in understanding and utilizing directional terms, suggesting a strong link between language proficiency and spatial concept acquisition (Ramos & Romero, 2006).

The challenges children face can also be attributed to their evolving visualization skills, which are essential for grasping spatial concepts such as directionality (Balinha & Mamede, 2020). Additionally, children exhibit directional biases, favoring either a left-to-right or right-to-left orientation. These biases impact their ability to learn spatial order and can be either reinforced or hindered by practices, such as reading habits (Johnson, 1990). Research indicated that children often exhibit a lateral bias, frequently placing objects on the left, which corresponds to cultural reading directions. This bias influences their representation of spatial concepts and must be taken into account in instructional strategies (Braine et al., 1993). Furthermore, preschoolers address left-right and up-down challenges using an egocentric frame of reference, even in the absence of perceptual aids. This ability suggests that such skills do not solely rely on visual cues (Fisher & Braine, 1982).

Given the complexity of spatial skills, it is crucial that teaching strategies are designed to effectively support children in mastering them (Harris, 1972). In fact, previous research has demonstrated the malleability of spatial skills (e.g., Terlecki et al., 2008), suggesting that it is indeed possible to enhance them through targeted training and specific tasks. However, the impact of such training remains inconclusive. For example, some studies have reported significant enhancements resulting from spatial training courses (e.g., Sorby, 2009). In contrast, other research has identified only moderate effect sizes (Uttal et al., 2013), while there are studies in which minimal or nonsignificant effects were observed (e.g., Sims & Mayer, 2002). It has to be noted that investigations involving preschool children are relatively scarce and primarily aim to determine how these abilities are utilized at different stages of early development (Newcombe & Frick, 2010).

## The understanding of numbers and quantities by very young children

Children's comprehension of mathematical concepts, such as number recognition, subitizing, comparing, ordering, and estimating numbers, progresses through distinct developmental stages. Initially, children possess a fundamental understanding of numbers. Then, they develop the ability to identify small quantities and form small groups of objects without relying on verbal counting. During this stage, they can also perceptually and nonverbally compare similar items. By the age of four to five, children can identify the preceding and succeeding numbers in a sequence and create groups with a small number of objects. Additionally, they can match and compare item groups and make comparisons by counting objects from one to five when the objects are of similar size. However, they might perceive a group with larger objects as having a greater number of items. By around five years of age, children can grasp the concept of cardinality, count backward, utilize number patterns, compare objects without being influenced by their physical size, and begin to understand the decimal system and place value. At approximately six years of age, children advance to conceptual subitizing, efficiently group quantities, estimate numerical magnitudes using mental number lines, grasp the concept of place value, and compare numbers (MacDonald & Shumway, 2016; MacDonald & Wilkins, 2016).

The ability to compare numerical magnitudes, both symbolic and non-symbolic, is a key milestone in early numerical development. This skill is supported by understanding cardinality and spatial mapping, which can be enhanced through digital tools (Sella et al., 2018). Early numerical competence, particularly symbolic number knowledge, is a strong predictor of performance in number line tasks (Fanari et al., 2017). Furthermore, children's ability to compose and decompose collections is crucial for understanding quantities and should be integrated into early education (Benz, 2014). However, children often struggle to determine quantities, indicating a need for targeted educational strategies (Mariana, 2010). As for set comparison, kindergarten children employ various tactics, such as length, number, and correspondence. The correspondence tactic, which involves perceiving a one-to-one correspondence between elements, is often underutilized by young children due to a lack of visual cues and cognitive development (Gullen, 1978).

Young learners encounter numerous other obstacles while learning mathematics that arise from cognitive, pedagogical, and socio-cultural factors. Therefore, the development of mathematical competence in young children is a complex, multidimensional process, necessitating focus on diverse content areas such as logic, numeracy, geometry, and data processing (Dunekacke et al., 2024). Ineffective instructional methods and a lack of stimulating, meaningful activities can obstruct children's mathematical learning. Although open-ended and intricate tasks can enhance their learning experiences, they might also complicate the learning process for some students (Freiman, 2018). Furthermore, socio-cultural factors, including the level of support from family and educational institutions, can result in learning gaps, highlighting the need for equitable access to high-quality math education (Fuson et al., 2015; Moss et al., 2015).

Coming to learning the arrangement and comparison of numbers and quantities, kindergarten students also face several challenges. Young children frequently struggle with focusing on numerosity because they must filter out irrelevant stimuli (Henik, 2021). Cognitive processes, such as statistical learning, structure mapping, and spatial cognition, play a critical role in number learning. Nevertheless, these processes can pose challenges if not properly supported (Mix, 2022). Mastery of the sequence of number words, particularly those beyond 20, represents a significant obstacle for kindergarten students. This challenge is amplified by irregularities in the number systems of various languages (Gould, 2016). Understanding and employing written number symbols is often difficult, as children need to learn to associate these symbols with corresponding quantities and operations (Zhou et al., 2006). Additionally, there are challenges in reading multi-digit numbers and comprehending mathematical symbols (Bayaga & Nzuza, 2022).

## Digital game-based learning, digital educational games, and kindergarten students

As stated in the "Introduction," DGBL is recognized for its potential to develop cognitive skills, motivate learners, and promote experiential learning. It is particularly effective in enhancing critical thinking and problem-solving abilities, as games demand that players strategize, make decisions, and solve complex problems, leading to improved cognitive capabilities (Shaheen & Fotaris, 2024). The interactive aspect of games significantly elevates student motivation and engagement. Research indicated that students exhibited increased interest in learning when it was enriched with game-based elements, resulting in better retention and comprehension of the material (Aeschbach et al., 2024). Furthermore, DGBL offers a safe space for students to experiment, experience failure, and learn from their mistakes, which is essential for the understanding of the subject matter (Shaheen & Fotaris, 2024).

Despite its promise, there are concerns regarding the methodological rigor of studies assessing DGBL's effectiveness. That is because a number of studies exhibited a lack of transparency and consistency, influencing the findings' reliability (Aeschbach et al., 2024). Additionally, an over-reliance on games could diminish the value of traditional learning methods, as not all students may respond favorably to game-based learning. The success of DGBL also relies on the quality of game design and its alignment with educational objectives.

DGBL has been established as a promising educational strategy for kindergarten students. It capitalizes on the inherently playful nature of games to cultivate a range of skills. A systematic review of DGBL in early childhood education underlined its potential to enhance thinking skills and cognitive development, although additional research was deemed necessary (Behnamnia et al., 2022). DGBL significantly strengthened literacy abilities in kindergarten students, rendering learning enjoyable but also fostering the transfer of the skills acquired to real-world applications (Guo, 2023). In addition, DEGs have been found to improve the vocabulary of young learners compared to traditional methods (Wei & Wang, 2022).

While the body of research investigating the role of DEGs in enhancing spatial skills among kindergarten children remains limited, studies have noted their promising potential. They can enhance spatial skills through activities that require children to mentally manipulate objects and visualize spatial relationships (Choi & Feng, 2017). For example, digital geometric puzzle games stimulated spatial intelligence in four- to five-year-olds, surpassing traditional media in their impact (Saroinsong et al., 2021). Activities such as navigating mazes, enhance children's ability to interpret signs and avoid obstacles; interestingly, girls have shown particular attentiveness in these tasks (Perez et al., 2016).

In addition, they offer unique opportunities to present spatial information that is not accessible in the real world, thus, broadening the spectrum of spatial experiences available to young learners (Polinsky et al., 2023). Spatial-learning games often integrate storybook elements and encourage collaborative participation, rendering the learning process personally meaningful (Dang et al., 2024). There is also evidence that a child's spatial abilities are correlated with their success in spatially focused games, suggesting a relationship between digital spatial play and the development of spatial skills (Polinsky et al., 2021).

In general, it can be argued that DEGs support very young children's mathematical development (e.g., Miller, 2018; Rogowsky et al., 2017), by increasing their motivation and engagement with mathematics (Salinas & Ly, 2015), and by making learning more engaging and interactive (Sallik et al., 2022). For example, the use of digital puzzle games with a Realistic Mathematics Education approach has been validated as effective for kindergarten students, suggesting that such games are well-suited to capture children's interest and facilitate learning (Kurniasih & Ngastiti, 2024).

Although literature concerning the comparison and arrangement of numbers and quantities is somewhat sparse, the influence of DEGs appears to be beneficial. They can effectively support the development of number sense in young children (Kermani, 2017). Laurillard (2016) also concluded that DEGs, especially those providing intrinsic feedback, support independent learning and assist low-achieving learners in improving their number sense and the understanding of numerical magnitude. Yet, in another study related to number sense (Miller, 2018), it was observed that there was only a small positive difference in the numeracy skills, although collaboration between students was increased.

App-based number lines have been proven slightly more effective than traditional paper methods for teaching number comparison. These tools provided flexibility and visual cues that enhanced the understanding of numerical order and magnitude (Weng & Bouck, 2016). Furthermore, research by Ramani et al. (2020) revealed that tablet-based number games had a significant positive effect on children's numerical knowledge, with these improvements persisting over time. Lastly, Can (2020) reported that games focused on number recognition, subitizing, and object counting for children aged four to six, supported learning trajectories related to number recognition, counting, and comparison, although the author acknowledged a need for more games centered on estimation skills.

## Statement of the problem, issues in current research

To summarize what was presented in the preceding sections, a number of interesting points can be noted:

- Directional concepts, crucial for mathematical and cognitive development, often challenge young children due to age-related developmental factors. Research demonstrated that spatial skills can be improved, although effects vary across studies.
- Children's understanding of mathematical concepts, such as number and quantity recognition and estimation is also crucial. As with directional concepts, kindergarteners face challenges due to cognitive, pedagogical, and socio-cultural factors, highlighting the importance of math education from an early age.

- DEGs are effective in fostering critical thinking, problem-solving abilities, motivation and engagement. Moreover, they provide a safe environment for students to experiment, experience failure, and learn from mistakes. In the context of kindergarten education, DEGs emerge as a promising strategy, as they leverage the playful nature of games to enhance a variety of skills. On the other hand, existing research on DEGs reveals certain gaps, such as concerns regarding the methodological rigor of studies.
- The existing body of research investigating the role of DEGs in enhancing spatial skills among kindergarten children, while promising, remains limited. Although studies have demonstrated the potential of DEGs, the mechanisms through which these games surpass traditional media in fostering spatial skills require further investigation.
- DEGs have been found to significantly enhance mathematical development in very young children. They have also demonstrated slight superiority over conventional paper methods in teaching number comparison and numerical magnitude understanding. Yet, there is limited literature on the comparison and arrangement of numbers and quantities.

## Method

To address the research gaps and issues identified in the preceding section, a research project was designed and implemented. It was decided to examine the effectiveness of DEGs relative to conventional educational materials. The focus was on basic spatial and mathematical skills, specifically directional concepts (such as "up-down," "left-right," "in front-behind," and "above-below"), as well as students' abilities to organize and compare numbers and quantities up to ten, as these align well to the current curricula for kindergarten students. A between-subjects research design with two groups was applied; the control group utilized conventional educational materials, while the experimental group engaged with DEGs. As sex, age, and prior knowledge seem to play a role, it was also decided to take into considerations their effects. Moreover, to ensure the reliability and validity of the data, each subject area was examined across three separate sessions. The following research questions were examined:

- RQ1a-b. Compared to conventional materials and controlling for the effects of participants' sex, age, and prior knowledge, do DEGs have a significantly greater impact on learning outcomes of kindergarten students in two specific domains: (a) basic spatial skills, particularly those associated with directional concepts, and (b) basic mathematical skills, specifically those involving the comparison and arrangement of quantities and numbers up to ten?
- RQ2a-c. Compared to conventional materials and controlling for the effects of participants' sex and age, do DEGs exhibit a more substantial effect on kindergarten

students' (a) enjoyment and (b) motivation compared to conventional materials? Are they (c) easier to use?

- RQ3a-c. Do (a) enjoyment, (b) motivation, and (c) ease of use influence the learning outcomes of kindergarten students in the areas of basic spatial and mathematical skills?

## Participants

A convenience sample was employed consisting of 84 students coming from four classes of a private kindergarten school located in a city in Greece. Their age was between four and six years old. A significant inclusion criterion was that the students had not previously received instruction in the subjects examined in the study. With few exceptions, all were native Greeks, belonging to the middle class in terms of their socio-economic status. Further details about their sex and age distribution are provided in section "Results." Half of the participants were assigned to the control group, while the remaining participants were allocated to the experimental. The Ethics and Research Committee of the Department of Primary Education, University of the Aegean, provided its approval for the project. Moreover, students' parents and legal guardians provided their written consent.

## Materials

As previously mentioned, this study concentrated on spatial skills related to directional concepts, and basic mathematical skills involving the comparison and sequencing of quantities and numbers up to ten. Table 1 provides the breakdown of the subjects covered in each session.

**Table 1**

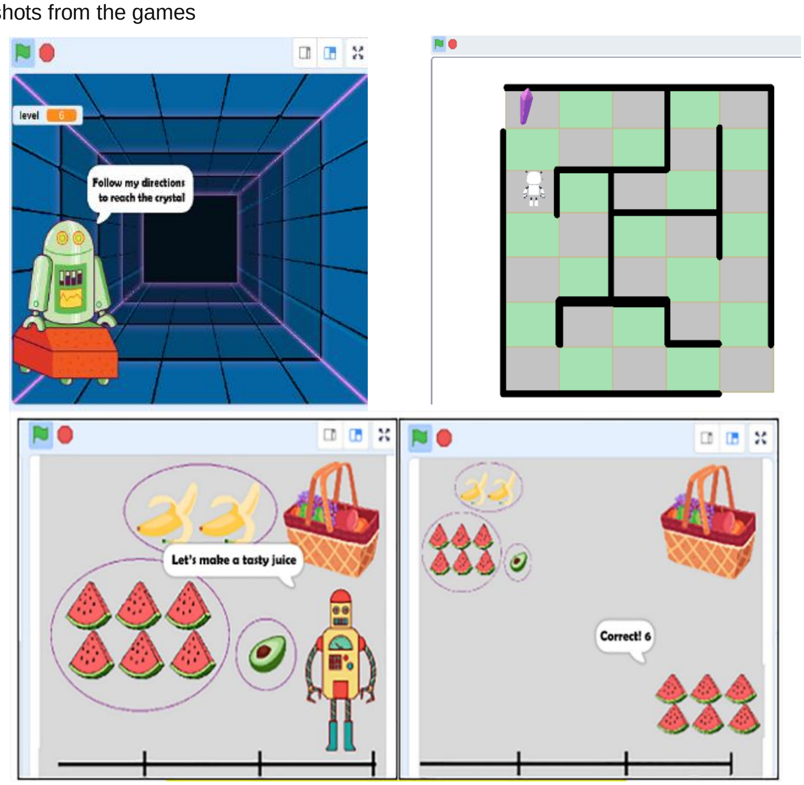
Subjects per session

| Session | Spatial skills | Number comparison/arrangement |
| --- | --- | --- |
| 1/4 | Directional concepts (up-down, etc.) | Arrangement of numbers and quantities from 1 to 5 |
| 2/4 | Spatial demarcation in relation to the self | Arrangement of numbers and quantities from 6 to10 |
| 3/6 | Spatial demarcation in relation to a different reference point | Number and quantity comparison |

The control group received instruction through printed materials such as mazes, numbers, arrows, number lines, various objects (e.g., plastic fruits), and tables designed for arranging numbers and quantities. Additionally, the teaching incorporated worksheets featuring diverse in-classroom activities and oral instruction. In contrast, the experimental group only used laptops and DEGs specifically developed for this study using Scratch (Figure 1). An innovative feature introduced to the DEGs was the unconventional control mechanism for the games, which did not rely on the traditional mouse and keyboard setup. Instead, the games were controlled through a device known as Makey-Makey (https://makeymakey.com/). This inexpensive circuit board interfaces with a computer through a USB port and is automatically recognized as a human-computer interface, without the need for additional drivers or software installation. By employing cables and alligator clips, Makey-Makey can be connected to any conductive material, including Play-Doh, aluminum foil, or even fruits. Utilizing highly sensitive resistance switching, it is capable of detecting closed circuits even when connected to materials with low conductivity. Upon closure of a circuit, Makey-Makey interprets the action as a mouse click or keystroke, which can then serve as an input command for any software application. This device, either independently or in conjunction with other tools and applications, has been utilized in educational settings to teach a variety of subjects, from music to mathematics (e.g., Fokides & Alatzas, 2022; Julia et al., 2019). The rationale for incorporating Makey-Makey was based on the hypothesis that it would render the games more engaging and fun to play. Central to the games was a character in the form of a robot, called "Robie," fulfilling the role of a teacher. This character delivered all narrative components of the games, including verbal instructions, explanations, guidance on required tasks, and feedback. These audio instructions were not merely necessary due to participants' inability to read. Previous research indicated that verbal instruction can enhance performance (Miller et al., 2016). Given this, it was crucial to ensure that verbal instructions were also provided in the DEGs, similar to those given in the control group.

**Fig. 1**

Screenshots from the games



Every effort was made to ensure that each conventional activity had a corresponding digital equivalent. For instance, during an in-classroom activity, students were instructed by the teacher to place their hands in various positions, such as placing the left hand in front of the nose. In the corresponding digital game activity, students were required to perform the same actions to Robie. In another in-classroom activity, a student stood in the center of the class while peers answered questions such as "Who is in front of the student?" and "Who is to the left of the student?" This was mirrored in a digital activity where Robie was placed at the center of the game area, surrounded by objects, and students had to identify the location of each object relative to Robie. In an in-classroom activity, students directed a classmate to exit the room while avoiding obstacles, by giving commands such as "move forward one step." In the digital games, students guided Robie to collect crystals within a maze or helped him reach the maze's exit.

Coming to the numbers and quantities sessions, in a classroom activity, the teacher utilized a drum to produce a random number of beats. Students were tasked with indicating with their fingers the number of beats. To elevate student interest, the beats alternated between rapid and slow tempos. In the corresponding game activity, Robie generated a random number of "beeps," prompting students to press a button corresponding to their number. Mirroring the classroom activity, the frequency of these beeps varied. In a group activity, students were provided with paper trees and leaves, along with a set of cards numbered one through ten. Each student drew a card and was required to attach to the tree a number of leaves corresponding to the drawn card's number. Subsequently, the next student, upon drawing a card, had to determine and state whether the new number was greater or smaller than the previous one before placing the appropriate number of leaves on the tree. In a related game-based task, Robie instructed students to place a randomly generated quantity of bananas into a basket. Similar to the conventional materials activity, Robie prompted students to compare the current randomly generated number with the previous one, assessing whether it was larger or smaller. Furthermore, in a worksheet exercise, students were presented with a fruit juice recipe that specified various required quantities of different fruits. Students were tasked with writing the number of each type of fruit required and then arrange the fruits in descending order on a number line. This identical task was integrated into a gaming activity.

## Instruments

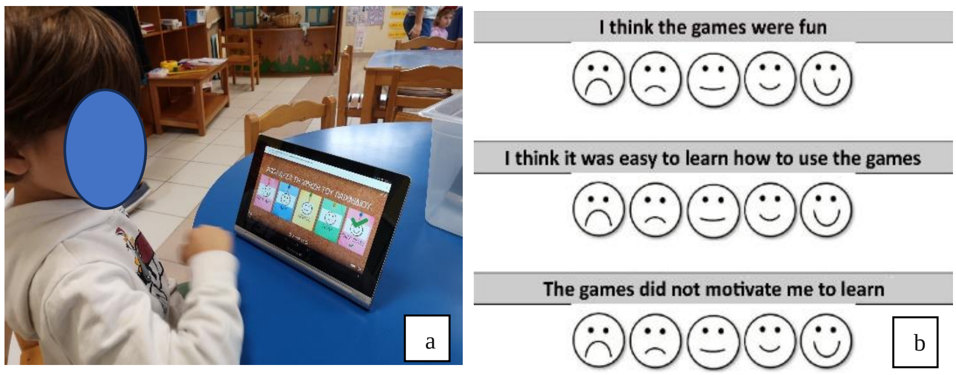
For data collection purposes, a pre-test (to assess students' prior knowledge), six evaluation tests (one per session), and a questionnaire were employed. The pre-test was conducted prior to the beginning of the study, while the evaluation tests were administered at the end of each session. The questionnaire was distributed during the final session in which a particular medium was utilized. Given the young age of the students and their limited reading and writing skills, it was necessary to adapt the data collection tools to be age-appropriate. The tests and questionnaire were trialed on a small sample of non-participating students, to verify the clarity of the questions and to make any necessary adjustments. For both the tests and the questionnaire, tablets were used, enabling students to "tap" their selected answers rather than write them (Figure 2a). Both the evaluation tests and questionnaires were completed individually, with kindergarten teachers reading the questions aloud prior to students recording their responses. No fixed time limit was imposed for completion for both the evaluation tests and the questionnaire.

Given the absence of standardized tests, the evaluation tests were developed ad hoc. All questions had the form of activities, to allow participants to articulate their understanding and beliefs, while minimizing the chances of random guessing. It is important to note that all questions closely mirrored the activities presented during the sessions, ensuring that students were familiar and comfortable with the tasks they were required to undertake. In the evaluation tests assessing spatial concepts, the questions were structured in two formats: (i) mazes and (ii) guided drawings. In the maze-based tasks, students were required to navigate to specific locations, such as reaching particular objects or exiting mazes of increasing complexity, by following directions (e.g., go up three steps, then turn left and proceed two steps). Alternatively, they were asked to provide the necessary directions to achieve these goals. In the guided drawing tasks, students were instructed to color specific parts of shapes (e.g., the left side of a heart), color objects in relation to others (e.g., color the object above the house), and create progressively complex drawings by following specific directions (e.g., draw a sun in the top left corner of the canvas, a tree below the sun, and a cloud to the left of the sun). The evaluation tests related to the comparison and arrangement of quantities and numbers also included activities of escalating difficulty. In these tasks, students were challenged to identify errors in number lines and correct them, draw circles equal to, less than, or one more than a given number, circle an equal number of items as indicated by the number above them, count and record the number of items presented, compose and decompose groups with specific number of items, and arrange numbers on a number line in either ascending or descending order. Sample questions from these evaluation tests can be found in Appendix I.

The questionnaire utilized items from a validated modular scale to assess factors influencing the learning experience in DEGs (Fokides et al., 2019). For this study, three factors were chosen, corresponding to the factors examined in RQ2a-c: motivation (three items), enjoyment (four items), and perceived ease of use (five items). To enhance the user-friendliness of the questionnaire, emoticons were employed in place of the traditional five-point Likert-type scale (Figure 2b, where the left-hand emoticon signifies none/not at all, and the right-hand emoticon signifies a lot/very much). The questionnaire is presented in the Appendix II.

**Fig. 2**

Screenshot from the data collection process (a) and sample questions from the questionnaire (b)




## Procedure

Prior to the beginning of the main sessions, a familiarization session was conducted to introduce the experimental group students to the use of games and Makey-Makey. During this session, students engaged with a game not included in the main study. Each session for both groups lasted two teaching hours, with students organized into groups of four (Figure 3). This method is well-suited for students of this age group, fostering a conducive environment for cooperation and mutual support. Pre-existing groups within each class were primarily utilized to streamline the learning process. Students were encouraged to discuss and exchange ideas freely at any point during a session.

**Fig. 3**

Screenshots from the experimental group sessions

In the control group, each session began with teachers providing a brief introduction to the session's topic, followed by a short discussion. Subsequently, students engaged in various activities included in the session. At the conclusion of each session, group discussions were held to allow teachers to summarize what students had learned and to draw relevant conclusions. In the experimental group, while the teachers were present, they did not provide explanations or answers to students' questions concerning the learning material. With the exception of group discussions at the end of each session, the "lesson" was conducted entirely through the games. There was no direct teaching involved, as the study aimed to examine the intrinsic effect of DEGs on learning. Incorporating any form of teaching could have confounded the results, thus making it unclear whether the outcomes were attributable to the medium, the teaching method, or the teacher's skills.

## Results

### Initial data processing

Due to their absence in one or more sessions, data from three participants were excluded from the analysis, resulting in a final sample size of 81 students for the study. The control group (conventional materials) consisted of 40 students (22 boys and 18 girls). Of these, 19 were younger than five years old (but more than four), while the remaining 21 were older than five (but less than six). Similarly, the experimental group (DEGs) consisted of 41 students (25 boys and 16 girls), with 19 participants under five years old and 22 participants over five years old.

A 10-point scale was employed for grading both the evaluation tests and the pre-test. Following this, the data from these tests and the questionnaires were imported into SPSS 29 for subsequent analyses. Initially, two new variables were calculated representing students' average scores in the subjects of spatial concepts and the comparison and arrangement of quantities and numbers. Next, the internal consistency of the questionnaires was assessed using Cronbach's α. The results verified that the internal consistency was acceptable, as no instances were noted where the α coefficient, either the overall or for any individual factor, fell below the recommended minimum threshold of .70 (the overall α was determined to be 0.85, with factor-specific α values ranging from 0.76 to 0.88), consistent with the guidelines set by Hair et al. (2019). Additionally, three variables were calculated to represent the average score per factor for each participant. Detailed descriptive statistics for the study's variables are provided in Table 2.

**Table 2**

Descriptive statistics for the study's variables

| Variable | Control group ($n$ = 40) | | | | Experimental group ($n$ = 41) | | | |
|---|---|---|---|---|---|---|---|---|
| | Boys ($n$ = 22) | | Girls ($n$ = 18) | | Boys ($n$ = 25) | | Girls ($n$ = 16) | |
| | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| Pre-test | 6.07 | 3.02 | 6.44 | 2.06 | 4.58 | 2.64 | 6.78 | 2.07 |
| Spatial score | 7.22 | 1.93 | 7.83 | 1.41 | 8.63 | 0.96 | 8.86 | 1.09 |
| Maths score | 7.43 | 2.04 | 8.22 | 1.78 | 8.97 | 1.02 | 9.11 | 0.80 |
| Enjoyment | 4.04 | 0.57 | 3.57 | 0.61 | 4.64 | 0.41 | 4.21 | 0.83 |
| Motivation | 4.12 | 0.90 | 3.76 | 1.01 | 4.65 | 0.48 | 4.52 | 0.50 |
| Ease of use | 4.21 | 0.88 | 4.19 | 0.77 | 2.95 | 0.71 | 2.91 | 0.68 |

## Analysis of the evaluation tests

In addressing RQ1a-b, it was essential to control for the effects of students' prior knowledge, age, and sex on the learning outcomes, given that these variables could potentially influence the evaluation test scores. An Analysis of Covariance (ANCOVA) was identified as the appropriate statistical technique. The evaluation test scores served as the dependent variables, while pre-test scores, age, and sex were incorporated as covariates. Prior to the analysis, the suitability of the data for ANCOVA was examined. It was noted that the residuals of the dependent variables exhibited significant deviations from normality, necessitating an alternative approach. Consequently, it was decided to employ Quade's (1967) test of equality of conditional population distributions, which is the non-parametric equivalent of ANCOVA. The findings of this analysis are detailed in Table 3.

**Table 3**

Quade's ANCOVA results for the evaluation tests

| Result | Variable | |
|---|---|---|
| | Spatial score | Maths score |
| *dfh* | 1 | 1 |
| *dfe* | 79 | 79 |
| *F* | 19.42 | 22.14 |
| *r* (effect size) | .44 (medium) | .46 (medium) |
| Pairwise comparison (control vs experimental group) | | |
| *t* | 4.41 | 4.71 |
| *p* | < .001 | < .001 |

*Note*. dfh and dfe are the hypothesis and error degrees of freedom

## Analysis of the questionnaires

To address research questions RQ2a-c and given the necessity to control for the effects of students' age and sex, an ANCOVA was determined to be the most appropriate statistical procedure. The dependent variables were the factors' scores, with age and sex serving as covariates. Once again, Quade's (1967) test was utilized as the residuals of the dependent variables significantly deviated from normality. The outcomes of the analyses are presented in Table 4.

**Table 4**

Quade's ANCOVA results for the questionnaires

| Result | Variable | | |
|---|---|---|---|
| | Enjoyment | Motivation | Ease of use |
| *dfh* | 1 | 1 | 1 |
| *dfe* | 79 | 79 | 79 |
| *F* | 28.31 | 11.22 | 53.10 |
| *r* (effect size) | .51 (large) | .35 (medium) | .63 (large) |
| Pairwise comparison (control vs experimental group) | | | |
| *t* | -5.32 | -3.35 | 7.29 |
| *p* | < .001 | 001 | < .001 |

## Analysis of the factors affecting learning outcomes

To address RQ3a-c, which examined whether the factors of the questionnaire (enjoyment, ease of use, and motivation) influenced the learning outcomes, a multiple linear regression was initially deemed the appropriate statistical method. However, due to significant deviations from normality in the residuals of the dependent variables, as previously noted, a generalized linear model was chosen. Based on the specific type and distribution of the variables, the Gamma model with a log link function was selected. The evaluation test results served as the dependent variables, while the three factors from the questionnaire were utilized as covariates. The findings of these analyses are presented in Tables 5 and 6. Given the small sample size, careful consideration is advised when interpreting the results.

**Table 5**

The results of the generalized linear model for the spatial tests

| Group | Variable | *B* | Std. Error | 95% Wald Confidence Interval | | Hypothesis Test | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Lower | Upper | Wald $\chi^2$ | *df* | *p* |
| Control (*n* = 40) | Enjoyment | .05 | .06 | -.07 | .16 | 0.66 | 1 | .417 |
| | Motivation | .03 | .04 | -.06 | .11 | 0.46 | 1 | .500 |
| | Ease of use | -.07 | .04 | -.14 | .01 | 3.38 | 1 | .066 |
| Experimental (*n* = 41) | Enjoyment | .05 | .04 | -.02 | .12 | 1.86 | 1 | .172 |
| | Motivation | .04 | .04 | -.04 | .12 | 0.98 | 1 | .323 |
| | Ease of use | .02 | .02 | -.02 | .06 | 1.47 | 1 | .226 |

**Table 6**

The results of the generalized linear model for the maths tests

| Group | Variable | *B* | Std. Error | 95% Wald Confidence Interval | | Hypothesis Test | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Lower | Upper | Wald $\chi^2$ | *df* | *p* |
| Control (*n* = 40) | Enjoyment | .09 | .07 | -.06 | .23 | 1.41 | 1 | .236 |
| | Motivation | -.01 | .03 | -.06 | .05 | 0.03 | 1 | .856 |
| | Ease of use | -.08 | .04 | -.16 | .01 | 3.03 | 1 | .082 |
| Experimental (*n* = 41) | Enjoyment | .06 | .02 | .02 | .10 | 7.88 | 1 | .005 |
| | Motivation | .03 | .04 | -.04 | .11 | 0.80 | 1 | .371 |
| | Ease of use | -.01 | .02 | -.05 | .03 | 0.26 | 1 | .611 |

### Summary of the results, answers to the research questions

Based on the results, the following conclusions can be drawn in response to the research questions:

- RQ1a-b. DEGs demonstrated a significantly greater positive impact on learning outcomes in both spatial concepts and assessment and arrangement of numerical values and quantities up to ten, as compared to conventional materials. The effect size was medium.
- RQ2a-c. DEGs also exhibited a more substantial positive effect on students' enjoyment and motivation compared to conventional materials. For enjoyment the effect size was large, while for motivation it was medium. However, it was noted that conventional materials were easier to use than DEGs and the effect size was large.
- RQ3a-c. When utilizing DEGs, enjoyment emerged as the sole factor influencing learning outcomes in the mathematical concepts. None of the factors had an effect on learning outcomes in spatial concepts. For conventional materials, no factors influenced learning outcomes.

## Discussion

### Discussion of the findings related to RQ1a-b

Regarding spatial skill development (RQ1a), the study's findings are in line with existing research that highlighted the effectiveness of DEGs in providing interactive and experiential learning environments (e.g., Santórum et al., 2023), surpassing that of traditional media (Saroinsong et al., 2021). A plausible explanation is that the games employed in the study required students to visualize spatial relationships and navigate mazes, both of which have been shown to enhance spatial skills (Choi & Feng, 2017; Perez et al., 2016). As the goals set in each game were relatively easy to achieve, this may have also contributed to the outcomes, considering that previous research suggested a correlation between success in spatially focused games and the development of spatial skills (Polinsky et al., 2021). The findings also align with evidence from the broader DGBL literature, which underscored the potential of DEGs in cultivating cognitive abilities through experiences that allow students to experiment, experience failure, and learn from their mistakes (Shaheen & Fotaris, 2024). Piaget's (2013) developmental framework emphasized that spatial skills start forming at a very young age. The study's results are consistent with these developmental principles, highlighting the adaptive efficacy of DEGs. Furthermore, language and motor activities are shown to influence spatial skill enhancement, with research suggesting that verbal instruction can amplify spatial task performance (Miller et al., 2016). Considering the above, the study's DEGs incorporated auditory cues. Thus, they offered a rich platform for integrating language and spatial learning, fostering cognitive development.

In relation to RQ1b, the effectiveness of DEGs in advancing mathematical skills related to number and quantity comprehension is similarly notable. Kindergarten students often encounter challenges in understanding numerical concepts due to developmental constraints and pedagogical limitations (Henik, 2021; Mix, 2022). On the basis of the study's results, it seems that DEGs mitigate these obstacles, probably because they provide immediate feedback (Laurillard, 2016) and visualization aids, which enhance number sense and operational understanding (Weng & Bouck, 2016). Such capabilities confirm the views of others who noted the role of DEGs in facilitating early numerical competence, (e.g., Kermani, 2017; Kurniasih & Ngastiti, 2024). Given that young learners often struggle with numerosity (Henik, 2021), it can be supported that DEGs help scaffold these foundational skills through activities that are in line with their learning preferences. Though others suggested that in the field of basic mathematical skills DEGs have a small advantage over conventional media (Miller, 2018), in this study the advantage was rather significant. This gives support to prior studies that advocated for the integration of DEGs in early education (Henik, 2021; Sakka & Gouscos, 2023).

Though the results are favorable for DEGs, they also have to be viewed with caution because of the "novelty effect." The term refers to the initial fascination that individuals experience when encountering new technology, environments, or stimuli. This effect can significantly influence -either positively or negatively- learning outcomes, cognitive processing, and motivational dynamics. The novelty effect is often temporary and diminishes over time, potentially impacting the effectiveness of learning and engagement (Marek et al., 2021). Given the short duration of the study and given its innovative nature, it is quite plausible that the novelty effect had an -undetermined- impact on learning outcomes.

## Discussion of the findings related to RQ2a-c

One of the objectives of this study was to evaluate the comparative effects of DEGs versus conventional educational materials on students' enjoyment (RQ2a), motivation (RQ2b), and ease of use (RQ2c), critical factors that influence learning outcomes in early education contexts. The findings related to enjoyment and motivation are consistent with the literature, which concluded that the interactive nature of DEGs is instrumental in creating engaging learning environments (Aeschbach et al., 2024; Shaheen & Fotaris, 2024). Such environments not only maintain the children's interest but also significantly contribute to deeper learning (Sakka & Gouscos, 2023), by encouraging active participation and sustained attention (Sakka & Gouscos, 2023; Sallik et al., 2022). The substantial increase in motivation is in line with previous research, which highlighted that DEGs, by their very nature, are effective in motivating learners (Salinas & Ly, 2015) and promoting sustained engagement with educational content (Aeschbach et al., 2024; Kurniasih & Ngastiti, 2024; Sallik et al., 2022). This underlines the capacity of DEGs to surpass traditional methods in creating an intrinsic motivation to learn, which is crucial at the kindergarten level. The findings also illustrated that DEGs served as a medium for teaching directional and numerical concepts in a manner that is enjoyable to young children as others suggested (e.g., Guo, 2023). The enjoyable and playful nature of DEGs, aligns well with the preschool pedagogical emphasis on learning through play.

On the other hand, the study's findings indicated that conventional materials were easier for students to use than DEGs. This observation suggests a potential accessibility barrier posed by digital platforms, which may require a familiarity with technology that young children have yet to fully develop. It stresses the necessity for user-friendly and age-appropriate digital interfaces that can be intuitively navigated by young learners and tailored to the cognitive and motor skills of preschool children (Santórum et al., 2023).

## Discussion of the findings related to RQ3a-c

Addressing RQ3a-c, the findings indicated that enjoyment was the only factor that played a significant role in enhancing learning outcomes, only in the case of basic mathematical skills, and only when utilizing DEGs. Motivation and ease of use did not play a role whatsoever, regardless of the type of educational materials used. This points out the nuanced interplay between these factors and their impact on early childhood education.

The ability of DEGs to captivate children's interest and present learning content in an engaging/playful manner significantly contributing to positive learning outcomes aligns with previous research indicating that DEGs, by incorporating game-based elements, increase student enjoyment (e.g., Guo, 2023). The interactive nature of games enhances critical thinking and problem-solving abilities, providing a dynamic learning environment that promotes not only comprehension but also retention of mathematical concepts (e.g., Ramani et al., 2020; Weng & Bouck, 2016). Thus, the heightened enjoyment derived from DEGs likely facilitated cognitive processes essential for numerical understanding and spatial skill development.

Yet, motivation, while generally positively impacted by the use of DEGs (e.g., Salinas & Ly, 2015), did not emerge as a significant factor. This finding may suggest that while motivation contributes to the positive perception of learning activities, it does not directly translate into measurable learning gains under certain conditions. The impact of motivation might be more subtle, influencing engagement levels, yet not robust enough to affect the complex cognitive tasks involved in mastering spatial and numerical concepts.

On the other hand, the absence of ease of use as a significant factor in learning outcomes with DEGs can be viewed as a positive outcome, especially considering that DEGs were perceived as more challenging to use than conventional materials. Usability issues are known to potentially hinder both learning and learning experiences. Therefore, the findings suggest that, although DEGs may be less user-friendly compared to conventional materials, the associated challenges were not significant enough to adversely impact the learning process.

Regarding conventional educational materials, no significant effects were observed on learning outcomes for spatial concepts or numerical tasks. This highlights a potential limitation of conventional methods in engaging students and fostering conceptual understanding in the same manner as DEGs. As traditional methods may not adequately address the diverse needs and learning styles of young learners (Sharpe, 1999), this highlights the necessity for innovative approaches, such as DEGs, that better align with the playful, experiential nature of early childhood education.

## Implications for research and practice

The study extends the existing literature by focusing on very young students and by comparing the impact of DEGs relative to conventional materials. Thus, it provides interesting insights for researchers, educators, and software developers involved in the field of DEGs, particularly concerning early childhood skill development. For researchers, the significant benefits observed in using DEGs over conventional materials, calls for further investigation into the mechanisms by which DEGs enhance spatial intelligence and number sense, the identification of factors that contribute, and their interplay across diverse learner groups. For developers, the study's results provide indications of the importance of designing educational games targeting young learners. The noted ease-of-use issues call for developers to prioritize intuitive interfaces and user-friendly experiences tailored to the developmental stages of kindergarten students. Developers are also advised to incorporate elements that enhance user engagement, such as gamified feedback and adaptive difficulty levels, which can sustain the observed high levels of enjoyment and motivation. Moreover, designing games that address both spatial and mathematical skills simultaneously can provide holistic learning benefits.

Educators can draw from this study the importance of integrating DEGs into early childhood educational settings. The enhanced enjoyment and motivation associated with DEGs suggests that these tools can be powerful allies in fostering a positive and engaging learning environment for young children. Thus, educators are encouraged to incorporate DEGs into their teaching methods, recognizing that while these games may present initial usability challenges, the benefits in student engagement and motivation can lead to improved educational outcomes.

Developing the games utilized in this study demanded considerable time and expertise. Although these tasks are manageable for users with average to advanced skills, it is doubtful whether educators have the necessary time, resources, and motivation to engage in such activities, given their current workload. Consequently, it is crucial for educational administrators to provide educators with a repository of ready-to-use DEGs. In-service training programs will equip teachers with the essential skills, enhancing their proficiency in creating and deploying these games. Furthermore, since integrating DEGs and associated activities into the existing teaching framework demands extra time, it is essential for education policymakers to consider revising school timetables and curricula, which are often rigid and inflexible.

## Limitations and future work

The study has several limitations that need to be acknowledged. In detail:

- A primary limitation is the sample size; increasing the number of participants would greatly enhance the confidence and reliability of the results.
- Another significant issue is the reliability of self-reported responses from the study's participants, given their young age.
- The study's focus on kindergarten students and two specific subjects raises questions about the generalizability of its findings.
- Moreover, the limited number of sessions may not be adequate to yield meaningful conclusions.
- The research compared DEGs with conventional materials but did not explore other technologies or methods; thus, the question of whether DEGs outperform these alternatives was left unanswered.
- Additionally, the study considered only a limited set of factors that might influence learning outcomes. Incorporating more variables could have provided a more comprehensive understanding of the essential elements impacting learning in DEGs.
- Future research can address these limitations by:
- Involving more diverse target populations with varying ages and educational backgrounds and employing larger sample sizes, so to gain more robust insights.
- Exploring other learning domains and application types.
- Examining additional elements such as cognitive load, game quality, and game-design considerations, so as to achieve a more comprehensive understanding of the key factors affecting learning outcomes in DEGs.
- Including qualitative data such as interviews and observations, in order to develop a more thorough understanding on how DEGs impact learning.
- Conducting longitudinal studies for delving deeper into the educational potential of DEGs.
- Finally, though sex, age, and prior knowledge were considered in this study, due to limitations in the statistical procedures that were followed, it was possible to remove

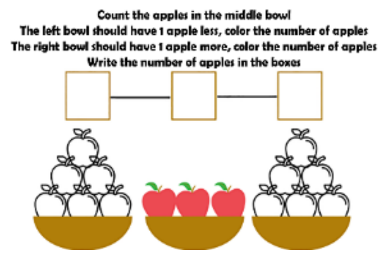
their effects but not quantify them. As sex differences and developmental stages play a role and as they may be addressed through tailored DEGs, future studies can be designed specifically to examine the impact of these factors.

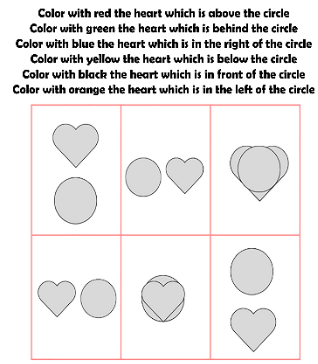
## Conclusion

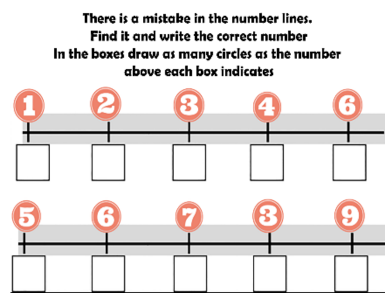
The study highlighted the significant role of DEGs in the early educational landscape, particularly in enhancing kindergarten students' basic spatial and numerical skills. The findings demonstrated that DEGs improve learning outcomes related to directional concepts and the comparison and arrangement of numbers and quantities up to ten, surpassing the effectiveness of conventional educational materials. The DEGs also enhanced students' enjoyment and motivation, although they presented some challenges in ease of use compared to conventional materials. Enjoyment emerged as a critical factor influencing learning outcomes in numerical tasks. These insights advocate for the continued integration of DEGs into early childhood curricula, suggesting a promising avenue for future educational endeavors. The study also calls for further exploration into optimizing the usability and efficacy of DEGs, ensuring they meet the developmental needs and learning preferences of very young children. In conclusion, the study's findings suggest that DEGs offer a versatile and engaging learning modality that holds considerable promise for fostering foundational skills essential for future academic success in young learners. However, their effective integration requires administrative support, professional development, and curricular flexibility to ensure educators have both the resources and capacity to implement these tools successfully.

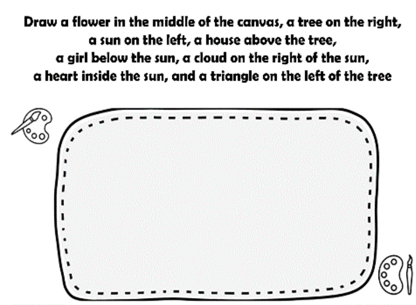
## Appendix I

Sample questions from the evaluation tests




## Appendix II

The study's questionnaire

| Factor | Item |
|---|---|
| Enjoyment | I think the games were fun |
| | I felt bored while using the games* |
| | I enjoyed using the games |
| | I really enjoyed studying with these games |
| Perceived ease of use | I think it was easy to learn how to use the games |
| | I found the games complex to control* |
| | I needed to learn a lot of things before I could get going with these games* |
| | I felt that I needed help from someone else in order to use the games because It was not easy for me to understand how to control them* |
| Motivation | The games did not hold my attention* |
| | When using the games, I did not have the impulse to learn more about the learning subject* |
| | The games did not motivate me to learn* |

*Notes*. * = Item for which its scoring was reversed. The word "games" was replaced with the phrase "conventional materials" in the control group

**Abbreviations**

ANCOVA: Analysis of Covariance
DEGs: Digital educational games
ICTs: Information and Communication Technologies

**Author's contributions**

All authors contributed equally to the study. All authors have read and agreed to the published version of the manuscript.

**Author's information**

Dr. Emmanuel Fokides is an Associate Professor and director of the Mathematics, Didactics, and Multimedia lab, in the Department of Primary Education, University of the Aegean, Greece. His academic and research endeavors are focused on the educational applications of emerging technologies, virtual and augmented reality, digital storytelling, and serious games. Since 1994, he has been involved in numerous research projects related to distance and lifelong learning and the educational uses of virtual and augmented reality. He has also established the Emerging Technologies in Education initiative (ETiE), a platform designed to promote the exploration and implementation of innovative technological solutions in education. His scholarly contributions to the field include over 200 published works in peer-reviewed conference proceedings, book chapters, and journal articles. Additionally, he has co-authored three books.

Christina Konstantopoulou is an experienced kindergarten teacher with a solid academic background. She holds a degree from the University of Patras and a Master's degree in Educational Sciences. She has participated in training programs in Special Education and Intercultural Education, enriching her pedagogical approaches with diverse methods of inclusion and differentiation. Additionally, she has developed expertise in designing and implementing STEAM and Robotics programs for young children, with active participation in national festivals and competitions. She has also participated in conferences, contributing articles on innovative practices in early childhood education and the integration of ICT in the learning process. Her goal is to cultivate a creative, inclusive, and innovative learning environment that inspires children to explore, experiment, and develop their skills.

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**Availability of data and materials**

Data will be made available on reasonable request from the corresponding author.

## Declarations

**Institutional review board statement**

The research was conducted in accordance with all pertinent legislation and institutional protocols. The Research Ethics Committee of the Department of Primary Education, University of the Aegean reviewed and approved the methodologies and practices of this study (protocol code 3145).

**Informed consent statement**

The parents and legal guardians of the participating students were briefed and their informed consent was obtained. The privacy and rights of the students involved were protected; no personal data were collected and/or processed.

**Ethical statement**

The authors declare that this manuscript is the result of their independent creation under the reviewers' comments. This manuscript does not contain any research achievements that have been published or written by other individuals or groups, or by AI tools. During the preparation of this work the authors used Ghostwriter in order to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

**Competing interests**

The authors declare that they have no competing interests.

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**References**

Aeschbach, L. F., de Castro Hüsler, A. B., & Opwis, K. (2024). *Systematic review on the methodological rigor and effectiveness of digital game-based learning in education*. OSF. https://files.osf.io/v1/resources/6qgvp/providers/osfstorage/6634925ce8eec511356bed3d?action=download&direct&version=2

Balinha, F., & Mamede, E. (2020). Exploring kindergarten children's perception of spatial relations. *Zero-a-Seis, 22*(41), 204–223. https://doi.org/10.5007/1980-4512.2020v22n41p204

Bayaga, A., & Nzuza, P. (2022). Examining challenges associated with numerical cognition in early years. International *Journal on Research in STEM Education, 4*(1), 1–14. https://doi.org/10.31098/ijrse.v4i1.884

Behnamnia, N., Kamsin, A., Ismail, M. A. B., & Hayati, S. A. (2022). A review of using digital game-based learning for preschoolers. *Journal of Computers in Education, 10*(4), 603–636. https://doi.org/10.1007/s40692-022-00240-0

Benz, C. (2014). Identifying quantities—Children's constructions to compose collections from parts or decompose collections into parts. In *Early mathematics learning: Selected papers of the POEM 2012 conference* (pp. 189–203). Springer. https://doi.org/10.1007/978-1-4614-4678-1_12

Braine, L. G., Schauble, L., Kugelmass, S., & Winter, A. (1993). Representation of depth by children: Spatial strategies and lateral biases. *Developmental Psychology, 29*(3), 466–479. https://doi.org/10.1037/0012-1649.29.3.466

Can, D. (2020). Supporting learning trajectories for the development of number concept: Digital games. *Journal of Theoretical Educational Science, 13*(4), 663–684. https://doi.org/10.30831/akukeg.692165

Choi, H., & Feng, J. (2017). Using video games to improve spatial skills. In *Handbook of research on serious games for educational applications* (pp. 93–114). IGI Global. https://doi.org/10.4018/978-1-5225-0513-6.ch005

Clements, D. H., & Sarama, J. (2007). Effects of a preschool mathematics curriculum: Summative research on the Building Blocks project. *Journal for Research in Mathematics Education, 38*(2), 136–163. https://doi.org/10.2307/748360

Crollen, V., & Noël, M. P. (2015). The role of fingers in the development of counting and arithmetic skills. *Acta Psychologica, 156*, 37–44. https://doi.org/10.1016/j.actpsy.2015.01.007

Dang, H., Rai, P., Fleer, M., & Li, J. (2024). Digital spatial game development and practice analysis in the home setting. In M. Fleer, M. Hedegaard, & N. Veresov (Eds.), *Cultural-historical digital methodology in early childhood settings* (vol. 13, pp.169–182). Springer. https://doi.org/10.1007/978-3-031-59785-5_14

Dunekacke, S., van den Ham, A. K., Grüßing, M., & Heinze, A. (2024). Structure and development of kindergarten children's mathematical competence. *Journal of Early Childhood Research*, 1476718X231221393. https://doi.org/10.1177/1476718X231221393

Fanari, R., Meloni, C., & Massidda, D. (2017). Early numerical competence and number line task performance in kindergarteners. P*roceedings of the 14th International Conference on Cognition and Exploratory Learning in the Digital Age, CELDA 2017* (pp. 70–76). IADIS press.

Fisher, C. B., & Braine, L. G. (1982). Left-right coding in children: Implications for adult performance. *Bulletin of the Psychonomic Society, 20*(6), 305–307. https://doi.org/10.3758/BF03330109

Fokides, E., & Alatzas, K. (2022). Using digitally enhanced tangible materials for teaching fractions: Results of a project. *Technology, Knowledge and Learning, 28*, 1589–1613. https://doi.org/10.1007/s10758-022-09605-x

Fokides, E., Atsikpasi, P., Kaimara, P., & Deliyannis, I. (2019). Let players evaluate serious games. Design and validation of the Serious Games Evaluation Scale. *International Computer Games Association Journal, 41*(3), 116–137. https://doi.org/10.3233/ICG-190111

Freiman, V. (2018). Complex and open-ended tasks to enrich mathematical experiences of kindergarten students. In F. M. Singer (Ed.), *Mathematical creativity and mathematical giftedness: Enhancing creative capacities in mathematically promising students* (pp. 373–404). Springer. https://doi.org/10.1007/978-3-319-73156-8_14

Fuson, K. C., Clements, D. H., & Sarama, J. (2015). Making early math education work for all children. *Phi Delta Kappan, 97*(3), 63–68. https://doi.org/10.1177/0031721715614831

Gould, P. (2016). Hurdles in acquiring the number word sequence. In B. White, M. Chinnappan, & S. Trenholm (Eds.), *Opening up mathematics education research (Proceedings of the 39th Annual Conference of the Mathematics Education Research Group of Australasia)* (pp. 271–278). MERGA.

Gullen, G. E. (1978). Set comparison tactics and strategies of children in kindergarten, first grade, and second grade. *Journal for Research in Mathematics Education, 9*(5), 349–360. https://doi.org/10.2307/748771

Guo, P. (2023). Approaches to enhance game-based teaching literacy for kindergarten major students. *Pacific International Journal, 6*(4), 120–124. https://doi.org/10.55014/pij.v6i4.489

Hair, J. F., Babin, B. J., Anderson, R. E., & Black, W. C. (2019). *Multivariate data analysis* (8th ed.). Pearson Prentice.

Harris, L. J. (1972). Discrimination of left and right, and development of the logic of relations. *Merrill-Palmer Quarterly of Behavior and Development, 18*(4), 307–320.

Henik, A. (2021). Early difficulties in numerical cognition. In W. Fias, & A. Henik (Eds.), *Heterogeneous contributions to numerical cognition* (pp. 383–398). Academic Press. https://doi.org/10.1016/B978-0-12-817414-2.00016-6

Huang, A. (2023). The effect of digital game-based learning on motivation for EFL. *Journal of Education, Humanities and Social Sciences, 23*, 18–22. https://doi.org/10.54097/ehss.v23i.12726

Johnson, G. J. (1990). Directional biases in children's perception of spatial order. *The Journal of Experimental Education, 59*(1), 19–29. https://doi.org/10.1080/00220973.1990.10806548

Julia, J., Iswara, P. D., & Supriyadi, T. (2019). Redesigning and implementing traditional musical instrument in integrated technology classroom. *International Journal of Emerging Technologies in Learning, 14*(10), 75–87. https://doi.org/10.3991/ijet.v14i10.10197

Kerckaert, S., Vanderlinde, R., & van Braak, J. (2015). The role of ICT in early childhood education: Scale development and research on ICT use and influencing factors. *European Early Childhood Education Research Journal, 23*(2), 183–199. https://doi.org/10.1080/1350293X.2015.1016804

Kermani, H. (2017). Computer mathematics games and conditions for enhancing young children's learning of number sense. *Malaysian Journal of Learning and Instruction, 14*(2), 23–57. https://doi.org/10.32890/mjli2017.14.2.2

Kónya, E. (2006). A mathematical and didactical analysis of the concept of orientation. *Teaching Mathematics and Computer Science, 4*(1), 111–130. https://doi.org/10.5485/TMCS.2006.0108

Kurniasih, E., & Ngastiti, P. (2024). Results testing the validity of media puzzle digital game with a realistic mathematics education approach for kindergartens. *Proceedings of the E3S Web of Conferences* (vol. 483, 03009). EDP Sciences. https://doi.org/10.1051/e3sconf/202448303009

Laurillard, D. (2016). Learning number sense through digital games with intrinsic feedback. *Australasian Journal of Educational Technology, 32*(6), 32–44. https://doi.org/10.14742/ajet.3116

MacDonald, B. L., & Shumway, J. F. (2016). Subitizing games: Assessing preschoolers' number understanding. *Teaching Children Mathematics, 22*(6), 340–348. https://doi.org/10.5951/teacchilmath.22.6.0340

MacDonald, B. L., & Wilkins, J. L. (2016). Seven types of subitizing activity characterizing young children's mental activity. In S. Marx (Ed.), *Qualitative research in STEM* (pp. 256–286). Routledge.

Marek, M. W., & Wu, W. C. V. (2021). Motivational affordances of the novelty effect in TELL. *Proceedings of the 2021 International Conference on Advanced Learning Technologies (ICALT)* (pp. 268–269). IEEE. https://doi.org/10.1109/ICALT52272.2021.00086

Mariana, N. (2010). Birthday cake activity structured arrangement for helping children determining quantities. *Indonesian Mathematical Society Journal on Mathematics Education, 1*(1), 53–70. https://doi.org/10.22342/jme.1.1.790.53-70

Miller, H. E., Patterson, R., & Simmering, V. R. (2016). Language supports young children's use of spatial relations to remember locations. *Cognition, 150*, 170–180. https://doi.org/10.1016/j.cognition.2016.02.006

Miller, T. (2018). Developing numeracy skills using interactive technology in a play-based learning environment. *International Journal of STEM Education, 5*, 1–11. https://doi.org/10.1186/s40594-018-0135-2

Mix, K. S. (2022). The cognitive foundations of early childhood numeracy. In *Handbook of research on innovative approaches to early childhood development and school readiness* (pp. 317–348). IGI Global. https://doi.org/10.4018/978-1-7998-8649-5.ch014

Moss, J., Bruce, C. D., & Bobis, J. (2015). Young children's access to powerful mathematics ideas: A review of current challenges and new developments in the early years. In L. D. English, & D. Kirshner (Eds.), *Handbook of international research in mathematics education* (pp. 153–190). Routledge.

Newcombe, N. S., & Frick, A. (2010). Early education for spatial intelligence: Why, what, and how. *Mind, Brain, and Education, 4*(3), 102–111. https://doi.org/10.1111/j.1751-228X.2010.01089.x

Pérez, B., Vera, F. H., González, D., & V-Niño, E. D. (2016). Designing educational video games to improve spatial learning. *Proceedings of the 2016 XLII Latin American Computing Conference (CLEI)* (pp. 1–6). IEEE. https://doi.org/10.1109/CLEI.2016.7833386

Piaget, J. (2013). *Child's conception of space: Selected works* (vol. 4). Routledge. https://doi.org/10.4324/9781315006239

Polinsky, N., Flynn, R., & Uttal, D. H. (2023). How children's app play could facilitate spatial skill development. *Translational Issues in Psychological Science, 9*(3), 228–237. https://doi.org/10.1037/tps0000360

Polinsky, N., Flynn, R., Wartella, E. A., & Uttal, D. H. (2021). The role of spatial abilities in young children's spatially-focused touchscreen game play. *Cognitive Development, 57*, 100970. https://doi.org/10.1016/j.cogdev.2020.100970

Pruden, S. M., Levine, S. C., & Huttenlocher, J. (2011). Children's spatial thinking: Does talk about the spatial world matter? *Developmental Science, 14*(6), 1417–1430. https://doi.org/10.1111/j.1467-7687.2011.01088.x

Quade, D. (1967). Rank analysis of covariance. *Journal of the American Statistical Association, 62*(320), 1187–1200. https://doi.org/10.1080/01621459.1967.10500925

Ramani, G. B., Daubert, E. N., Lin, G. C., Kamarsu, S., Wodzinski, A., & Jaeggi, S. M. (2020). Racing dragons and remembering aliens: Benefits of playing number and working memory games on kindergartners' numerical knowledge. *Developmental Science, 23*(4), e12908. https://doi.org/10.1111/desc.12908

Ramos, D. E. G., & Romero, V. M. A. (2006). Conceptos polares espaciales en casos con antecedentes de encefalopatía perinatal. *Revista Española de Neuropsicología, 8*(1), 1–27.

Rigal, R. (1994). Right-left orientation: Development of correct use of right and left terms. *Perceptual and Motor Skills, 79*(3), 1259–1278. https://doi.org/10.2466/pms.1994.79.3.1259

Rogowsky, B. A., Terwilliger, C. C., Young, C. A., & Kribbs, E. E. (2017). Playful learning with technology: The effect of computer-assisted instruction on literacy and numeracy skills of pre-schoolers. *International Journal of Play, 7*(1), 60–80. https://doi.org/10.1080/21594937.2017.1348324

Sakka, T., & Gouscos, D. (2023). The children's rights education via game-based activities: An intervention in kindergarten. *International Journal of Serious Games, 10*(1), 53–79. https://doi.org/10.17083/ijsg.v10i1.546

Salinas, A. & Ly, C. (2015). Mathematics gaming in early childhood: Describing teacher moves for effective and appropriate implementation. In D. Polly (Ed.), *Cases on technology integration in mathematics education* (pp. 351–364). IGI Global. https://doi.org/10.4018/978-1-4666-6497-5.ch017

Sallik, N. A., Hipiny, I., & Ujir, H. (2022). A gamified approach for learning elementary arithmetic operations. *Proceedings of the 2022 International Conference on Computer and Drone Applications (IConDA)* (pp. 51–54). IEEE. https://doi.org/10.1109/ICONDA56696.2022.10000395

Santórum, M., Carrión-Toro, M., Yánez, D., Maldonado-Garcés, V., Galindo, J., & Acosta-Vargas, P. (2023). Enhancing spatial-temporal orientation skills through a psychoeducational serious game. *Proceedings of the 2023 Fourth International Conference on Information Systems and Software Technologies (ICI2ST)* (pp. 89–96). IEEE. https://doi.org/10.1109/ICI2ST62251.2023.00020

Saroinsong, W. P., Imara, F. U., Simatupang, N. D., & Maulidiyah, E. C. (2021). The effectiveness of m-puzzle toward preschooler spatial skill. *Jurnal Indria (Jurnal Ilmiah Pendidikan Prasekolah dan Sekolah Awal), 6*(2), 109–131. https://doi.org/10.24269/jin.v6i2.3960

Sella, F., Lucangeli, D., & Zorzi, M. (2018). Spatial and verbal routes to number comparison in young children. *Frontiers in Psychology, 9*, 776. https://doi.org/10.3389/fpsyg.2018.00776

Shaheen, A., & Fotaris, P. (2024). Enhancing digital game-based learning through reflective game design (RGD). *Proceedings of the 18th European Conference on Games Based Learning* (pp. 1163–1172). Academic Conferences International. https://doi.org/10.34190/ecgbl.18.1.3107

Sharpe, P. (1999). Learning about numbers in kindergarten. *The Mathematics Educator, 4*(2), 70–82.

Shuker, M. J., & Terreni, L. (2013). Self-authored e-books: Expanding young children's literacy experiences and skills. *Australasian Journal of Early Childhood, 38*(3), 17–24. https://doi.org/10.1177/183693911303800304

Sims, V. K., & Mayer, R. E. (2002). Domain specificity of spatial expertise: The case of video game players. *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition, 16*(1), 97–115. https://doi.org/10.1002/acp.759

Situmorang, R. P., Suwono, H., Susanto, H., Chang, C. Y., & Liu, S. Y. (2024). Learn biology using digital game-based learning: A systematic literature review. *Eurasia Journal of Mathematics, Science and Technology Education, 20*(6), em2459. https://doi.org/10.29333/ejmste/14658

Sorby, S. A. (2009). Educational research in developing 3-D spatial skills for engineering students. *International Journal of Science Education, 31*(3), 459–480. https://doi.org/10.1080/09500690802595839

Terlecki, M. S., Newcombe, N. S., & Little, M. (2008). Durable and generalized effects of spatial experience on mental rotation: Gender differences in growth patterns. *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition, 22*(7), 996–1013. https://doi.org/10.1002/acp.1420

Uehara, I. (2013). Left-right and up-down mirror image confusion in 4-, 5-and 6-year-olds. *Psychology, 4*(10), 736–740. https://doi.org/10.4236/psych.2013.410104

Uttal, D. H., Miller, D. I., & Newcombe, N. S. (2013). Exploring and enhancing spatial thinking: Links to achievement in science, technology, engineering, and mathematics? *Current Directions in Psychological Science, 22*(5), 367–373. https://doi.org/10.1177/0963721413484756

Vogel, J. J., Bowers, C. A., & Vogel, D. S. (2003). Cerebral lateralization of spatial abilities: A meta-analysis. *Brain and Cognition, 52*(2), 197–204. https://doi.org/10.1016/S0278-2626(03)00056-3

Wei, X., & Wang, J. (2022). An experimental inquiry into early childhood language learning based on game learning. *Proceedings of the 2022 International Symposium on Educational Technology (ISET)* (pp. 178–182). IEEE. https://doi.org/10.1109/ISET55194.2022.00045

Weng, P. L., & Bouck, E. C. (2016). An evaluation of app-based and paper-based number lines for teaching number comparison. *Education and Training in Autism and Developmental Disabilities, 51*(1), 27–40.

Zhou, X., Wang, Y., Wang, L., & Wang, B. (2006). Kindergarten children's representation and understanding of written number symbols. *Early Child Development and Care, 176*(1), 33–45. https://doi.org/10.1080/0300443042000302645

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