Augmenting Spatial Learning and Problem-Solving in Game-Based Education Through Virtual Environments

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Abstract: Rapid developments in virtual environments and their association with game-based educational processes have altered traditional learning methods. Although this study depends on how users engage with these environments on the levels of learning competence and cognitive processes, these new ways of navigating within architectural spaces focus on spatial cognition and problem-solving issues through task-based interactivity, a well-structured method in which users interact with goal-oriented assignments to fulfill the necessities of cognitive load and game-based learning efficiency. Furthermore, the study investigates spatial grounding, recollection, and cognitive processing the grade of interactive engagement. This study utilizes a task-based interactivity procedure to reveal possible outcomes of the interrelations between interactive spatial assignments and cognitive performance. With the issued VR-based spatial assignments, participants are asked to engage gradually in complex tasks, starting with passive exploration and wayfinding and navigation with simple tasks. Collected data relies on evaluating the precision of assessments, user experience questionnaires. This intake fosters insight into spatial intelligence and how it can impact the effects of structured engagement in game-based learning settings, cognitive load, and adaptability in digital learning environments. The study explores data that validates the optimization of learning efficiency regarding advanced grades of task-based interactivity through the cognitive load in game-based learning and enhanced problem-solving skills. Moreover, the study validates that interactivity in goal-driven tasks results in broader cognitive interaction and advanced spatial cognizance. These conjectures anticipate a prominent insight into VR-based practices and programs, educational game design, and learning strategies. With a focus on the contribution to the developing discourse issuing VR-based education by addressing spatial learning procedures and cognitive processes, this study reveals the potential of first-person exploration and thought processes that emerge from sensory and motor engagements within game-based learning.

Keywords: Task-Based interactivity, Spatial cognition, Cognitive load, Virtual environments, Game-Based learning

1. Introduction

This paper investigates the impact of task-oriented interaction in immersive virtual environments on spatial cognitive learning, orientation, and mental workload by illustrating an evidence-based replicable spatial cognition test based on 360° virtual environment use, Mental Rotation Tests (MRT), spatial recall training, task performance metrics, and subjective workload rating. For its applicability to situations with low technical backgrounds and time restrictions, study merges established testing instruments and embodied cognition to analyze the spatial solving consequence correlation with immersive learning. Spatial reasoning is an elementary component of human perception as well as decision-making. Spatial abilities to imagine and reconfigure spaces in the mind are highly relevant to career fields such as architecture, city planning, and engineering. With the advent of immersive technology such as virtual reality (VR), opportunities exist to take spatial learning through experiential embodied interaction to new levels. This potential is supported by meta-analytic research showing that immersive VR environments significantly improve learning outcomes across disciplines, particularly in comparison to traditional and computer-assisted methods (Coban, Bolat, and Goksu, 2022). Proposed work fills the gap in theoretical knowledge regarding spatial knowledge and empirical application of 360° virtual environments in short-term studies. by showing the formal application of a multi-method approach within reach of those with limited availability of development facilities.

Spatial learning, or the cognitive process of perceiving, structuring, and remembering information concerning spatial conditions, is a consideration across domains from architecture and design through cognitive science and schooling (Newcombe and Shipley, 2015). With increasing use coming from Immersive Technology in the form of VR, there has been increasing enthusiasm directed towards how these kinds of virtual spaces might be used in supporting spatial cognition, as well as more intuitive reasoning (Parsons et al, 2013). Spatial abilities regarding spatial memory, orientation, and spatial visualization are mentally working through spatial relationships. Shepard and Metzler (1971) demonstrated that people rotate an object in mind with some measurable speed, on which the later spatial measures, such as the MRT, were based. Their quantitative test assessed spatial ability and stressed cognitive efficiency and spatial performance relationships. The combination of theory with more recent digital tools is also supported by research in embodied cognition, where perceptual experience and body interaction have formatted cognitive mapping (Johnson-Glenberg, 2018). Based on Wilson (2002) and Slater and Sanchez-Vives (2016), studies in embodied cognition show that body interaction with space affects cognitive processes. More than one sense is engaged through the interface provided by VR technology. Lin et al (2024) reinforce this by demonstrating that multisensory, embodied design in VR science games can meaningfully improve learning outcomes, particularly when interaction and motor engagement are emphasized. It is a concept used in developing learning spaces in which sensory and kinesthetic input triggers spatial memory and orientation. The usability and learner response to VR has also been evaluated in several design education contexts. Ozgen, Afacan, and Sürer (2021) found that VR-based design tools enhanced perceived enjoyment and usability compared to traditional paper-based design. This suggests that engaging, immersive environments can increase learners' willingness to explore and complete complex tasks, directly supporting design-based pedagogy.

On the other hand, immersive learning methods and environments engage and retain people better by simulating world complexity and scale. Learning in space is asserted to be superior by Tversky (2003) compared to navigating in an environment in the physical sense as opposed to passive viewing. In additional studies, Richardson et al (1999) confirmed navigation provides better spatial information than navigation in maps or imagery with weaker retention in memory. 360° virtual environments offer new ways to support spatial learning, especially under technical or time constraints. This study recommends a mixed-methods approach to evaluate task-based VR's impact on learning and workload without relying on intensive qualitative methods like interviews or think-aloud protocols.

This study aims to explore task-based interaction in spatial reasoning, assess spatial memory in passive and active navigation, examine cognitive workload during problem-solving, and evaluate the usability and satisfaction of 360° VR environments.

2. Methodology

The study involved five second-semester undergraduate students from Bahçeşehir University’s Interior Architecture and Environmental Design department. All participants were proficient in spatial visualization, 3D composition, and orthographic drawing. This purposive sampling ensured a baseline level of spatial cognition to engage meaningfully with the MRT and VR-based environment. The aim was not to teach basic spatial reasoning but to assess whether immersive VR could enhance spatial judgment in students already trained in spatial thinking. Selecting spatially able students ensured the MRT served as a sensitive post-intervention measure rather than a basic ability test. Studies comparing VR and conventional tools for spatial learning show that immersive environments can reduce perceived workload while increasing satisfaction and engagement (Banerjee, Chowdhury, and Yein, 2023). When well-designed, VR integration in spatial education supports usability and can enhance cognitive processing. This aligns with the study’s focus on enrichment rather than remediation. Participants were selected based on their technical drawing course skills, taught by the researcher, ensuring familiarity with 3D spatial tasks. Spatial visualization abilities were also informally assessed through prior coursework. While no prior VR experience or familiarity with the case study space was required, participants were asked about their familiarity, which was considered in evaluating sketch accuracy and recall. For reporting, participants were anonymized as P01–P05.

The study used an Oculus Quest 2 VR headset and 360° images of the Bahçeşehir University Material Library, captured with a 360° camera. A Google Forms-based Mental Rotation Test (MRT) pre-test and pen-and-paper drawing tasks were used for measurement. The process began with the MRT pre-test, followed by a VR session involving 360° immersive tasks, wayfinding, and object location. Post-tests included a second MRT, spatial recall sketches, the NASA Task Load Index (NASA-TLX) for workload assessment, the System Usability Scale (SUS), and the User Experience Questionnaire (UEQ) to evaluate usability. Participants completed a 10-question MRT before and after the VR task. All procedures were evaluated in detail. The test shows pairs of three-dimensional objects and asks whether they are one another's rotated version. While this test was initially developed by Shepard and Metzler (1971), it has been proven to be a valid spatial visualization test. Subsequent research focuses on individual variations in suck skills as they are impacted by experience within spatial contexts (Hegarty and Waller, 2005). Participants of the study create the outline of the environment in the virtual world, and answer formally posed questions in response to object locations and paths of motion. Drawing is evaluated on a rubric based on the accuracy of object locations, directional context, and completion. Multiple-choice memory questions test memory retention in a formal style. These assessments quantify mapping and orientation skills, which are key to spatial learning (Montello et al, 2004).

Table 1 represents the primary measures utilized to quantify task performance in VR interaction for every task assigned. These measures provide objective data on spatial efficiency and environmental stimulus sensitivity. NASA-TLX focuses on the workload to measure scores in six parameters: mental, physical, and temporal demand, performance, effort, and frustration. The NASA-TLX survey is administered to participants upon task completion.

The scales are measured on a 0 to 10-point basis, instead of 0 to 100-point to ease the task, and can be normalized based on the task's perceived relevance (Hart and Staveland, 1988). UEQ assessment relies on user satisfaction and system usability, which is gauged by SUS, a five-item Likert-scale questionnaire (Brooke, 1996), UEQ, measuring attractiveness, efficiency, and reliability. These tools assessed how comfortable, easy to use, and enjoyable the VR process was. For data analysis, paired t-tests compared MRT scores before and after the VR session to identify any statistically significant improvement in spatial cognition. Spatial recall sketches were scored using a 0–10 rubric evaluating object placement, directional accuracy, and spatial coherence. Performance errors were analyzed descriptively and compared across conditions. Correlational analysis examined the relationship between task performance and NASA-TLX cognitive workload scores. SUS and UEQ were scored according to their respective standards to assess usability.

Table 1: Measurement methods

Instrument	Phase	Type	Purpose
Mental Rotation Test (MRT)	Pre + Post-Guided	Cognitive Test	Spatial visualization ability
Spatial Sketch (Unguided experience)	Post-Unguided	Visual Recall	Baseline spatial memory
Spatial Sketch (Guided experience)	Post-Guided	Visual Recall	Task-enhanced spatial memory
Spatial Memory Questions	Post-Unguided + Guided	Short Text	Location recall and sequence
NASA-TLX	Post-Unguided + Guided	Workload Rating	Subjective cognitive workload
System Usability Scale (SUS)	Post-Guided	Usability Scale	System usability perception
User Experience Questionnaire (UEQ)	Post-Guided	UX Evaluation	User experience: attractiveness, stimulation…

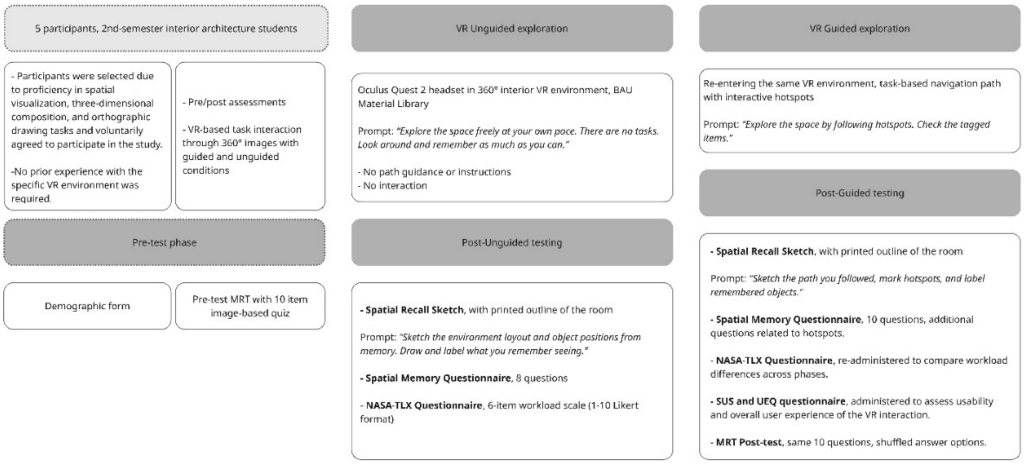
Virtual Reality Conditions

The VR session consisted of two phases:

- Unguided Tour: Participants viewed one sequence of 360° panoramic 13 images, but this sequence was predetermined, without tags, hotspots, or interactions. The state approximated free exploration, with both spatial encoding and attention left to the participant.
- Guided Tour: Participants experienced a VR tour with the same 360° panoramic images, but with labeled/tagged objects and hotspots. Participants clicked on the hotspots to move forward in sequence and checked the tagged objects along the way. This made participants aware of spatial relationships and salient environmental elements.

This apparent difference in exploration styles enabled measuring how task-focused interaction supports spatial knowledge, object location memory, and path recall.

3. Procedure



- Participants were selected due to proficiency in spatial visualization, three-dimensional composition, and orthographic drawing tasks and voluntarily agreed to participate in the study.

-No prior experience with the specific VR environment was required.

- Pre/post assessments

- VR-based task interaction through 360° images with guided and unguided conditions

Oculus Quest 2 headset in 360° interior VR environment, BAU Material Library

Prompt: *"Explore the space freely at your own pace. There are no tasks. Look around and remember as much as you can."*

- No path guidance or instructions
- No interaction

- **Spatial Recall Sketch**, with printed outline of the room

Prompt: *"Sketch the environment layout and object positions from memory. Draw and label what you remember seeing."*

- **Spatial Memory Questionnaire**, 8 questions

- **NASA-TLX Questionnaire**, 6-item workload scale (1-10 Likert format)

Re-entering the same VR environment, task-based navigation path with interactive hotspots

Prompt: *"Explore the space by following hotspots. Check the tagged items."*

- **Spatial Recall Sketch**, with printed outline of the room

Prompt: *"Sketch the path you followed, mark hotspots, and label remembered objects."*

- **Spatial Memory Questionnaire**, 10 questions, additional questions related to hotspots.

- **NASA-TLX Questionnaire**, re-administered to compare workload differences across phases.

- **SUS and UEQ questionnaire**, administered to assess usability and overall user experience of the VR interaction.

- **MRT Post-test**, same 10 questions, shuffled answer options.

Figure 1: Workflow

Figure 1 summarizes the overall procedures for the conducted case studies.

MRT

The MRT measured spatial visualization and mental rotation ability. It included 10 items, each showing one target 3D object and four rotated options. Participants selected the correct match from a different perspective. The same items were used in pre- and post-tests, with shuffled answers to reduce memorization. Each test had a maximum score of 10, with one point per correct response. The MRT is a widely validated tool for assessing spatial reasoning, especially in design and architecture.

Spatial Recall Assessment

Participants' spatial memory was assessed using two tools:

- Sketch-Based Spatial Recall: After each VR session, participants drew a schematic floor plan from memory. Sketches were scored on a 4-criteria rubric: (1) object recall accuracy, (2) object placement, (3) overall layout, and (4) path clarity (guided phase only). Each criterion was scored from 0–2, with a maximum of 6 (unguided) or 8 (guided).
- Spatial Memory Questions: Participants answered eight open-ended questions after each session (e.g., "Which objects were closest to the entrance?"). Responses were scored 0–2, with a maximum of 16 per session. Three additional questions followed the guided session to assess route and object memory.

NASA-TLX

The NASA-TLX was used after both VR conditions to assess perceived cognitive workload across six dimensions: Mental, Physical, and Temporal Demand, Performance, Effort, and Frustration. Each was rated on a 1–10 Likert scale (1 = minimal, 10 = extreme workload). Instead of weighted scoring, unweighted averages were used. The performance dimension was reverse-interpreted, with higher scores indicating better performance and lower cognitive load.

SUS

Usability was assessed using a modified 10-item SUS, with responses on a 1–5 Likert scale. Items included both positive and negative statements (e.g., "The VR system was easy to use" and "The system was unnecessarily complex"). Scores were averaged per participant, with values above 3.0 indicating better usability. Unlike the standard 0–100 format, this study kept the 1–5 scale for simpler interpretation.

UEQ

To assess affective and interactional aspects of the VR system, participants completed 10 adjective pairs from UEQ. Items were rated on a 7-point scale (−3 to +3) across five subscales: Attractiveness, Perspicuity, Efficiency, Dependability, and Stimulation. Each subscale was averaged from two related items, with higher scores indicating a more positive experience.

4. Case Study and Findings

The findings provide insight into how immersive virtual environments affect spatial cognition, recall accuracy, and user experience. Data were collected through objective tests and subjective ratings after unguided and guided VR sessions. Results are presented across six areas: MRT, Spatial Recall Sketches, Spatial Memory Questions, NASA-TLX, SUS, UEQ, and Guided Tour Trace Recall. The case study area (Figure 2) and user experience record (Figure 3) are shown below.

Figure 2: Case study area

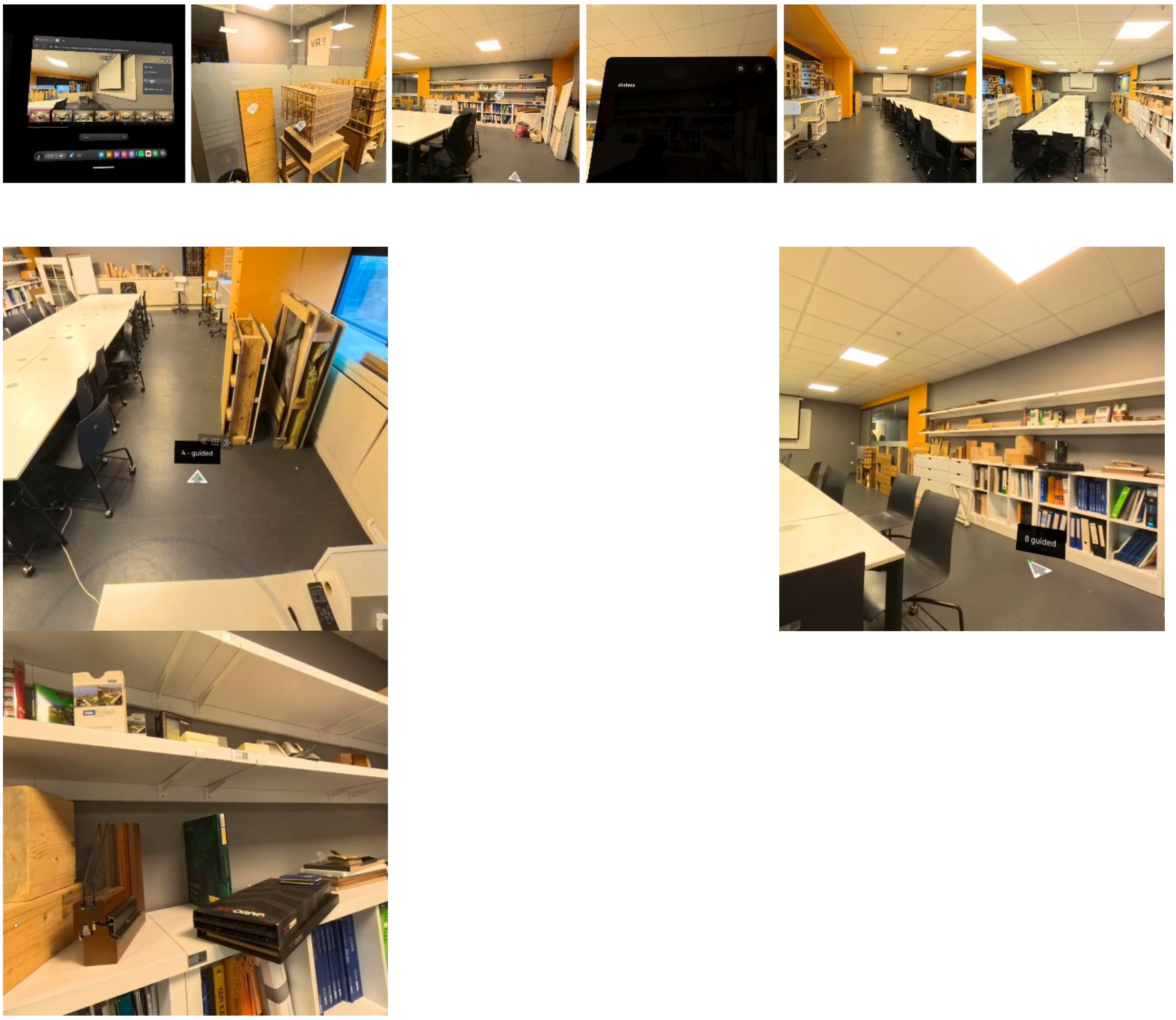


Figure 3: P02 VR guided experience record screenshots

MRT

Participants completed a 10-item MRT before and after completing the VR learning tasks (Table 2). Pre-test scores were already high, with a group mean of 9.6 out of 10. Post-test scores increased slightly to a perfect mean of 10.0. A paired-sample t-test showed that this increase was not statistically significant (t(4) = 1.63, p > 0.05), likely due to ceiling effects and the small sample size. Although the data does not have statistical significance, using a paired t-test remains common in studies assessing short-term cognitive gains following immersive learning interventions, particularly when examining spatial reasoning and perceptual skill development (Wang and Dunston, 2013; Radianti et al, 2020). The consistently strong performance across both phases suggests that the VR experience did not hinder spatial reasoning and may have reinforced participants' mental rotation skills.

Table 2: MRT pre-and post-test results

Participant	MRT Pre-Test Score	MRT Post-Test Score	Gain
P01	9	10	1
P02	10	10	0
P03	9	10	1
P04	10	10	0
P05	10	10	0

Spatial Recall Sketch Accuracy

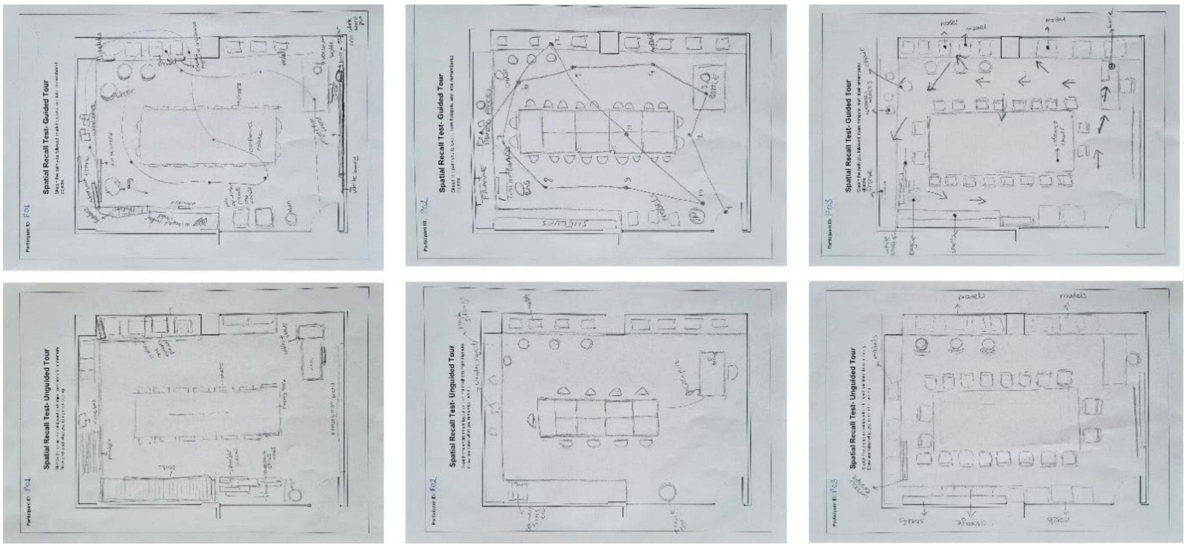


Figure 4: P01, P02, P03 (left to right) VR guided (first row) and VR unguided (second row) spatial recall sketches

Participants drew floor plan sketches after unguided and guided VR tours (Figure 4). Sketches were scored on object recall, placement accuracy, spatial layout, and path clarity (guided only). Results showed better performance in the guided condition (Table 3), where sequential navigation and tagged points supported higher scores across all categories. Participants who were less familiar with space (P01, P02, P05) showed clear improvements in recall and organization. Those familiar with the environment (P03, P04) also improved in the guided session, especially in path clarity and completeness. Guided interaction with hotspots aided spatial encoding, supporting that structured VR interaction enhances memory more than passive viewing.

Table 3: Spatial recall sketch evaluation

Scoring Scale: 0 = Absent/Incorrect, 1 = Partial, 2 = Fully Accurate

Participant	Familiarity	Phase	Object Recall	Placement	Layout	Path Clarity	Total
P01	Unfamiliar	Unguided	2	1	1	-	4/6
P01	Unfamiliar	Guided	2	2	2	1	7/8
P02	Unfamiliar	Unguided	1	1	1	-	3/6
P02	Unfamiliar	Guided	2	2	2	2	8/8
P03	Very Familiar	Unguided	1	2	2	-	5/6
P03	Very Familiar	Guided	2	2	2	1	7/8

Participant	Familiarity	Phase	Object Recall	Placement	Layout	Path Clarity	Total
P04	Very Familiar	Unguided	1	2	2	-	5/6
P04	Very Familiar	Guided	1	2	2	1	6/8
P05	Somewhat Familiar	Unguided	1	1	1		3/6
P05	Somewhat Familiar	Guided	1	2	1	2	6/8

Spatial Memory Scoring

Participants answered eight open-ended spatial memory questions after each VR session, focusing on object positions and environmental features (e.g., “Which wall had the shelves?”). Each was scored from 0–2, with a maximum of 16 per session (Table 4). Scores generally improved in the guided condition. While unguided scores ranged from 8 to 16, all participants maintained or improved after guidance. P01 improved from 9 to 15; P04 and P05 also showed gains, with P05 scoring 16/16 in both sessions. P03, already scoring 12/16, showed little change, possibly due to a ceiling effect. Overall, guided tours with hotspots and labels enhanced spatial recall, especially for those with lower initial scores, supporting the idea that structured engagement improves memory in immersive environments.

Table 4: Spatial recall results

VR Unguided experience									
Participant	**Q1 (Entrance Objects)**	**Q2 (Window-side Objects)**	**Q3 (Table Items)**	**Q4 (Seating Count)**	**Q5 (Dominant Color)**	**Q6 (Vacuum Bottle Location)**	**Q7 (Shelves Location)**	**Q8 (Projection Screen)**	**Total (Max 16)**
P01	1	1	1	0	2	0	2	2	9
P02	2	1	1	2	1	2	1	1	11
P03	2	2	2	1	2	0	2	1	12
P04	1	1	0	1	2	0	1	2	8
P05	2	2	2	2	2	2	2	2	16
VR Guided experience									
Participant	**Q1 (Entrance Objects)**	**Q2 (Window-side Objects)**	**Q3 (Table Items)**	**Q4 (Seating Count)**	**Q5 (Dominant Color)**	**Q6 (Vacuum Bottle Location)**	**Q7 (Shelves Location)**	**Q8 (Projection Screen)**	**Total (Max 16)**
P01	2	1	2	2	2	2	2	2	15
P02	2	2	2	2	1	2	2	2	15
P03	1	1	2	2	1	2	2	1	12
P04	1	1	2	1	2	2	2	2	13
P05	2	2	2	2	2	2	2	2	16

NASA-TLX Workload Ratings

Managing cognitive load is a well-documented challenge in immersive VR settings. While immersive experiences can foster a strong sense of presence, they can inadvertently increase the extraneous load and reduce learning efficiency if not properly structured (Makransky, Terkildsen, and Mayer, 2019). NASA-TLX scores were collected for unguided and guided conditions across six workload dimensions. Instructional design techniques, such as pre-training, have effectively reduced initial cognitive overload and improved knowledge retention and transfer in immersive environments (Meyer, Omdahl, and Makransky, 2019). Structured scaffolding, as used in this study, supports effective VR task design. Average workload scores remained low in both conditions (3.0–4.5 on a 10-point scale). Some participants reported slightly higher temporal demand during the guided session, likely due to sequential tasks, but overall ratings were stable or lower. This suggests that guidance did not increase cognitive load and may have improved task fluency (Table 5).

Table 5: Workload comparison

Participant	Unguided TLX Mean	Guided TLX Mean	Gain
P01	4.50	4.17	-0.33
P02	2.50	3.83	+1.33
P03	3.83	3.83	+0.00
P04	4.50	4.33	-0.17
P05	3.17	3.50	+0.33

SUS

Participants completed a 10-item SUS using a 1–5 Likert scale. Average scores ranged from 3.3 to 4.3, with all five participants rating the system above the neutral usability threshold of 3.0 (Table 6). These findings suggest that the VR interface was perceived as accessible and functionally usable, even for novice users. No participants reported usability issues significant enough to impede interaction or task completion.

Table 6: SUS averages

Participant	SUS Mean Score (1–5)
P01	3.80
P02	4.10
P03	3.30
P04	3.60
P05	4.30

UEQ

Ten adjective pairs from UEQ assessed interaction quality across five dimensions. Mean subscale scores (−3 to +3) showed high ratings for Dependability and Stimulation, with more variation in Efficiency and Attractiveness (Table 7). P02 and P05 rated the system as highly stimulating, though P05 gave a lower Efficiency score, suggesting individual differences in task ease. Overall, UEQ results reflect a positive user experience.

Table 7: UEQ results in grouped subscales

Participant	Attractiveness	Perspicuity	Efficiency	Dependability	Stimulation
P01	0.00	1.50	0.50	1.00	0.50
P02	0.50	1.00	1.00	2.50	1.50
P03	-1.00	1.00	0.50	3.00	0.50
P04	0.50	1.50	1.50	3.00	1.00
P05	1.50	1.00	-2.50	3.00	1.00

Guided Tour Spatial Trace Recall

Three final questions assessed memory of the guided tour sequence: first hotspot, path description, and last object recalled. Each was scored 0–2 (max 6) (Table 8). P02, P04, and P05 recalled the sequence with near-perfect accuracy. P01 remembered the path but only partially recalled other items, while P03 showed general partial recall with minor deviations. These results support that guided tours with visual tags enhance sequence memory and procedural recall.

Table 8: Selected questions of guided VR experience

Participant	First Hotspot	Path Sequence	Final Object Recall	Total (Max 6)
P01	1	2	1	4
P02	2	1	2	5
P03	1	1	1	3
P04	2	2	1	5
P05	2	1	2	5

5. Discussion and Conclusion

This study explored how task-based interactivity in virtual environments can improve spatial learning and cognitive performance in architectural education. It offers insights for designers, researchers, and educators developing learning technologies and educational games. The case study involved five participants (ages 20–22; three females, two males). Two had prior VR experience; three used VR for the first time. Overall, guided task-based interaction improved spatial memory, supported environmental understanding, and was perceived as manageable and user-friendly.

This paper presents a structured, usable system for assessing task-orientated interaction and spatial cognition within virtual environments while offering empirical evidence on the cognitive impact of immersive virtual learning by integrating structured VR experiences with validated assessment tools, including the MRT, spatial recall sketches, memory questions, and subjective workload and usability ratings. Findings demonstrated that guided VR experiences, enriched with labeled hotspots and interactive cues, led to higher spatial recall scores, more accurate sketch representations, and improved recollection of object locations and environmental features. This agrees with Lin et al (2024), who discovered that structured interaction and guidance in VR can support increased cognitive gain in task-based spatial thinking. Banerjee et al (2023) also proved that reduced cognitive load and increased perceptions of usability in VR tools directly impacted participants' task completion and participation. Regarding motivation, studies confirm that immersive VR experiences can significantly enhance learner satisfaction and attention. Portuguez-Castro and Santos-Garduño (2024) found that VR boosted all components of the ARCS motivation model, especially attention and satisfaction. These dimensions directly correlate with the observed improvements in task engagement and memory recall during guided sessions in our study. These outcomes were especially pronounced among participants with limited familiarity with the physical space, indicating that goal-oriented navigation supports more effective spatial encoding. While MRT scores were already high at baseline and exhibited limited gains due to ceiling effects, the retention of strong performance suggests that VR did not hinder spatial reasoning and may have reinforced pre-existing spatial abilities. Although all participants had sufficient spatial ability, individual learning differences or prior familiarity may have influenced engagement. Two participants were already taking a course in the case study area, which directly engaged with the materials and objects in space, such as timber samples in the material library. Despite this hands-on familiarity, their performance in the unguided VR tour was not distinctively better than others, and even they showed clear improvement in the guided condition. This suggests that prior exposure alone was insufficient; structured, task-based interaction in VR more effectively enhanced spatial understanding. Workload assessments validate that the structured VR experience did not increase the perceived cognitive burden, and user experience ratings indicated that the system was accessible and engaging. The integration of game-based learning principles and embodied interaction, particularly the coupling of movement, attention, and sensory input, supported deeper cognitive processing and environmental awareness.

While this study does not directly compare VR to traditional or screen-based learning, existing research and participant feedback suggest that immersive, guided interaction offers stronger engagement and spatial recall benefits than passive or 2D methods. The findings correlate with broader literature indicating that when structured with guided tasks, immersive VR can outperform traditional methods in fostering spatial understanding and user engagement.

6. Limitations and Future Studies

This project introduces an actionable test procedure to test spatial understanding through immersive technology. It provides a low-barrier approach relevant to short studies or instruction scenarios with no programming prerequisites and validated measures on cognitive, performance, and subjective instruments. Moreover, it proposes a bridge between embodied cognition theory and applied design pedagogy while addressing a gap in VR learning literature and reviewing methodological feasibility for small-scale academic settings. With the spatial content, the findings present a direction for designing educational games and virtual learning settings. Highlighting guided exploration and structured tasks can help learners develop spatial understanding more effectively. The performance gap between unguided and guided conditions highlights the value of embedded instructions and progression-based interaction in supporting engagement and retention.

This study offers meaningful findings, with opportunities for future work to enhance generalizability through larger, randomized samples. While 360° photos provided immersion, adding real-time interaction could enrich the experience. Exploring long-term learning effects and increasing task complexity through dynamic VR environments would further strengthen future studies. In addition, long-term retention and more significant numbers of participants with diverse demographics should be arranged for testing. As shown by Makransky et al (2021), the motivational richness of VR can be a double-edged sword unless supported by generative learning strategies such as enactment or reflection. Future implementations should include cognitive scaffolds that channel learner motivation into lasting learning gains.

Ethics declaration: Confidentiality was ensured throughout data collection and storage, with all data anonymized. No identifying personal information was used. Participants received a notification form outlining the study's scope, purpose, and procedures, and provided written consent to participate.

AI declaration: In this study, AI tools were used to compile the study content and check for grammatical errors.

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References

Banerjee, S., Chowdhury, A., and Yein, N. (2023). "User Experience Evaluation of a Virtual Reality Tool Used for 3D Modelling in Industrial Design Education: A Study in the Indian Context". *Designs*, 7(5), 105. https://doi.org/10.3390/designs7050105

Brooke, J. (1996) "SUS: A "quick and dirty" usability scale", in Jordan, P.W., Thomas, B., Weerdmeester, B.A. and McClelland, I.L. (eds.) Usability Evaluation in Industry. London: Taylor & Francis, pp. 189–194.

Coban, M., Bolat, Y. I., and Goksu, I. (2022). "The Potential of Immersive Virtual Reality to Enhance Learning: A Meta-Analysis". *Educational Research Review*, 36, Article 100452. https://doi.org/10.1016/j.edurev.2022.100452

Hart, S. G., and Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock & N. Meshkati (Eds.), *Human mental workload* (pp. 139–183). North-Holland. https://doi.org/10.1016/S0166-4115(08)62386-9

Hegarty, M., and Waller, D. A. (2005). Individual Differences in Spatial Abilities. In P. Shah (Ed.) & A. Miyake, *The Cambridge Handbook of Visuospatial Thinking* (pp. 121–169). Cambridge University Press. https://doi.org/10.1017/CBO9780511610448.005

Johnson-Glenberg, M. (2018). "Immersive VR and education: Embodied design principles that include gesture and hand controls". *Frontiers Robotics AI*, 5(JUN), Article 81. https://doi.org/10.3389/frobt.2018.00081

Lin, X., Li, R., Chen, Z., and Xiong, J. (2024). "Design strategies for VR science and education games from an embodied cognition perspective: a literature-based meta-analysis". *Frontiers in psychology*, 14, 1292110. https://doi.org/10.3389/fpsyg.2023.1292110

Makransky, G., Andreasen, N. K., Baceviciute, S., and Mayer, R. E. (2021). "Immersive virtual reality increases liking but not learning with a science simulation and generative learning strategies promote learning in immersive virtual reality". *Journal of Educational Psychology*, 113(4). https://doi.org/10.1037/edu0000473

Makransky, G., Terkildsen, T. S., and Mayer, R. E. (2019). "Adding immersive virtual reality to a science lab simulation causes more presence but less learning". *Learning and Instruction*, 60, 225–236. https://doi.org/10.1016/j.learninstruc.2017.12.007

Meyer, O. A., Omdahl, M. K., and Makransky, G. (2019). "Investigating the effect of pre-training when learning through immersive virtual reality and video: A media and methods experiment". *Computers & Education*, 140, Article 103603. https://doi.org/10.1016/j.compedu.2019.103603

Montello, D. R., Hegarty, M., Richardson, A. E., and Waller, D. (2004) "Spatial memory of real environments, virtual environments, and maps", in Allen, G.L. (ed.) *Human Spatial Memory: Remembering Where*. Mahwah, NJ: Lawrence Erlbaum Associates, pp. 251–285.

Newcombe, N.S. and Shipley, T.F. (2015) "Thinking about spatial thinking: New typology, new assessments", in Gero, J.S. (ed.) *Studying Visual and Spatial Reasoning for Design Creativity*. Dordrecht: Springer, pp. 179–192. DOI: 10.1007/978-94-017-9297-4_10

Ozgen, D. S., Afacan, Y., and Sürer, E., (2021). "Usability of virtual reality for basic design education: a comparative study with paper-based design". *International Journal of Technology and Design Education*, vol.31, no.2, 357-377. https://doi.org/10.1007/s10798-019-09554-0

Parsons, T. D., Courtney, C. G., Dawson, M. E., Rizzo, A. A. and Arizmendi B. J. (2013) "Visuospatial processing and learning effects in virtual reality based mental rotation and navigational tasks", in Harris, D. (ed.) Engineering Psychology and Cognitive Ergonomics: Understanding Human Cognition – 10th International Conference, EPCE 2013, Held as Part of HCI International 2013, Proceedings, Part I. Berlin: Springer, pp. 75–83.

Portuguez-Castro, M., and Santos Garduño, H. (2024). "Beyond Traditional Classrooms: Comparing Virtual Reality Applications and Their Influence on Students' Motivation". *Education Sciences*, 14(9), 963. https://doi.org/10.3390/educsci14090963

Radianti, J., Majchrzak, T. A., Fromm, J., and Wohlgenannt, I. (2020) "A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda", *Computers & Education*, 147, p. 103778. https://doi.org/10.1016/j.compedu.2019.103778

Richardson, A. E., Montello, D. R., and Hegarty, M. (1999). "Spatial knowledge acquisition from maps and from navigation in real and virtual environments". *Memory & cognition*, 27(4), 741–750. https://doi.org/10.3758/bf03211566

Shepard, R. N., and Metzler, J. (1971). "Mental rotation of three-dimensional objects". *Science*, 171(3972), 701–703. https://doi.org/10.1126/science.171.3972.701

Slater, M. and Sanchez-Vives, M.V. (2016) “Enhancing our lives with immersive virtual reality”, *Frontiers in Robotics and AI*, 3, p. 74. https://doi.org/10.3389/frobt.2016.00074

Tversky, B. (2003). “Structures Of Mental Spaces: How People Think About Space”. *Environment and Behavior*, 35(1), 66-80. https://doi.org/10.1177/0013916502238865

Wang, X. and Dunston, P.S. (2013) “Design, strategies, and issues towards an augmented reality-based construction training platform”, *Journal of Information Technology in Construction* (ITcon), 18, pp. 362–379.

Wilson, M. (2002) “Six views of embodied cognition”, *Psychonomic Bulletin & Review*, 9(4), pp. 625–636. DOI: 10.3758/bf03196322