A Preliminary Evaluation of an Educational Game for Developing Spatial Ability Using Minecraft and Generative AI Scaffolding

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Abstract

Spatial ability is vital for addressing daily and scientific challenges. This study aims to design and conduct a preliminary evaluation of an educational game integrating the Minecraft virtual world with generative AI (GenAI)-guided scaffolding. Fifteen undergraduate and graduate students (8 female, 7 male) participated in the game, with comprehensive assessment conducted through flow, activity anxiety, cognitive load scales, spatial ability tests, and qualitative feedback. Results indicate participants experienced flow states during gameplay, with significantly higher scores than the median of 3 on dimensions including “clear goals,” “immediate feedback,” “concentration,” and “loss of time perception.” Cognitive load analysis revealed the activity had significant “germane cognitive load” (p = .004), while “activity anxiety” remained significantly below 3. Regarding spatial ability performance, the post-test average score (80.00) exceeded the pre-test score (73.33), though the difference did not reach statistical significance (p = .078). Qualitative analysis revealed that over 85% of participants found the GenAI robot helpful for problem-solving; 93.3% agreed the game process enhanced spatial sense application; and 80% believed skills learned were transferable to real life. Collectively, this study preliminarily confirms the game's potential in creating immersive learning experiences and promoting germane cognitive load, while receiving strong learner endorsement.

Keywords: Minecraft, spatial ability, GenAI, game-based learning, scaffolding

Introduction

Spatial ability is a core cognitive skill involving the understanding and manipulation of object location, orientation, and structure. Consequently, effectively cultivating and assessing learners' spatial abilities in educational settings has long been a focal point in educational psychology and learning sciences.

With the rise of digital games and immersive learning environments, open-world virtual platforms like Minecraft have increasingly been applied in education (Bile, 2022; Lee & Hou, 2025; Nkadimeng & Ankiewicz, 2022). Their highly flexible three-dimensional construction features allow learners to naturally engage in spatial reasoning and problem-solving processes through exploration, building, and problem-solving within the game context.

In recent years, advances in generative artificial intelligence have opened new opportunities for educational scaffolding design. Multiple studies have demonstrated that generative AI can effectively support higher-order cognitive activities (Chien et al., 2025; Ngu et al., 2025). When combined with immersive environments like Minecraft, it has the potential to form an interactive and adaptive learning model, offering innovative teaching solutions for enhancing spatial ability development.

Research Questions

This study aims to develop a scenario-based puzzle game integrating GenAI NPCs and explore the application of Minecraft Education in spatial competence instruction. The primary objectives are as follows:

1. Evaluate participants' spatial competence performance in the "Minecraft and GenAI-guided educational game."
2. Evaluate participants' flow in the "Minecraft and GenAI-guided educational game."
3. Evaluate participants' learning anxiety "Minecraft and GenAI-guided educational game."
4. Evaluate participants' cognitive load in the "Minecraft and GenAI-guided educational game."
5. Evaluate participants' qualitative feedback "Minecraft and GenAI-guided educational game."

Game Design

This educational game, developed on the Minecraft platform, utilizes command blocks to create game modules capable of calculating time and displaying game information. It incorporates a generative AI (GenAI) character, the "Village Chief," as scaffolding. The aim is to guide learners in cultivating spatial representation ability through exploration and problem-solving within the virtual world. The game is set in the "Mysterious Mining Village," where learners assume the role of a challenger undergoing trials. They must complete multiple tasks and safely escape amidst a village fire crisis. The narrative design enhances situational immersion, while coordinate-based mission design directly addresses the research core—the development of spatial orientation and reasoning abilities.

Figure 1
Utilizing Command Blocks to Develop Game Modules, Calculate Time, and Display Game Information

The game begins at the Village Chief's House (S0), which also serves as a tutorial area. Learners can understand the basic XYZ coordinate system and directional rules through conversations with the GenAI Village Chief. The GenAI Village Chief provides hints at different levels based on the learner's questions or performance, such as explaining relative positions in text or offering more concrete operational suggestions to help players complete tasks.

The main quest consists of three stages. The first is the Iron Mine (S1), where learners must locate targets using relative positional information. For example, the GenAI Village Chief might offer a key clue:

> To withstand the blazing heat, you must first find the 'Miner's Fireproof Armor' crafted by our ancestors. This armor is hidden in the iron mine west of the village. The mine's X-coordinate is smaller than that treehouse over there, while its Z-coordinate is exactly 60 meters higher than my home.

Next, learners must locate a hidden mechanism to enter the mine and retrieve the armor. The Village Chief then offers a decisive hint:

> Be aware that the mine entrance was recently blocked by falling rocks from an earthquake. You must locate the 'Old Mine Lever' beneath a dead tree near the treehouse beside the entrance to activate the mechanism and open the secret passage.

This design requires players to flexibly apply coordinate judgment and spatial reasoning while integrating problem-solving strategies.

Figure 2
Consulting the GenAI Village Chief NPC Provides Hints, Enhancing Players' Spatial Reasoning

Second, if players encounter a "poisoning" scenario during exploration, they must proceed to the Ranch (S2). By determining the ranch's relative position to the treehouse and iron mine, they locate the correct spot to obtain "magical milk." The Village Chief guides:

> The village air is filled with toxic mist from the fire. If you're unlucky enough to be poisoned, the only antidote is milk from the 'magical cow' at the pasture. The pasture lies on a vast green field north of the treehouse and west of the iron mine.

This task tests learners' ability to synthesize judgments based on multiple reference points.

Finally, when the player's health is critically low, they must seek the "Miraculous Herb" in the cave (S3). The cave is positioned northeast of the pasture, elevated approximately 15 meters above it. The village chief advises: "If you're injured during the trial and your health is nearly depleted, hurry to find the 'Fire-Resistant Herb' in the cave. It will swiftly heal your wounds." That cave is hidden high up, northeast of the pasture. Its X-coordinate is larger than the pasture's, and its height (Y-coordinate) is nearly 15 meters higher than the pasture. This task not only requires learners to correctly deduce the relationship between the X, Y, and Z axes but also adds challenge and immersion by simulating the loss of life and spatial disorientation experienced in adventure mode.

Figure 3
NPCs in Each Level Provide Critical In-Game Resources

Participants

The study invited 15 undergraduate and graduate students (8 female, 7 male) to participate in the game. All participants were recruited online for camp activities and had no prior experience with this educational game course integrating Minecraft and GenAI-guided scaffolding.

Measurement

To assess learners' spatial abilities, we employed pre- and post-test learning evaluations designed by an instructor with 20 years of teaching experience, ensuring expert validity. The questions were divided into three sections: the first section comprised 8 items on spatial verbal reasoning; the second section included 7 items on spatial pictorial reasoning; and the third section featured 5 items on spatial visualization.

In order to ascertain the degree of involvement of the learners in this game, the present study adopted the Chinese version of the flow scale by Kiili (2006). This 22-item version was translated into Chinese by Hou and Chou (2012) and included flow antecedents and flow experience. Flow antecedents consists of five sub-dimensions: challenge, goal, feedback, control, and playability. These sub-dimensions were used to measure learners' perceptions of the game. Learners' experience in the game was measured by four sub-dimensions of flow experience: concentration, time distance, autotelic experience, and loss of self-consciousness. All dimensions were measured using a five-point Likert scale, with 1 being strongly disagree and 5 being strongly agree. Higher scores on a dimension (sub-dimension) indicate a more positive evaluation or experience of that dimension, and the flow scale was highly reliable in this study (Cronbach's $\alpha = .95$).

The cognitive load scale used in this study was adapted from the measure developed by Leppink et al. (2013). This scale assesses three components: internal cognitive load, external cognitive load, and germane cognitive load. Items were rated on a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). The overall reliability of the scale for the current sample was Cronbach's $\alpha = .63$.

Procedure

To evaluate the "Educational Game Guided by Minecraft and GenAI Scaffolding," we conducted a total of 100 minutes of learning activities.

Table 1
Research Procedure

Procedure	Session time	Description
Description of teaching activity	5 minutes	The researcher explained the content of the activity and the experimental procedure
Pre-test	15 minutes	Complete pre-testing questionnaires online to evaluate learners' spatial abilities in advance.

Basic operation experience	10 minutes	Each learner experiences the standard version of minecraft gameplay to familiarize themselves with basic controls such as WASD movement, jumping, and opening the inventory.
Teaching activity	50 minutes	Play the Survive@Mine game
Post-test	20 minutes	Fill out post-testing questionnaires to assess learners' spatial ability, flow, activity anxiety, and cognitive load.

Results and Discussion

Table 2–5 summarizes the findings of this study. Regarding spatial ability, Table 2 shows that participants' post-test mean score (M = 80.00, SD = 9.64) was higher than their pre-test mean score (M = 73.33, SD = 9.57). Although scores improved, this difference did not reach statistical significance ($Z = -1.76$, p = .078). Nevertheless, this result indicates a positive trend of progress.

Table 2
Pre- and Post-test of Spatial Ability (n = 15)

Dimension	*Mean* (*SD*)		*Z*	*p*
	Pre-test	Post-test		
Score	73.33 (9.57)	80.00 (9.64)	−1.76	.078

Regarding students' experiences with the Survive@Mine game, Table 3 summarizes the game flow scale. Using the Wilcoxon signed-rank test with a scale median of 3, data analysis indicates participants achieved a significant overall flow level (M = 3.8) during the activity. Dimensions with particularly prominent scores include: loss of time perception, immediate feedback, clear goals, and focus on the task at hand. Additionally, “self-forgetfulness” and “loss of self-awareness” also reached significant levels.

Table 3
Nonparametric Test Summary for Flow Scale (n = 15)

Dimension	*M*	*SD*	*Z*	*p*
Challenge-skills Balance	2.98	1.08	−0.15	.877
Clear Goals	4.13	.93	2.96^{*}	.003
Unambiguous Feedback	4.20	.62	3.23^{*}	.001
Sense of Control	3.50	1.21	1.37	.170
Action-awareness Merging	3.00	1.13	−0.04	.964
Concentration	4.11	1.16	2.83^{*}	.004
Time Distortion	4.40	.71	3.36^{***}	.000
Autotelic Experience	3.87	1.17	2.49^{*}	.012
Loss of Self-consciousness	3.70	1.14	2.08^{*}	.038
Total	3.80	.85	2.84^{*}	.004

Note. $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Table 4 summarizes participants' activity anxiety in this study, tested using the Wilcoxon signed-rank test against the scale median of 3. Data analysis indicates participants did not experience high anxiety during activities. The mean activity anxiety score was 2.45 (*SD* = .90), significantly lower than the scale median of 3 ($p = .024$), indicating that this game environment constitutes a low-anxiety learning context.

Table 4
Summary of Nonparametric Tests for Activity Anxiety (n = 15)

Dimension	*M*	*SD*	*Z*	*p*
Activity Anxiety	2.45	.90	-2.25^{*}	.024

Note. $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Table 5 summarizes the data for each dimension of cognitive load in the education game. This study employed the Wilcoxon signed-rank test with a median of 3 for the scale. Learners' mean score for cognitive load was 4.00 (*SD* = .91), significantly higher than the median of 3 ($p = .004$). In contrast, neither intrinsic cognitive load ($M = 2.98$) nor extrinsic cognitive load ($M = 2.73$) reached statistical significance, indicating that the task difficulty and interface design did not impose excessive cognitive burden on learners. The significant level of generative cognitive load ($M = 4$) suggests learners experienced high spatial cognitive processing during the task.

Table 5
Summary of Nonparametric Cognitive Load Tests (n = 15)

Dimension	*M*	*SD*	*Z*	*p*
Intrinsic Cognitive Load	2.98	.57	−0.44	.660
Extrinsic Cognitive Load	2.73	.49	−1.92	.060
Germane Cognitive Load	4.00	.91	2.92^{**}	.004

Note. $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

In qualitative feedback, the vast majority (over 85%) of participants found GenAI helpful. The primary ways GenAI assisted were by providing directions and coordinates, as well as prompting task objectives and steps. Participants identified challenges primarily in two areas: "spatial orientation" and "game operation." Furthermore, nearly all participants agreed that this experience significantly enhanced the application of spatial awareness and orientation skills. They generally found this learning approach more "proactive," "hands-on," and "engaging." Regarding learning method transformation and skill transfer, most participants believed skills acquired through the game could be applied to real life, particularly "learning how to effectively utilize AI" and "the ability to decompose problems."

Conclusion

This preliminary study evaluated the effectiveness of using Minecraft and GenAI scaffolding to cultivate spatial abilities, yielding positive supporting evidence. Findings indicate that the game design successfully created an immersive, low-anxiety learning experience. The "clear objectives" and "immediate feedback" provided by GenAI scaffolding strongly guided learners into a flow state while significantly reducing learning anxiety.

Second, the learning activities effectively promoted germane cognitive load. GenAI handled external cognitive load tasks like "how to read coordinates" and "where to go next," freeing learners' cognitive resources to focus on core spatial schema construction—such as "understanding XYZ axis concepts" and "locating within a 3D environment." Although the pre-post spatial ability test difference did not reach statistical significance (p = .078), a positive trend emerged within the small sample (n = 15). Qualitative data strongly corroborated GenAI's value as a "cognitive partner": 86.7% of participants affirmed GenAI's assistance, and 80% believed skills like problem decomposition and AI tool utilization would benefit real life, indicating potential for skill transfer.

Research limitations primarily stem from the small sample size (n = 15) and absence of a control group. Future studies should expand the sample size, establish a control group, and employ more rigorous experimental designs. Long-term tracking and analysis of in-game behavioral data are recommended to deepen understanding of this learning method's sustained effectiveness and underlying mechanisms.

Overall, this study preliminarily validates the potential of GenAI as an effective scaffolding tool and cognitive partner in gamified spatial learning. Furthermore, the study did not analyze behavioral patterns of student interactions to explore how scaffolding within games facilitates better learning (Bakeman & Gottman, 1997; Chan et al., 2023; Hou, 2015). Furthermore, given the limitations of technical equipment, students' gaming experiences may be constrained by hardware performance, which represents a future direction for game design adjustments and improvements.

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