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Analytical comparison of physical and virtual LEGO modules in architectural design education

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Abstract

The educational potential of games has increasingly attracted attention within architectural pedagogy, fostering investigations into game-based learning approaches. Among these, LEGO has gained prominence in both physical and digital formats, offering unique yet complementary contributions to design education. Physical LEGO sets strengthen students' manual dexterity, three-dimensional reasoning, and confidence by engaging them in tangible construction processes. Virtual LEGO platforms, in contrast, advance technological literacy, spatial visualization, and digital exploration, thereby preparing students for the demands of contemporary design environments. This study examines the role of both physical and virtual LEGO modules in architectural and interior design education through a comparative analysis. Student groups from different levels were tasked with reconstructing a pre-designed architectural plan using both formats. Upon completion, participants completed a structured questionnaire designed to evaluate their learning experiences, perceived challenges, and skill development. Data were analyzed using SPSS to identify statistical relationships between the two approaches. Findings revealed significant correlations between the modules, indicating their complementary nature in fostering spatial literacy and design skills. Physical LEGO modules were particularly effective in promoting hands-on engagement, efficiency, and confidence, while virtual modules enhanced creativity in digital environments and cultivated a sense of achievement. The comparison demonstrates that rather than competing, physical and digital formats enrich architectural pedagogy by addressing different dimensions of the design process. By situating LEGO within the broader discourse of game-based learning in architecture, this study underscores the importance of integrating traditional tactile methods with emerging digital tools. Such integration not only bridges the gap between physical and virtual realms but also provides a rational perspective on contemporary educational challenges in an increasingly digitized world. Ultimately, the results highlight the potential of LEGO to serve as a versatile pedagogical medium that cultivates both foundational design skills and adaptability to future technological contexts.

Keywords: architectural education, design education, educational materials, game-based education, LEGO

1. Introduction

Game-based learning is an innovative instructional approach designed to make the learning process more engaging and enjoyable for students (Gee, 2003). This method facilitates students' understanding and application of knowledge by incorporating active participation and problem-solving. In contemporary education, games have become central within frameworks where traditional learning environments intersect with digital-based education. Spatial literacy, defined as the ability to visualize and reason about spatial objects and their relationships, is a fundamental skill in architectural education (Strand & Nielsen, 2024). LEGO modules, both physical and virtual, serve as effective tools to foster these skills, bridging the gap between traditional and digital learning approaches.

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Previous research highlights the importance of direct architectural experiences in shaping students' problem-solving and conceptualization abilities (Ashrafganjouei & Nadimi, 2024). Games play a critical role in this process by actively engaging students and encouraging them to participate meaningfully in their own learning. Active learning emphasizes experiential engagement, where students learn by doing and apply their knowledge in practical contexts (Petty, 2014). Through gameplay, students develop skills such as rule-following, problem-solving, and collaborative thinking, resulting in deeper and more lasting learning outcomes (Squire, 2005). The evolution of LEGO itself from a purely physical construction toy to a sophisticated transmedia and digital ecosystem underscores its unique position as a pedagogical tool that can adapt to both tactile and digital learning paradigms. This dual nature of LEGO as a "materially digital medium" allows it to serve as a consistent variable for comparative studies in educational settings (Taylor & Ingraham, 2020).

Additionally, game-based learning captures students' attention, enhances motivation, and promotes sustained engagement (Prensky, 2007). This approach has been shown to be particularly effective for learners with diverse educational backgrounds, providing enriched learning experiences across various domains (Torun & Tatar, 2023). Studies have also emphasized the growing interest of the "digital generation" in using games as a learning medium, contrasting with traditional methods that may lack stimulation and decrease classroom motivation (Prensky, 2006; Squire & Jenkins, 2003). Furthermore, digital games have proven to be powerful tools for fostering engagement and motivation in the learning process (Machado et al., 2018). Educators widely recognize their potential to enhance both students' enthusiasm and learning outcomes (Huizenga et al., 2017). The transformative impact of digitalization on traditional industries, including toys, illustrates how digital tools can extend and enrich core competencies rather than replace them, a lesson exemplified by LEGO's strategic shift to smart specialization and digital-physical integration (Gürçaylılar Yenidoğan & Gül, 2021).

Game-based learning in architecture, the primary focus of this research, has been utilized to impart knowledge and skills in engineering and design, among various academic outcomes. This learning method aims to equip architecture students with skills related to real-world problems while providing an enjoyable and motivating activity. Consequently, it not only teaches students how structures are built and function but also fosters abilities in engineering and design (de Freitas et al., 2011). For instance, a game resembling "Minecraft" could demonstrate building and functioning structures, while a game similar to "SimCity" could impart knowledge and skills in city design and management. Furthermore, the advantage of game-based learning in the architectural context lies in the physical context, allowing students the opportunity to physically construct buildings and experience how components come together. This facilitates a more enduring impact on students' memories, aiding in a better understanding of the taught material. Innovative pedagogical approaches, such as Design Thinking integrated with physical tools like LEGO® Serious Play®, have demonstrated significant potential in unlocking student creativity, facilitating idea generation, and enhancing collaborative problem-solving in architectural education, particularly in contexts transitioning towards more interactive learning models (Holubchak, 2020).

Game materials that enrich gaming environments have been deemed as crucial as the games themselves by experts. These materials assist students in initiating and enhancing social interactions. Additionally, through these gaming tools, students interact with each other (Jalongo & Isenberg, 2013). Therefore, it is evident that the consideration of games and gaming materials, particularly in architecture education where social interaction is prominent, is essential.

Approaching the subject from a generational perspective, Carstens and Beck (2005) termed today's generation, who have grown up with digital computer games, as the "game generation." Traits such as competitiveness, the pursuit of alternatives, and ideals of heroism in this generation are a consequence of growing up with games. Traditional learning materials like books and notebooks are perceived as dull and ineffective for this generation. In this sense, comparing digital and physical games in relevant contexts becomes crucial for obtaining scientific data. This generational shift aligns with observations in broader media studies, where adult engagement with LEGO transcends simple play, evolving into complex communities of practice that explore identity, craftsmanship, and materiality through both physical and digital extensions of the medium (Taylor & Ingraham, 2020).

This study undertakes research in the context of game-based learning in architecture, motivated by the aforementioned definitions and approaches, using both the physical and virtual modules of LEGO. A group of architecture and interior architecture students were tasked with creating models using LEGO's physical and virtual modules based on given plan schematics. Subsequently, their evaluations regarding the study were collected through a questionnaire. The study employed a diverse group of 55 students from various classes who had received architectural modeling and technical drawing education and some of whom had experience with digital games. The choice of LEGO as a comparative tool is further justified by its inherent computational logic; the modular, grid-based nature of LEGO systems, especially evident in advanced lines like LEGO® Technic, provides a tangible and virtual grammar for spatial reasoning and structural problem-solving that is highly relevant to architectural education (Xu et al., 2019).

The aim was to conduct a comparative analysis to uncover how the distinct affordances of physical and virtual LEGO modules differentially contribute to skill development and learning experience in architectural education. In this context, the following research questions and hypotheses were established to guide the comparative investigation:

- **Research Question 1:** How do physical LEGO modules affect architecture students' three-dimensional thinking skills?
- **Hypothesis 1:** Physical LEGO modules will yield significantly higher ratings in hands-on engagement, task efficiency, and tactile confidence compared to the virtual module.
- **Research Question 2:** How do virtual LEGO modules influence students' technological skills and spatial construction abilities?
- **Hypothesis 2:** Virtual LEGO modules will yield significantly higher ratings in digital tool fluency, perceived precision, and a sense of achievement compared to the physical module.

The study's findings are discussed in light of these research questions and hypotheses to provide insights into the complementary interplay of physical and digital tools in architectural education.

1.1. Methodological Approach and Tool Selection

To address these research questions and test the proposed hypotheses, a comparative experimental study was designed, employing LEGO modules in both physical and virtual formats as the primary pedagogical tool. LEGO is among the most recognized construction toys globally and is noted for its open-ended nature, which can transform into diverse shapes with each use, significantly contributing to students' development while providing entertainment (Güneş & Tuğrul, 2020; Kazez & Zülfü, 2016; Tuğrul, 2010). Its established integration into architectural education (Coşkun, 2019; Doma & Şener, 2022; Legény & Teixeira, 2019; Mohamed, 2017) and its parallel evolution into a "digital tool" with virtual modules make it an ideal and coherent comparative material. This coherence stems from LEGO's nature as a "materially digital medium," offering a consistent modular grammar across physical and digital platforms, which is ideal for comparative educational research (Taylor & Ingraham, 2020). This allows for a direct investigation into the physical and virtual dimensions of game-based learning in architecture, focusing on their complementary roles without the confounding variable of differing core mechanics. The choice of LEGO is further justified by its documented role in fostering innovation and specialization strategies, demonstrating its adaptability as a pedagogical tool aligned with contemporary digital transformation trends (Gürçaylılar Yenidoğan & Gül, 2021). The following sections detail the experimental procedure, participants, data collection instruments, and analysis methods used to implement this comparative approach.

2. Theoretical Background

This study situates itself within two converging research trajectories: the integration of game-based learning in architectural education and the pedagogical use of LEGO as a versatile spatial medium. Research on game-based learning has established foundational design frameworks, such as the model proposed by Shi and Shih (2015), which outlines eleven critical factors -including objectives, mechanics, and challenge- that structure effective educational games. Meta-analyses, like that of Toraman et al. (2018), consolidate empirical evidence, confirming the approach's positive impact on academic achievement while noting important contextual variations across studies. In architectural education specifically, this has evolved into tangible explorations of gamification strategies to structure the design process (Torun & Tatar, 2023) and the adoption of digital sandbox platforms like Minecraft, which share LEGO's modular logic, to create dynamic, student-centered learning environments (Coşkun, 2019). A parallel and significant trend involves the adoption of immersive technologies, such as Virtual Reality (VR), which are leveraged for complex spatial and historical education (Varinlioğlu, 2020) and for architectural design exercises utilizing virtual LEGO pieces, offering unique affordances like scalable user perspective (Doma & Şener, 2022). These pedagogical and technological developments are not isolated; they mirror the broader industrial process of digital transformation. This strategic paradigm involves the deliberate integration of digital layers with physical core products to create enhanced, hybrid value—a process clearly demonstrated in the LEGO Group's own innovation history and strategic recovery, which serves as a relevant case study in managing digital-physical synergy (Gürçaylılar Yenidoğan & Gül, 2021).

Concurrently, LEGO itself has been the focus of substantial and multi-faceted scholarly interest as a pedagogical tool. Its efficacy in enhancing spatial reasoning, structural understanding, and creativity in architecture and urban design contexts is well-argued (Legény & Teixeira, 2019) and discussed as a transferable, hands-on methodology for learning development (James, 2013). This application extends beyond simple modeling into sophisticated, facilitated methodologies like LEGO Serious Play, which is shown to unlock implicit knowledge, foster empathy, enhance collaborative ideation, and overcome conceptual blockages in educational settings (Holubchak, 2020). The cultural and material significance of LEGO transcends formal education, as richly evidenced by global adult enthusiast communities (AFOLs) where the tangible materiality of the brick, the precision of its clutch power, and the creative, iterative process of "LEGOfication" -translating concepts into the system's modular grammar- are central to practice, identity, and community building (Taylor & Ingraham, 2020). Furthermore, the technical and cognitive dimensions underpinning LEGO construction are formally analyzed in computational design research, which develops automated systems and algorithms to solve the complex combinatorial, geometric, and structural problems inherent in advanced LEGO models, thereby highlighting and formalizing the sophisticated spatial and logical reasoning its use can entail (Xu et al., 2019). Ongoing research also continues to explore hybrid physical-digital interfaces, such as Augmented Reality (AR) systems designed to guide and enhance the accuracy of physical LEGO assembly (Yan, 2019).

Thus, the literature presents two robust, interconnected strands: one concerning the theory and application of game-based and digitally-augmented pedagogical strategies in architecture, and another deeply examining LEGO as a consistent, multi-modal tool for spatial learning and creative expression. These strands are conceptually woven together by the overarching strategic principle of "smart specialization"—the focused enhancement of a core competency (in this context, spatial thinking and design logic through modular systems) with carefully selected and complementary digital capabilities, rather than through unrelated diversification (Gürçaylılar Yenidoğan & Gül, 2021). However, a direct, comparative empirical investigation of the physical and virtual instantiations of the same modular medium –LEGO- within a controlled, pedagogical setting remains an underexplored area. This study aims to address this specific gap, contributing methodical empirical evidence and nuanced analysis to this integrated and evolving discourse on hybrid learning tools.

3. Experimental Study

This section details the implementation of the comparative methodology outlined in Section 1.1. It describes the participant profile, the specific materials and digital tools used, the experimental task, and the procedures for data collection and analysis.

3.1. Participants

The study comprised a diverse group of 55 students from different classes in the architecture and interior design departments of a single university. The participant demographics are summarized in Table 1. The group consisted of 40% architecture and 60% interior architecture students. Among these students, 27.3% were from the 1st year, 20% from the 2nd year, 25.5% from the 3rd year, 12.7% from the 4th year, and 14.5% were postgraduate students. All participants had prior education in architectural modeling and technical drawing, with some having additional experience with digital games.

Table 1 Participants' Demographic Characteristics

Variable	Group	n	%
Department	Architecture	22	40.0%
	İnt. Architecture	33	60.0%
Degree	D1	15	27.3%
	D2	11	20.0%
	D3	14	25.5%
	D4	8	14.5%
	MA	7	12.7%
	Total	**55**	**100**

3.2. Materials and Digital Tool

Physical LEGO Application: For the tangible construction task, a LEGO® Classic Medium Creative Brick Box (set number 10696) was used. This set provides an open-ended assortment of 484 pieces, including a variety of bricks in different shapes, sizes, and colors, suitable for architectural modeling without prescribing a specific outcome.

Virtual LEGO Application: The digital modeling task was performed using LEGO Digital Designer (LDD) software (version 4.3.11). LDD is an official, freeware computer-aided design (CAD) tool developed by the LEGO Group, allowing users to build models using a virtual library of LEGO pieces (Wikipedia, 2023). The software, accessible through the official LEGO service pages (LEGO, n.d.), features an intuitive graphical user interface. This interface enables users to select from a comprehensive digital inventory of bricks, manipulate them in a three-dimensional virtual workspace (through rotation, connection, and color change tools), and construct complex models without the physical limitations of piece availability. This tool was selected for its direct conceptual analogy to physical LEGO construction and its status as a recognized platform for digital brick-based design.

3.3. Task and Procedure

The experimental procedure followed a structured sequence:

- **Task Introduction:** All participants were provided with an identical architectural floor plan consisting of three interconnected volumes.
- **Physical Modeling Phase:** Participants were first asked to create a physical model accurately representing the given floor plan using the provided LEGO Classic bricks. The time taken to complete this model was recorded individually.

- **Virtual Modeling Phase:** Subsequently, participants were instructed to recreate the same floor plan digitally using the LEGO Digital Designer (LDD) software on a computer. Completion time for the virtual model was also recorded.
- **Survey Administration:** Upon completing both tasks, all participants filled out a structured questionnaire. The survey contained demographic questions, two Likert-type scales (5-point, from 1=Strongly Disagree to 5=Strongly Agree) designed to evaluate their learning experiences, perceived challenges, and skill development in each environment, and direct comparative questions about enjoyment, educational value, and perceived success.

Figure 1 presents the provided floor plan alongside representative samples of the resulting physical and virtual models.

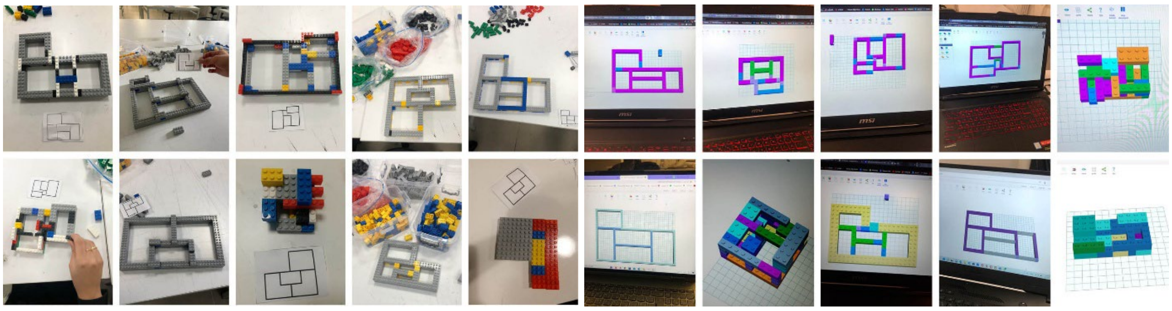

Figure 1 Sample images from the physical and virtual environment applications

3.4. Data Collection and Analysis

The structured questionnaire comprised three main sections: **(1)** Demographic information and prior experience with games; **(2)** Two identical 5-point Likert scales (1=Strongly Disagree, 5=Strongly Agree) assessing perceived skill development, engagement, and challenge for the physical and virtual modules separately. Scale items were designed around the constructs of manual dexterity, spatial reasoning, digital creativity, and self-efficacy; **(3)** Direct comparative questions forcing a choice between the two modules on enjoyment, educational value, and perceived success.

The Cronbach's Alpha reliability coefficient for the survey scales was calculated as 0.756, indicating acceptable internal consistency. All collected data were analyzed using SPSS 26 software.

The analyses employed both descriptive and inferential statistics:

- **Descriptive statistics** (arithmetic mean, median, standard deviation) were used to summarize participant responses and completion times.
- **The normality of distribution** was assessed using skewness and kurtosis values (accepted range: -1.5 to +1.5) (Tabachnick & Fidell, 2013).
- **An Independent Samples** T-Test was used to compare means between two independent groups (where applicable).
- **A one-way Analysis of Variance (ANOVA)** was conducted to detect significant differences among group means based on demographic variables (e.g., year of study).
- **Pearson Correlation Analysis** was employed to measure the strength and direction of linear relationships between continuous variables (e.g., computer skill level and virtual application success).

The analyses were conducted to answer the following key questions:

- How successful were the participants in each application based on their departments and classes?

- Did previous experience with physical/virtual games or computer skills influence their success?
- Were there significant correlations among participant responses?
- Which application did students find more enjoyable and educational?

3.5. Findings

Table 2 presents the sample size (N), minimum-maximum attitude scores (Min-Max), arithmetic mean (Mean), median (Median), standard deviation (SD), and skewness-kurtosis values for the research scale.

Table 2 Descriptive Data Regarding Participants' Responses and Completion Times

	N	Min	Max	Mean	Median	ss	Skewness	Kurtosis
Total values	55	2.56	10.00	6.7778	7.1111	1.71441	**-.595**	**.039**
Averages of completion times	55	1.50	25	7.5636	6.0000	4.90753	**.847**	**-.062**

The 'normality' distributions of the data from the normality test in Table 2 were examined, and Skewness/Kurtosis values were provided. According to the findings, the Skewness values are -.595 and .847, while the Kurtosis values are .039 and -.062, respectively. According to Tabachnick and Fidell, if these values fall within the range of -1.5 to +1.5, it can be assumed that the data follow a normal distribution (Tabachnick & Fidell, 2013).

Table 3 The Findings of the ANOVA Test Conducted to Detect Significant Differences Among the Survey Data

		Sum of s.	df	Mean Sq.	F	Sig. (p)
Time to complete physical app	Between Groups	270.566	4	67.641	1.815	.141
	Within Groups	1863.362	50	37.267		
	Total	2133.927	54			
Frequency of playing board games	Between Groups	46.135	4	11.534	1.388	.252
	Within Groups	415.611	50	8.312		
	Total	461.745	54			
How fun was the physical board app?	Between Groups	43.841	4	10.960	1.362	.260
	Within Groups	402.269	50	8.045		
	Total	446.109	54			
Self-assessment in terms of success in the board app	Between Groups	36.533	4	9.133	1.560	.200
	Within Groups	292.813	50	5.856		
	Total	329.345	54			
How educationally effective is the board app?	Between Groups	22.316	4	5.579	1.284	.289
	Within Groups	217.211	50	4.344		
	Total	239.527	54			
Time to complete virtual app	Between Groups	66.133	4	16.533	.703	.593
	Within Groups	1175.213	50	23.504		
	Total	1241.345	54			
Self-assessment of computer skill	Between Groups	39.276	4	9.819	1.960	.115
	Within Groups	250.470	50	5.009		
	Total	289.745	54			
Frequency of playing computer games	Between Groups	71.411	4	17.853	1.596	.190
	Within Groups	559.425	50	11.189		
	Total	630.836	54			
How fun was the virtual app?	Between Groups	79.877	4	19.969	3.659	.011
	Within Groups	272.851	50	5.457		
	Total	352.727	54			
Self-assessment of virtual application success	Between Groups	44.157	4	11.039	1.969	.114
	Within Groups	280.279	50	5.606		
	Total	324.436	54			
Self-assessment in terms of success in the virtual app	Between Groups	66.286	4	16.572	4.412	.004
	Within Groups	187.823	50	3.756		
	Total	254.109	54			

For the significance to be observed in the ANOVA test, the significance value should be p < .001. According to the data in Table 3, no significant differences were observed in terms of departmental values (p). Therefore, the analysis couldn't proceed to the "Post Hoc" tests to decipher the source of the differences.

To examine the correlation between the data, the research continued with the "Pearson Correlation Analysis." Since the compared values possessed an equal measurement level and also met the condition of a normal distribution, which indicates a "parametric" nature, the Pearson correlation coefficient was considered in this analysis. The findings obtained are presented in Table 4.

Table 4 To Determine the Significant Relationship Based on Correlation Between the Data, Findings of Pearson Correlation Analysis

		Department	Degree	Frequency of playing board games	How fun was the physical board app?	Self-assessment in terms of success in the board app	Time to complete physical app	How educationally effective is the board app?	Time to complete virtual app	Self-assessment of computer skill	Frequency of playing computer games	How fun was the virtual app?	Self-assessment in terms of success in the virtual app	How educationally effective is the virtual app?
Department	P.Cor.	1	-0.126	0.023	0.029	-0.158	-0.201	0.064	-0.050	-0.126	-0.173	-0.103	-0.113	-0.021
	Sig. (2 t.)		0.358	0.867	0.835	0.250	0.140	0.642	0.717	0.359	0.206	0.456	0.411	0.881
	N	55	55	55	55	55	55	55	55	55	55	55	55	55
Degree	P. Cor.	-0.126	1	-0.198	-0.103	-0.019	-0.072	-0.192	0.022	0.086	0.110	-0.208	-0.069	-0.258
	Sig. (2 t.)	0.358		0.147	0.455	0.888	0.599	0.161	0.871	0.532	0.423	0.128	0.617	0.057
	N	55	55	55	55	55	55	55	55	55	55	55	55	55
Frequency of playing board games	P. Cor.	0.023	-0.198	1	.311*	0.197	-0.126	0.157	-0.024	.323*	.287*	0.129	.330*	0.096
	Sig. (2 t.)	0.867	0.147		0.021	0.149	0.358	0.252	0.863	0.016	0.033	0.347	0.014	0.486
	N	55	55	55	55	55	55	55	55	55	55	55	55	55
How fun was the physical board app?	P. Cor.	0.029	-0.103	.311*	1	.488**	0.131	.542**	0.016	.447**	.378**	.561**	.609**	.442**
	Sig. (2 t.)	0.835	0.455	0.021		0.000	0.341	0.000	0.907	0.001	0.004	0.000	0.000	0.001
	N	55	55	55	55	55	55	55	55	55	55	55	55	55
Self-assessment in terms of success in the board app	P. Cor.	-0.158	-0.019	0.197	.488**	1	-0.037	.363**	-0.151	.408**	0.119	.381**	.617**	.362**
	Sig. (2 t.)	0.250	0.888	0.149	0.000		0.787	0.006	0.270	0.002	0.386	0.004	0.000	0.007
	N	55	55	55	55	55	55	55	55	55	55	55	55	55
Time to complete physical app	P. Cor.	-0.201	-0.072	-0.126	0.131	-0.037	1	0.140	.561**	0.072	0.085	0.000	-0.043	0.123
	Sig. (2 t.)	0.140	0.599	0.358	0.341	0.787		0.307	0.000	0.603	0.539	0.998	0.757	0.373
	N	55	55	55	55	55	55	55	55	55	55	55	55	55
How educationally effective is the board app?	P. Cor.	0.064	-0.192	0.157	.542**	.363**	0.140	1	0.144	0.204	0.251	.338*	.368**	.680**
	Sig. (2 t.)	0.642	0.161	0.252	0.000	0.006	0.307		0.294	0.135	0.065	0.012	0.006	0.000
	N	55	55	55	55	55	55	55	55	55	55	55	55	55
Time to complete virtual app	P. Cor.	-0.050	0.022	-0.024	0.016	-0.151	.561**	0.144	1	0.172	0.160	0.088	0.003	0.112
	Sig. (2 t.)	0.717	0.871	0.863	0.907	0.270	0.000	0.294		0.210	0.242	0.523	0.981	0.415
	N	55	55	55	55	55	55	55	55	55	55	55	55	55
Self-assessment of computer skill	P. Cor.	-0.126	0.086	.323*	.447**	.408**	0.072	0.204	0.172	1	.470**	.419**	.542**	.292*
	Sig. (2 t.)	0.359	0.532	0.016	0.001	0.002	0.603	0.135	0.210		0.000	0.001	0.000	0.031
	N	55	55	55	55	55	55	55	55	55	55	55	55	55
Frequency of playing computer games	P. Cor.	-0.173	0.110	.287*	.378**	0.119	0.085	0.251	0.160	.470**	1	.325*	.314*	0.234
	Sig. (2 t.)	0.206	0.423	0.033	0.004	0.386	0.539	0.065	0.242	0.000		0.016	0.019	0.086
	N	55	55	55	55	55	55	55	55	55	55	55	55	55
How fun was the virtual app?	P. Cor.	-0.103	-0.208	0.129	.561**	.381**	0.000	.338*	0.088	.419**	.325*	1	.627**	.553**
	Sig. (2 t.)	0.456	0.128	0.347	0.000	0.004	0.998	0.012	0.523	0.001	0.016		0.000	0.000
	N	55	55	55	55	55	55	55	55	55	55	55	55	55
Self-assessment in terms of success in the virtual app	P. Cor.	-0.113	-0.069	.330*	.609**	.617**	-0.043	.368**	0.003	.542**	.314*	.627**	1	.325*
	Sig. (2 t.)	0.411	0.617	0.014	0.000	0.000	0.757	0.006	0.981	0.000	0.019	0.000		0.016
	N	55	55	55	55	55	55	55	55	55	55	55	55	55
How educationally effective is the virtual app?	P. Cor.	-0.021	-0.258	0.096	.442**	.362**	0.123	.680**	0.112	.292*	0.234	.553**	.325*	1
	Sig. (2 t.)	0.881	0.057	0.486	0.001	0.007	0.373	0.000	0.415	0.031	0.086	0.000	0.016	
	N	55	55	55	55	55	55	55	55	55	55	55	55	55

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

The values marked with "*" in the Pearson Correlation row in Table 4 indicate significance at the .01 level, while values marked with "**" indicate significance at the 0.05 level. For all values below 0.05, a significant relationship can be considered. As this value drops below 0.05, it is inferred that the relationship between parameters increases (Cohen, 1988).

When interpreted according to this table, firstly, it was observed that neither the departments nor the classes had any statistically significant relationship with any other values. In other words, there was no impact of differences in completion times of applications, success levels, self-assessment in terms of entertainment and educational aspects based on classes and departments.

It was observed that those who play physical games also enjoyed the physical LEGO application (.311) and found themselves successful in the virtual LEGO application (.330). Moreover, this group was observed to also engage in playing virtual games (.287).

For those who play computer games, it was observed that they found enjoyment in both the virtual LEGO application (.325) and the physical LEGO application (.378). It was also determined that this group possessed high computer skills (.470). Hence, based on the results, a significant relationship can be deduced between students who play computer games and their computer-based skill levels. Furthermore, a correlation of 0.680 was found between those who found the virtual LEGO application educational and those who found the physical LEGO application educational.

A significant relationship was found only between completion times of the physical LEGO application and completion times of the virtual LEGO application (.561). Thus, no correlation was found between computer skills, entertainment, educational aspects, and the completion times of LEGO applications.

There was a significant correlation between students' computer skill levels and all other parameters related to the virtual application. This group also exhibited significant relationships with parameters related to the tabletop application. Hence, it can be stated that the participants' interest and skills in computers not only affect the values related to the virtual application but also influence other parameters related to the tabletop application in the same direction.

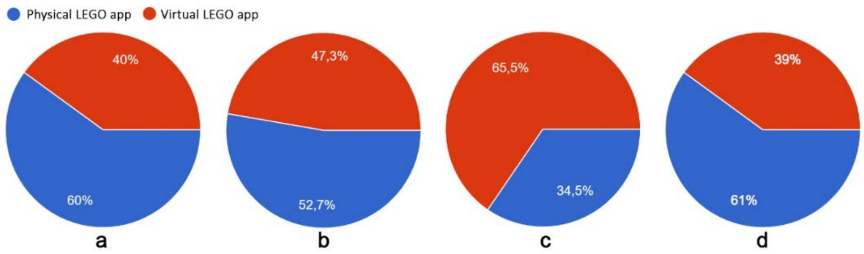

Figure 2 "The percentages of participant responses to questions '(a) Which application did you find more enjoyable?', '(b) Which application do you think is more beneficial in terms of education?' and '(c) In which application do you think you were more successful?' and '(d) mean percentages of completion times for the application'."

Participants were asked which application they found more educational or enjoyable and in which application they felt more successful. As depicted in Figure 2, 60% of the participants (Figure 2.a) found the physical LEGO application 'more enjoyable,' while 52.7% (Figure 2.b) evaluated the physical LEGO application as 'more beneficial' from a pedagogical perspective. In terms of skill-based comparison, 65.5% of students (Figure 2.c) mentioned that they were 'more successful' in the virtual LEGO application. In the comparison based on completion times (Figure 2.d), it is observed that 61% of participants completed the physical LEGO application 'later' compared to the virtual one.

4. Results and Discussion

This study employed a comparative framework to evaluate the distinct and complementary contributions of physical and virtual LEGO modules to spatial skill development in architectural education. The analysis of performance data and participant perceptions reveals a nuanced interplay between medium affordances, student profiles, and learning outcomes.

A foundational result was the lack of significant correlation between a student's academic year or department and their performance or perception in either medium. This suggests that the core spatial reasoning and modular logic engaged by LEGO are fundamental cognitive skills transcending standard curricular progression. The dominant influencing factors were instead individual digital affinity and prior experiential familiarity with games, reinforcing the profile of the contemporary "digital native" learner (Prensky, 2006; Carstens & Beck, 2005). This finding reflects a broader cultural shift where engagement with modular, creative systems is often driven by personal interest and medium-specific literacy rather than formal training, a phenomenon well-documented in adult fan communities (Taylor & Ingraham, 2020).

Notably, computer proficiency correlated positively with enhanced enjoyment and perceived efficiency in both the physical and virtual tasks. This challenges a simplistic analogue-digital divide, indicating the development of a transferable spatial-digital intelligence. Students adept with digital tools appeared better equipped to parse the structural logic and spatial planning required in the physical assembly. This synergy exemplifies the core principle of effective digital transformation, where digital literacy acts not as a replacement for tangible skill but as a cognitive enhancer that deepens engagement with fundamental concepts (Gürçaylılar Yenidoğan & Gül, 2021).

The direct comparison between media yielded a clear, complementary pattern of strengths. Participants found the physical LEGO application more enjoyable (60%) and faster to complete (61%). Its tangible nature provided irreplaceable haptic feedback and an immediate, error-prone engagement with gravity, scale, and structure—key components of "direct architectural experience" (Ashrafganjouei & Nadimi, 2024). This aligns with its validated use in participatory, embodied methodologies like LEGO Serious Play, where the physical act of building is central to unlocking tacit knowledge, fostering empathy, and prototyping ideas (Holubchak, 2020).

Conversely, the virtual LEGO environment (LDD) generated a stronger sense of success (65.5%) while being rated equally educational. The digital interface likely reduced friction from manual dexterity, offered limitless undo/redo capability, and provided an infinite brick inventory. This allowed students to focus purely on spatial composition and intentionality, scaffolding the learning process. This finding resonates with the design logic of computational LEGO systems, which automate lower-level combinatorial and structural constraints to allow designers to focus on higher-level formal and functional goals (Xu et al., 2019). The virtual module's capacity to boost confidence is a significant pedagogical asset, particularly for students early in their design education.

The statistically equivalent rating for educational value is perhaps the most instructive outcome. It confirms that while the cognitive and experiential pathways differ—the physical being episodic and tactile, the virtual being more semantic and abstractive (Ashrafganjouei & Nadimi, 2024)—both are effective vehicles for cultivating spatial literacy. This duality is inherent to LEGO's identity as a "materially digital medium," where a consistent grammar of modularity and connection operates across physical and virtual realms, making it an ideal tool for comparative pedagogical study (Taylor & Ingraham, 2020).

These results strongly advocate for a strategically integrated, rather than dichotomous, approach in the curriculum. This mirrors the "smart specialization" strategy observed in successful organizational innovation, where new capabilities (digital tools) are woven into the fabric of core competencies (tactile spatial reasoning) to create a more resilient and adaptive whole (Gürçaylılar Yenidoğan & Gül, 2021). Pedagogically, this suggests sequencing or pairing activities: using physical LEGO for foundational concept generation, team-based exercises, and understanding material constraints, followed by virtual LEGO for iteration, precision drawing, and introduction to digital modeling workflows. Future research should explore hybrid interfaces (e.g., Augmented Reality for guided physical assembly) and the integration of simpler computational design principles to further bridge the tactile and digital dimensions of spatial thinking in architectural education.

Limitations and Future Research

The findings of this study should be interpreted considering its limitations, primarily the sample drawn from a single institution, which may affect the generalizability of the results. Future multi-institutional and longitudinal studies could validate and extend these findings. Additionally, while LEGO Digital Designer provided a coherent virtual counterpart, exploring more advanced or immersive digital platforms (e.g., VR-based LEGO modeling) represents a valuable direction for future comparative work.

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CRediT Authorship Contribution Statement

Erdem Köymen: Writing – review & editing, Writing – original draft, Methodology, Investigation, Analysis, Data curation, Conceptualization, Data visualization. Mhd Feda Bouidani: Methodology, Investigation, Analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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