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Digital transformation and the strengthening of spatial skills through BIM environments in Architecture students

Transformación digital y fortalecimiento de competencias espaciales mediante entornos BIM en estudiantes de Arquitectura

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Abstract

Digital transformation has spurred the adoption of Building Information Modeling (BIM) tools as a pedagogical resource for strengthening professional competencies in higher education. Within architectural education, however, evidence on its specific contribution to the development of spatial skills remains scarce. This study set out to examine how the BIM methodology, used as a didactic environment, contributes to strengthening spatial skills among Architecture students. A quantitative, applied study was conducted using a one-group pre-experimental design with pretest and posttest measurements. An initial sample of 30 second-cycle students, selected through non-probabilistic convenience sampling, took part in the study; 27 of them completed both measurements and made up the sample analyzed at posttest. A structured questionnaire assessed three dimensions—spatial orientation, manipulation of three-dimensional objects, and spatial reasoning. Results revealed a significant increase in the overall mean score between pretest (M = 37.13) and posttest (M = 47.89), confirmed by the non-parametric Wilcoxon test applied to the 27 complete pairs (Z = -4.547; p < 0.001). Linear regression analysis performed on this same sample of 27 cases showed that pretest scores significantly predicted posttest scores (β = 0.899; R^2 = 0.808). These findings indicate that the BIM methodology strengthens spatial skills, particularly spatial orientation and reasoning, though it did not produce statistically significant changes in the manipulation of three-dimensional objects; the approach thus constitutes a pertinent strategy for supporting digital transformation processes in higher education.

Keywords: Building Information Modeling, spatial skills, higher education.

Resumen

La transformación digital ha impulsado el uso de herramientas basadas en el modelado de información (Building Information Modeling, BIM) como recurso didáctico para fortalecer competencias profesionales en la formación universitaria. Sin embargo, en la enseñanza de la Arquitectura existe todavía evidencia limitada sobre su aporte específico al desarrollo de las competencias espaciales. Esta investigación tuvo como objetivo analizar el aporte de la metodología BIM como entorno didáctico en el fortalecimiento de las competencias espaciales de estudiantes de Arquitectura. Se empleó un enfoque cuantitativo, de tipo aplicado, con un diseño preexperimental de un solo grupo con mediciones de pretest y postest, aplicado a una muestra inicial de 30 estudiantes del segundo ciclo, seleccionada mediante muestreo no probabilístico por conveniencia, de los cuales 27 completaron ambas mediciones y conformaron la muestra analizada en el postest. Se aplicó un cuestionario estructurado que evaluó las dimensiones de orientación espacial, manipulación de objetos tridimensionales y razonamiento espacial. Los resultados evidenciaron un incremento significativo de la media general entre el pretest (M = 37,13) y el postest (M = 47,89), confirmado mediante la prueba no paramétrica de Wilcoxon aplicada a los 27 pares con datos completos (Z = -4,547; p < 0,001). El análisis de regresión lineal, realizado sobre esta misma muestra de 27 casos, mostró que el pretest predice significativamente el postest (β = 0,899; R^2 = 0,808). Se concluye que la

metodología BIM fortalece las competencias espaciales, particularmente la orientación y el razonamiento espacial, sin producir cambios estadísticamente significativos en la manipulación de objetos tridimensionales, y constituye una estrategia pertinente para acompañar procesos de transformación digital en la educación superior.

Palabras clave: Building Information Modeling, competencias espaciales, educación superior.

Introduction

The incorporation of digital technologies into higher education has reshaped teaching and learning processes and spurred the development of new strategies aimed at strengthening professional competencies. In Architecture, these technologies facilitate the representation, visualization, and analysis of spatial information through digital environments. Cabrera and Peñafiel (2025), for instance, note that digitally supported teaching strategies foster more autonomous and meaningful learning, while Waqar et al. (2023) point out that BIM-based digital environments drive educational innovation through new forms of architectural representation.

A number of studies point to persistent difficulties among students in developing spatial skills. Guzmán et al. (2020) identified limitations in three-dimensional comprehension and in linking spatial representation to constructive processes; Medina (2020) reported difficulties with graphic representation and spatial perception; and Hernández et al. (2024) found inadequate levels of spatial orientation, manipulation of three-dimensional objects, and spatial reasoning among university students.

Conceptually, spatial competence is a multidimensional cognitive construct encompassing, among other components, perception, visualization, mental rotation, spatial relations, and orientation within one's environment. Within Architecture specifically, Berkowitz et al. (2021) showed, through a cross-sectional and longitudinal assessment of students at different stages of training, that domain-specific spatial abilities develop progressively over the course of the degree program, and that tests more closely tied to architectural practice discriminate most effectively between novice and advanced students. This finding lends support to the value of designing deliberate training strategies, rather than relying solely on generic curricular exposure, to strengthen these competencies from the earliest cycles of training onward. Along similar lines, Porat and Ceobanu (2024) documented that hybrid programs combining traditional teaching methods, computer-based learning, augmented reality, and the construction of physical three-dimensional models yield noticeable gains in the spatial ability of Architecture and Engineering students, with students themselves particularly valuing the components that allow for hands-on manipulation of objects in space.

Given this situation, Building Information Modeling (BIM) has gained prominence as a digital tool applied to architectural training, since it enables the creation of integrated three-dimensional models and facilitates the visualization of spatial elements. Apaza and Anahua (2021) note that BIM eases the understanding of architectural projects through collaborative digital environments, while Khudhair et al. (2021) highlight its contribution to the development of digital competencies and to interaction with three-dimensional models. Its incorporation into higher education, however, still faces obstacles: Böes et al. (2021) identified limited faculty training and resistance to methodological change as the main barriers, whereas Ruschel and Kehl (2024) underscore the importance of integrating BIM into university training, and Ashour et al. (2022) demonstrated that BIM-related digital environments can improve students' spatial abilities.

Further evidence from extended-reality environments reinforces this trend. Darwish et al. (2023) compared an experimental group of Architecture students who used extended-reality technology during the introductory design studio against a control group that used conventional methods, finding a noticeable improvement in overall spatial-ability scores for the experimental group, although they also identified technical difficulties and an adaptation curve associated with the use of immersive devices. These results suggest that, although digital technologies, BIM included, represent promising resources for strengthening

spatial skills, their effectiveness may be shaped by students' prior familiarity with the tools, the duration of exposure, and the pedagogical design of the activities, all of which merit consideration when interpreting the results of the present study.

In the Peruvian context, the Plan BIM Perú initiative has driven the gradual adoption of this methodology across the construction sector and higher education; even so, evidence on its use as a didactic strategy for strengthening specific spatial skills among Architecture students remains scarce. Abrahamzon et al. (2024) found that incorporating digital technologies into architectural teaching contributes to the development of spatial abilities, though they call for further studies assessing its impact in particular educational settings. Analyzing the contribution of BIM as a didactic environment for strengthening spatial skills among Architecture students is therefore a timely and relevant undertaking.

This study aimed to analyze the contribution of the Building Information Modeling (BIM) methodology, applied as a didactic environment, to strengthening spatial skills in Architecture students during 2025. It was hypothesized that the application of BIM would positively influence the strengthening of these students' spatial skills.

Methodology

The study followed a quantitative, applied approach and a one-group pre-experimental design with pretest and posttest measurements. According to Sánchez and Murillo (2021), this approach is characterized by the objective measurement of phenomena and the use of statistical procedures to test hypotheses; along the same lines, Castro et al. (2023) note that applied research seeks to draw on scientific knowledge to generate practical solutions within specific contexts, while Ramos (2021) explains that pre-experimental designs allow variations within a group to be analyzed before and after an intervention.

Although this type of design does not incorporate a control group or random assignment of participants, it proves useful in educational settings where institutional and ethical constraints make it difficult to form equivalent control groups, and it provides an initial empirical approximation of an intervention's effect before moving toward more robust quasi-experimental or experimental designs. This configuration nonetheless carries limitations with respect to the study's internal validity, since the influence of extraneous variables, such as participant maturation, familiarization with the measurement instrument, or motivation tied to technological novelty, cannot be entirely ruled out as contributors to the improvement observed between pretest and posttest. This limitation is revisited in the conclusions, where the scope of the findings is discussed.

The population consisted of 120 second-cycle students enrolled in the Architecture program, from which a sample of 30 students was selected through non-probabilistic convenience sampling. Students enrolled in the second cycle who participated voluntarily were included, while those who did not complete the assessments were excluded. Of the 30 students who took part in the pretest, 3 did not complete the posttest owing to absences; their pretest records were therefore excluded from the inferential analysis, so that both the Wilcoxon test and the linear regression analysis were applied to the 27 cases with complete measurements at both time points (N = 27 pairs). Data were collected using a structured spatial-skills questionnaire, administered at pretest and posttest, that assessed the dimensions of spatial orientation, manipulation of three-dimensional objects, and spatial reasoning.

These three dimensions draw on the specialized literature on spatial ability: spatial orientation refers to the capacity to maintain one's own position and establish reference relationships with objects or settings that are moving or undergoing a shift in perspective; manipulation of three-dimensional objects concerns the ability to mentally rotate, translate, and transform volumetric representations; and spatial reasoning encompasses the logical inference processes involved in understanding complex geometric and constructive relationships (Berkowitz et al., 2021; Porat & Ceobanu, 2024). Rather than operating in

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isolation, these dimensions are interdependent and come into play jointly during architectural design tasks, which justifies their combined assessment in the present study.

The procedure unfolded in three stages. In the first, the pretest was administered to establish students' baseline level of spatial skills. In the second, students took part in hands-on sessions using BIM tools aimed at creating, visualizing, and analyzing three-dimensional models applied to architectural design, after which the posttest was administered. These practical sessions, totaling 4 weeks (18 instructional hours) and conducted using Revit software, were organized progressively: they began with familiarization with the interface and the basic commands of the BIM environment before advancing toward the development of three-dimensional models of greater geometric and spatial complexity, thereby allowing students to gradually become acquainted with the digital representation of architectural space. In the third stage, the data were processed using SPSS version 25: descriptive statistics were applied, and for hypothesis testing, the non-parametric Wilcoxon test ($\alpha = 0.05$) was used together with a linear regression analysis to determine the explanatory power of BIM with respect to the strengthening of spatial skills. Throughout the study, the ethical principles of confidentiality, anonymity, and voluntary participation were upheld; students were also informed of the study's objectives, and it was ensured that their participation would have no bearing on their regular academic evaluation, thereby safeguarding their well-being and autonomy within the training process.

Results and discussion

Table 1. *Statistics of spatial skills in Architecture students according to pretest and posttest.*

Statistic	Pretest	Posttest
Valid	30	27
Mean	37.13	47.89
Median	41.00	49.00
Standard deviation	7.69	5.37
Coefficient of variation	21%	11%
Minimum	25.00	40.00
Maximum	46.00	55.00

Source: Author's own elaboration based on data processed in SPSS version 25.

The descriptive statistics point to an improvement in students' spatial skills following the introduction of BIM environments: the mean rose from 37.13 to 47.89 points, the median from 41.00 to 49.00, and the mode from 41.00 to 53.00. By dimension, spatial orientation increased from 18.27 to 27.00 points, manipulation of three-dimensional objects from 19.10 to 20.22 points, and spatial reasoning, the dimension showing the largest gain, from 8.70 to 20.89 points. Likewise, the decrease in the standard deviation (from 7.69 to 5.37) and in the coefficient of variation (from 21% to 11%) points to greater homogeneity in the results following the intervention, although the manipulation of three-dimensional objects dimension showed an increase in its coefficient of variation (63% to 77%), indicating greater dispersion within this particular dimension.

Table 2. *Wilcoxon signed-rank test for spatial skills, overall and by dimension.*

Wilcoxon test (Posttest–Pretest)	Z	Asymptotic sig. (2-tailed)
Spatial skills (overall)	-4.547	0.000
Spatial orientation	-3.478	0.001
Manipulation of three-dimensional objects	-0.195	0.845

Spatial reasoning	-2.834	0.005

Source: Author's own elaboration based on data processed in SPSS version 25.

The non-parametric Wilcoxon test revealed statistically significant differences between pretest and posttest in the overall spatial-skills score (Z = -4.547; p = 0.000), allowing the null hypothesis to be rejected in favor of the alternative hypothesis: the application of BIM produced significant improvements in the spatial skills of Architecture students. By dimension, significant differences emerged in spatial orientation (Z = -3.478; p = 0.001) and spatial reasoning (Z = -2.834; p = 0.005); manipulation of three-dimensional objects, by contrast, showed no significant differences (Z = -0.195; p = 0.845), indicating that BIM's contribution is not uniform across all dimensions of spatial skills.

Table 3. *Coefficient of determination for the regression model of spatial skills.*

Model	R	R^2	Adjusted R^2	Sig.
Pretest → Posttest	.899	0.808	0.800	0.000

Source: Author's own elaboration based on data processed in SPSS version 25.

The linear regression analysis showed that the pretest significantly predicts the posttest (B = 0.648; β = 0.899; t = 10.243; p = 0.000), with a correlation coefficient of R = 0.899 and a coefficient of determination of R^2 = 0.808, indicating that the model accounts for 80.8% of the observed variability in the spatial skills of Architecture students, with a statistically significant change in F (p = 0.000).

These findings support the claim that the application of BIM contributed to strengthening students' spatial skills, thereby fulfilling the study's objective. Consistent with this, Ashour et al. (2022) reported improvements in spatial abilities through BIM-related digital environments, lending further support to the idea that interaction with three-dimensional models is a valuable resource for strengthening spatial understanding during architectural training.

These results align with the evidence reported by Porat and Ceobanu (2024), who found that technological components based on the manipulation of three-dimensional models, whether through modeling software or augmented reality, were rated by students themselves as the most effective resources for developing spatial ability, ahead of traditional teaching methods. This pattern suggests that active interaction with three-dimensional digital representations, of the kind BIM environments offer, fosters experiential learning processes that go beyond mere conceptual exposure to course content.

The significant improvement in spatial orientation can be explained by the three-dimensional visualization and exploration opportunities that digital environments afford, allowing students to interpret different positions and relationships within architectural space. This result is consistent with Medina (2020), who identified difficulties in spatial perception and graphic representation and stressed the need for training strategies that foster a more dynamic understanding of space.

The lack of statistical significance in the manipulation of three-dimensional objects, by contrast, indicates that incorporating BIM does not produce uniform gains across all dimensions of spatial competence. One possible explanation relates to the conditions under which the methodology was implemented: Böes et al. (2021) identified limited faculty training and resistance to methodological change as barriers to incorporating BIM into higher education, suggesting that developing this particular skill may call for more targeted hands-on activities and more sustained use of three-dimensional tools.

This is consistent with what Darwish et al. (2023) observed when assessing the effect of extended-reality technologies on the overall spatial ability of Architecture students: they warned that the effectiveness of digital tools can be constrained among learners still navigating a technological adaptation curve, particularly in tasks requiring fine, sustained manipulation of virtual objects. In the present study, the exposure time allotted to BIM tools may not have been sufficient to consolidate significant change in this

particular dimension, underscoring the need to supplement the methodology with more targeted, longer-duration hands-on activities focused on three-dimensional manipulation.

From a broader perspective, manipulating three-dimensional objects calls for a type of sensorimotor coordination distinct from that required for spatial orientation and reasoning, since it involves simultaneously translating mouse and keyboard movements into mental transformations of the represented object (Porat & Ceobanu, 2024). In conventional BIM environments, this instrumental mediation limits the direct sensory feedback that augmented- or extended-reality technologies do provide, technologies that, according to Darwish et al. (2023), more clearly foster the development of this type of skill. This difference in interaction modality may explain why, despite the significant improvements observed in the other two dimensions, three-dimensional manipulation failed to reach statistically significant change over the relatively short span of the didactic intervention.

The largest descriptive gain was observed in spatial reasoning, a finding consistent with Guzmán et al. (2020), who reported difficulties in students' three-dimensional comprehension. This suggests that BIM models provide settings in which students can explore spatial relationships and develop reasoning processes linked to architectural representation.

The high explanatory power of the regression model ($R^2 = 0.808$) confirms the relevance of incorporating digital tools into architectural training, within a context marked by the growing digitalization of teaching. In this vein, Abrahamzon et al. (2024) found that the use of digital technologies in architectural instruction contributes to the development of spatial abilities, reinforcing the case for incorporating technological resources into training strategies.

These results carry concrete implications for curricular design in Architecture programs. First, in line with the evidence from Berkowitz et al. (2021) on the progressive, domain-specific development of spatial ability, it is advisable to integrate BIM environments in a staggered manner across the different training cycles, rather than concentrating their use in isolated courses, so that students can progressively consolidate each of the dimensions assessed. Second, given that the manipulation of three-dimensional objects showed no statistically significant change, academic programs might complement the use of BIM with augmented- or extended-reality technologies, as proposed by Darwish et al. (2023) and Porat and Ceobanu (2024), which afford more direct, hands-on interaction with three-dimensional models. Third, overcoming the barriers identified by Böes et al. (2021), such as limited faculty training and resistance to methodological change, calls for institutional programs of continuous faculty development in the pedagogical, not merely technical, use of BIM tools, so that their incorporation into the classroom reflects deliberate instructional design rather than mere software availability.

Conclusions

In light of the stated objective, it is concluded that incorporating the Building Information Modeling (BIM) methodology as a didactic strategy contributed to strengthening spatial skills in Architecture students. The use of three-dimensional digital environments made it possible to create learning conditions geared toward the comprehension and representation of architectural space.

With respect to the dimensions assessed, the application of BIM primarily fostered the development of spatial orientation and spatial reasoning, whereas manipulation of three-dimensional objects showed no statistically significant change. This shows that the contribution of the methodology can vary depending on which spatial competency is targeted and on the characteristics of the training activities implemented.

Incorporating BIM into university-level Architecture training therefore constitutes a pertinent way to complement traditional teaching strategies and strengthen competencies related to spatial understanding and three-dimensional representation; doing so successfully, however, requires pedagogical planning that aligns digital tools with specific activities targeting the development of each competency.

The study is subject to limitations that should be taken into account when interpreting the findings: a one-group pre-experimental design was used, without comparison to a control group; the sample consisted of 30 students selected through non-probabilistic convenience sampling, which limits the generalizability of the results; and three cases of missing data were recorded at posttest. In light of these limitations, future research could draw on larger samples and quasi-experimental or experimental designs with comparison groups, extend the duration of BIM implementation, develop interventions specifically targeting the manipulation of three-dimensional objects, and compare different BIM-based tools and didactic strategies to determine which yield the best results for each dimension of spatial competence.

Along these lines, the international evidence reviewed here (Berkowitz et al., 2021; Darwish et al., 2023; Porat & Ceobanu, 2024) suggests that multimodal designs, combining BIM with augmented- or extended-reality resources and physical model-building activities, could offer a more comprehensive approach to the balanced development of the different dimensions of spatial competence. Exploring such a combination within the context of Peruvian architectural training constitutes a promising line of inquiry, one that would allow the present evidence to be contrasted against pedagogical scenarios of greater technological complexity.

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Statement on ethics, transparency, and use of artificial intelligence (AI)

This study was conducted in accordance with the ethical principles of voluntary participation, confidentiality, and anonymity for the participating students. The information collected was used exclusively for academic and research purposes, and the results were processed in aggregate form without individually identifying any student. The author declares no conflicts of interest related to the conduct of this research. The study received no external funding.

Author contributions

Sindhy Nayeri Cedillo Lozada: conceptualization, data curation, formal analysis, research, methodology, project administration, resources, supervision, validation, visualization, writing – original draft, and writing – proofreading and editing.