Cubicle: An Adaptive Educational Gaming Platform for Training Spatial Visualization Skills

Ziang Xiao[1] **Helen Wauck**[1] **Zeya Peng**[2] **Hanfei Ren**[2] **Lei Zhang**[3]
Shiliang Zuo [4] **Yuqi Yao**[1] **Wai-Tat Fu**[1]
University of Illinois at Urbana-Champaign[1] Zhejiang University[2]
Shanghai Jiao Tong University[3] Tsinghua University[4]
{zxiao5,wauck2,yuqiyao2,wfu}@illinois.edu[1]
{zeyapeng,renhanfei}@zju.edu.cn[2]
rayne_@sjtu.edu.cn[3] zsl14@mails.tsinghua.edu.cn[4]

ABSTRACT
Research has demonstrated that spatial visualization skills are crucial for success in Science, technology, engineering, and mathematics (STEM) disciplines. With an increasing number of students entering STEM disciplines, the question of how to effectively train students' spatial visualization skills has become very important. While a scalable existing solution is to implement online workshops for students, the problem of how to motivate students to participate in these online workshops remains unsolved. In this study, we studied gamification as a way to motivate first year engineering students to take part in an online workshop designed to train their spatial visualization skills. Our game contains eight modules, each designed to train a different component of spatial visualization. The game records players' in-game behavior with high granularity, which allows us to provide automated, scalable feedback on players' problem-solving strategies. Ten students with different levels of spatial ability played our game and expressed a strong interest in using the game to train their spatial visualization skills in the future. In addition, our analysis of players' in-game behaviors shows the potential benefits of implementing adaptive and personalized learning guidance.

CCS Concepts
•**Applied computing** → **Interactive learning environments; Computer games;** *Computer-managed instruction;*
•**Computing methodologies** → **Spatial and physical reasoning;**

Author Keywords
Spatial Visualization Skills; Education; Video Games; Game Features; STEM; Player Behavior; Learning Analytics

INTRODUCTION
Established research has demonstrated that spatial visualization skills, which refer to the ability to understand the visual and spatial relationship among objects, are crucial to reasoning and solving complex problems in Science, technology, engineering, and mathematics (STEM) disciplines [19, 35, 36, 43, 47, 48].

With the increased number of students pouring into STEM disciplines, effectively evaluating and preparing students' spatial visualization skills for their future STEM coursework and careers has become a very important problem [12, 35, 36, 43, 47, 48]. An established solution is the use of scalable online training workshops [12, 47, 48]. Xiao et al built a scalable online platform for evaluating and training first year engineering students' spatial visualization skills [48]. They hosted a semester-long workshop for training spatial visualization skills. An evaluation with over 600 engineering students showed clear training effects and a strong potential for future deployment at a larger scale. However, the major problem they reported was low retention rate, as a lot of students quit in the middle of the workshop [48]. Therefore, a new method is needed to intrinsically motivate students to train their spatial visualization skills.

A popular way of providing intrinsic motivation is through gamification [8, 23, 25, 29, 44, 45]. Gamification can introduce higher levels of motivation and engagement than traditional instructional methods [8, 23, 25]. Instead of formal instruction, video game players learn through their actions and experiences in the game [26]. Video games allow self-directed learning via a trial-and-error approach. Meanwhile, when introducing new levels or game mechanics, video games provide tutorials and in-game assistance for players to facilitate the learning process. These properties of video games have great potential for increasing students motivation to learn [26, 31, 32]. Therefore, we gamified Xiao et al's online workshop into a scalable gaming platform, *Cubicle*. *Cubicle* aimed to motivate students to engage in effective spatial visualization skill training.

Cubicle is a modular educational gaming platform with multiple game modules. Such modular design allows for flexible game content and more generalizability. Although spatial visualization skills are critical for the STEM disciplines in general, different academic fields emphasize different aspects of these skills [35]. For example, mental rotation is more important for Organic Chemistry, where mental rotation is the key to visualizing and manipulating chemical modular structure, than for Mechanical Engineering, where visuliazing 3D object from 2D blue print is more important [35]. Flexible and expand-

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able game modules allow the platform to compose the most suitable learning materials for game players from different disciplines. Meanwhile, *Cubicle* also welcomes instructors to write their customized game modules and host them on our platform. Currently, *Cubicle* has eight game modules based on five major aspects of spatial visualization skills: 3D object visualization and manipulation, perspective taking, mental rotation, 2D to 3D transformation, and spatial memory.

Cubicle is designed not only to train players' spatial visualization skills, but also to help researchers or instructors acquire more insights into players' behavior and problem-solving strategies through the in-game player behavioral data [2, 13]. Our fine-grained in-game player behavior data collection allows for the possibility of implementing adaptive learning, personalized hints, error pattern analysis, and large-scale collaborative games. These learning analytic methods can give researchers and educators a better understanding of how people with different level of spatial visualization skills approach the problem and which problem-solving strategy best suits their skill level [2, 4, 6, 13].

We evaluated *Cubicle* with ten students from three entry-level STEM engineering graphics courses. The results of our evaluation showed that all eight modules on our game platform tap into players' spatial visualization skills. Feedback from student participants revealed high levels of interest and motivation to use our platform as a tool for training their spatial skills in the future. In addition, our gaming platform shows great potential for implementing learning analytics and adaptive learning at scale.

Our work provides three major contributions to the IUI community: First, we present an approach to build an intelligent educational gaming platform to train college students' spatial visualization skills. Second, we developed a gaming platform, *Cubicle*, based on this approach and evaluated it in an empirical study, demonstrating its potential as a motivational tool for spatial skill training. Third, we provide insights and design suggestions for future learning analytics features in educational games.

RELATED WORK

Spatial Visualization Skill Training

Due to the importance of spatial visualization skills, a lot of effort has been invested in training engineering student's spatial ability. Existed research shows the spatial visulizaton skills are malleable [35, 36, 40]. With proper training methods, people's spatial visulization skills can be improved signifciantly in several months [10, 15, 36, 48].The most well-known training material was developed by Sorby in 2011, and has been used at multiple universities [10, 15, 36, 48]. However, most workshops based on these materials were organized in a face-to-face classroom environment with less than 30 people. This approach is not scalable with the large number of students who need spatial skill training [48]. There are two major obstacles hindering the scaling of the workshop approach: 1) scheduling problems and 2) lack of resources. It is very difficult to schedule a time and location that can fit a large number of students' schedules. Also, teaching and grading requires considerable amount of work from the instructors and teaching assistants in a large class. To reduce the cost of scaling, researcher moved Sorby's workshop online and showed success [48]. Therefore, in *Cubicle*, we adapted the learning materials from Sorby with focus on five major aspects of the spatial visualization skills and considered the scalbility issue.

Increasing Learning Motivation through Video Games

As insufficient spatial ability is a barrier to success in STEM coursework, it is important to motivate students to train and improve their spatial ability [19, 35, 36, 43, 48]. Video games are one potential solution since gaming is fun and enjoyable to many people, and can intrinsically motivate players to engage [12, 16, 35, 36, 43]. Existing research suggests four main characteristics of games make them engaging educational tools: challenge, fantasy, complexity and control [16, 21]. Ideally, combining difficult game tasks, an attractive backgroud story, mutiple game modes and a free exploration map can acquire most interest from game players [21]. Thomas and Macredie mentioned that the key factor that draws players into a game is that their actions have no real world repercussions [39]. Without real world consequences, players will feel more encouraged to explore all potential solving strategies, which is key for effective learning, especially for those who don't have a clear direction to solve the game task.

In our game design, we incorporated those engaging features as well to make our game modules more motivational. The player needs to escape [control] from a dungeon maze [Fantasy] by solving multiple puzzles [challenge, complexity]. And players are free to keep trying to solve a puzzle repeatedly [no consequence for exploring the solution space].

Training Spatial Skills with Video Games

Using video games as a method for training spatial visualization skills has been investigated in recent years as well. Research on commercial games has shown that a wide variety of video games can train spatial visualization skills, such as Tetris, Zaxxon, Medal of Honor, Portal 2 and Super Mario [11, 14, 18, 33, 34, 38]. However, those commercial games usually only train a single aspect of spatial visualization and the content is not customizable. Wauck et al. looked into specific game features that may help improve spatial visualization skills and recommended two useful game features: 1) object rotation and 2) object alignment in 3D model construction [47]. Our designed game module specifically emphasized these features.

GAME PLATFORM DESIGN

We designed and developed an online game platform called *Cubicle* to incorporate features focused on training five aspects of spatial visualization: 3D object visualization and manipulation, perspective taking, mental rotation, 2D to 3D transformation, and spatial memory [35]. *Cubicle* contains eight modules: 1) Block Building, 2) Constructive Solid Geometry (CSG), 3) Plane Exploration, 4) View Point, 5) Transform Limitation, 6) Shape Revolving, 7) Cube Shift and 8) Flat Pattern (Table 1).

The premise of the game is that the player is trapped in a dungeon maze. To escape, the player needs to navigate through

Game Modules	*Target Spatial Skills*
Block Builder	3D Object Visualization & Manipulation 2D to 3D Transformation
Constructive Solid Geometry	3D Object visualization & manipulation Perspective Taking
View Point	Perspective Taking 2D to 3D transformation
Transform Limitation	Mental Rotation Perspective Taking 3D Object Visualization & Manipulation
Shape Revolving	Perspective Taking 2D to 3D transformation
Plane Exploration	3D object visualization & manipulation Perspective Taking
Cube Shift	Spatial Memory
Flat Pattern	Perspective Taking 2D to 3D transformation

Table 1: The eight game modules in *Cubicle* and their corresponding target spatial visualization skill(s)

the maze and unlock all the rooms. The player starts from a large center room with multiple smaller adjoining rooms. Each smaller room contains a totem, the entry to a game module. In each game module, a chain of locked rooms contains different levels in that game module. Finishing the game task in the room is the only way to unlock the door to the next room.

Game Module Design

Block Builder

The Block Builder is aimed at training the player's ability to mentally construct a 3D model from orthographic drawings (Figure 1b). We designed this module to improve the player's ability to visualize 3D objects through the process of transforming orthographic drawings into 3D models [36].

In this game, the target 3D block model is algorithmically generated for each level. The player is shown orthographic views of the target block model and asked to build the model on the 3×3 grid empty base by adding or deleting cubes. The interface also shows the 3-views of the current model next to the 3-views of the target model.The game will automatically end once all views match. The level of difficulty is controlled by the complexity of the generated 3D block model.

The interface strictly follows the rule of orthographic drawings in engineering graphics, with the front view at the bottom left, the top view at the top left, and the side view at the bottom right.

Constructive Solid Geometry

The Constructive Solid Geometry game is aimed at training player's ability to visualize 3D objects and manipulate them (Figure 1c) [28]. The main goal of the game is to construct a 3D object by performing Boolean operations, including Union, Intersection and Subtraction, on existing 3D objects. The player needs to mentally visualize what an operation would do to objects to complete this task [36].

In this game, the player is given several primitive objects (e.g., cube, cuboid, sphere, cylinder) and a complex target object generated by the primitive objects with Boolean operations. The player will perform a series of Boolean operations to create the complex target object. To emphasize the importance of mental visualization, the player is not allowed to undo any operation. As soon as the player makes a mistake, they lose the game and must reset to start over. Once the player believes their object matches the target object, they can check the result by submitting the object to the system for evaluation. The difficulty level increases with the increment number of operations needed to build the target model.

View Point

The View Point game aims to train the ability to imagine different perspectives or orientations in space, an important component in the spatial visualization skill sets (Figure 1d) [36]. The player is asked to mentally visualize a three-dimensional landscape from a two-dimensional map and determine the observation point that is being displayed. Mental rotation is needed to correctly visualize the scenes.

In the game, a variety of solid shapes are randomly generated on a circular base, with a camera randomly chosen from eight candidates, each with a different position and angle. All candidate cameras face the center of the base. The player needs to determine where the camera is based on the view of the chosen camera and the top view of the scene. The number of solids on the circular base increases with the game's difficulty.

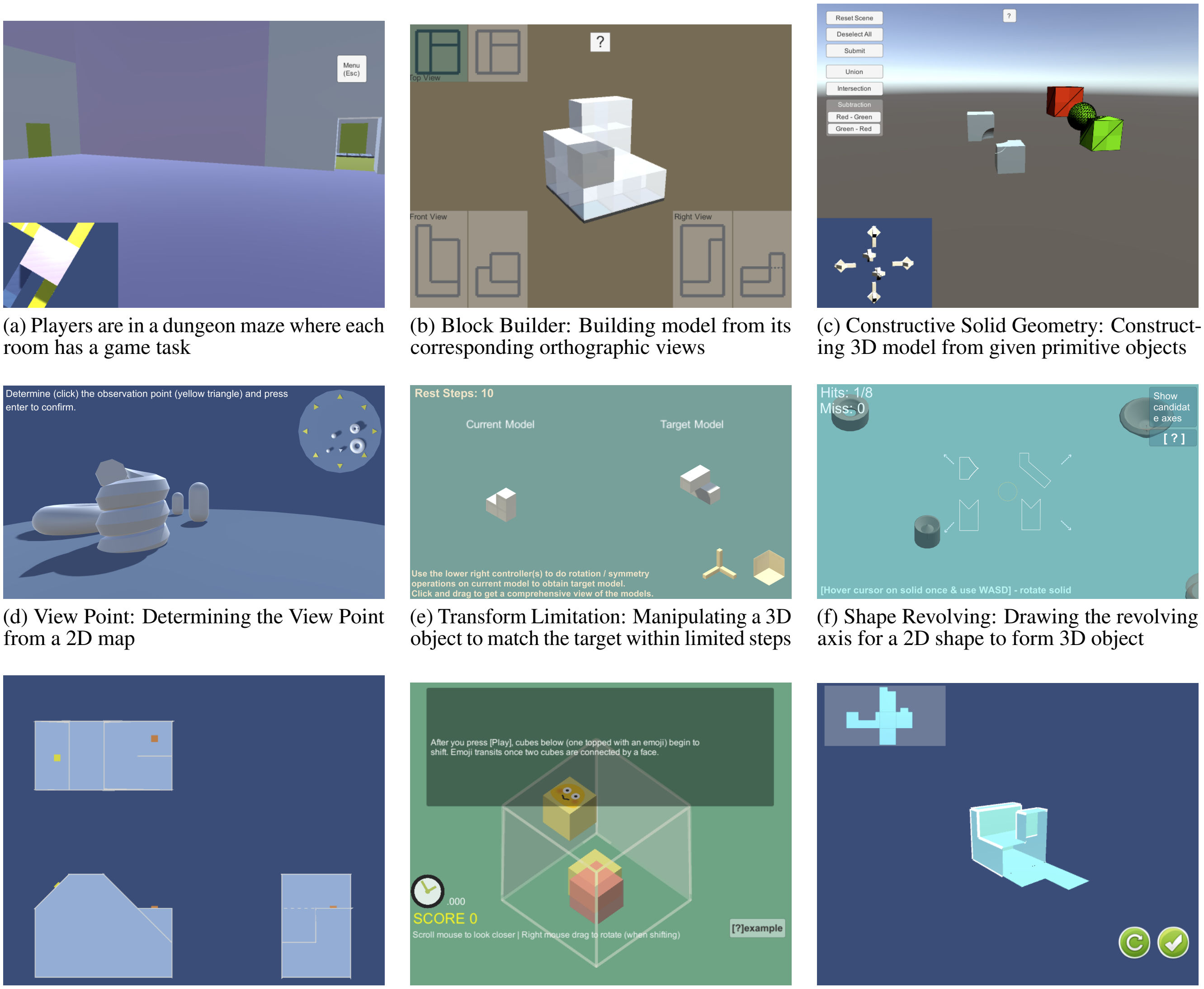
Transform Limitation

The Transform Limitation game taps into the player's mental rotation ability (Figure 1e). In this game, the player is asked to rotate or mirror a 3D object to match a target object within a limited number of steps. In each step, the player either rotates the object 90 degrees about an axis, or mirrors the object once. Since the number of steps is limited, the player needs to mentally rotate and visualize the result before taking an action. The difficulty of the game progresses as the number of operations required increases and the number of operations allowed decreases.

Shape Revolving

The Shaping Revolving game emphasizes 2D to 3D transformation (Figure 1f). The game aims to improve players' understanding of surfaces and solids from revolution. The player needs to envision the relationship between 3D objects and 2D shapes, mentally revolve a 2D shape about an axis, and visualize the created 3D model [36, 48].

In this game, the player is shown a 2D shape as well as a 3D object. Like the section "Rotation of Objects about Axes" in Sorby's book, the goal is to identify which axis the 2D



(a) Players are in a dungeon maze where each room has a game task

(b) Block Builder: Building model from its corresponding orthographic views

(c) Constructive Solid Geometry: Constructing 3D model from given primitive objects

(d) View Point: Determining the View Point from a 2D map

(e) Transform Limitation: Manipulating a 3D object to match the target within limited steps

(f) Shape Revolving: Drawing the revolving axis for a 2D shape to form 3D object

(g) Plane Exploration: Navigating on a 3D landscape with only orthographic views of the landscape

(h) Cube Shift: Keeping track of a series of cube shifting and idenfying the missing emoji

(i) Flat Pattern: Unfolding a 3D object to a target 2D pattern

Figure 1: Screenshots from the *Cubicle*. [a], The dungeon maze connects access eight game modules; [b - i], the screenshots from each game module

shape revolved around to generate the 3D model [36]. An advanced level of this game shows 4 pairs of shapes and objects simultaneously (Figure 1f). Over the course of the game, objects move gradually towards the center of the screen. The player needs to draw 8 correct axes to unlock the next level. If the player fails to draw the revolution axis before the object reaches the center, the object will disappear and one miss will be recorded. If the player missed more than 8 2D shapes, the counter for the correct answers will be reset to zero. Thus, the player must respond as fast as possible. The player completes a level once the number of successful attempts reaches a certain threshold. The game becomes steadily more difficult as the objects become more complex and their movement speed increases.

Plane Exploration

The Plane Exploration game is designed to train 3D object visualization and perspective taking (Figure 1g). Similar to "Orthographic Drawings" in Sorby's book, the player needs to understand standard orthographic drawings and mentally visualize the corresponding 3D model in order to win [36].

In this game, the player's goal is to guide a yellow square across a 3D landscape model to an orange square, with only orthographic views available. The game allows the player to climb upward or down via ramps but not stairs, so it is critical for the player to mentally visualize the 3D landscape before deciding which way to go. If the yellow square falls through a stair, the game is over.The difficulty of each level is controlled by the complexity of the 3D landscape model.

The 3D landscape models in the game come from existing spatial visualization training material, which follows the display rule of orthographic drawings in engineering graphics as well. A player's performance is measured by how long it takes for the player to reach the orange square and how many failed attempts are made.

Cube Shift

The Cube Shift game is designed to focus on spatial memory, which taps into two strong indicators of spatial abilities: working memory span and short-term memory [36] (Figure 1h). Cube Shift requires players to direct their attention to the image on a series of cubes while avoiding the distraction of their shifting movements. At the same time, players must also remember previous configurations of the cubes. The game design resembles the n-back tasks by Wayne Kirchner, where the subject is presented with a sequence of stimuli, and the task consists of indicating when the current stimulus matches the one from n steps earlier in the sequence [24]. It also resembles the Dot Memory task [22], a test of short-term memory, where the subject briefly views a 2D grid with dots shown in sequence inside of it. After the dots disappear, the subject indicates the dot locations in an answer grid.

In this game, the player sees a 3D grid with 3 (or more) cubes that shift position a specified number of times. There is an emoji on one of the cubes, which moves between cubes whenever two cubes' faces touch. Once the sequence of shifts ends, the emoji will disappear. The subject is asked to find where the emoji last appeared n steps earlier in the shift sequence. Different levels of game manipulate the factor n, the number of cubes, and the number of shifting steps to vary the difficulty level. The player wins once they successfully find the emoji five times and loses if they make more than eight mistakes.

Flat Pattern

The Flat Pattern aims to enhance students' capabilities of establishing the corresponding relationship between a 3D model and the unfolded 2D pattern (Figure 1i). This requires the ability of 2D to 3D transformation and perspective taking [36, 48]. During the gameplay, the player is expected to envision the spatial relationship between faces on a 3D model.

In this game, the player is shown a 2D flat target pattern and a corresponding 3D model. The player can cut an edge to unbind the two faces that it connects, then unfold the whole model progressively. The goal is to unfold the 3D model and make it the same pattern as the 2D target pattern. The player is only allowed to undo one edge cutting; otherwise, the level needs to be reset.

Different levels are designed based on the complexity of the 3D model and the number of hints to help the students acquire the related visuospatial skills gradually. At first, hints are given by displaying icons on certain faces to help the player establish the correspondence between the 3D model and the 2D pattern. As the difficulty increases, players must establish the relationship on their own with fewer hints and more complicated models.

Modular Game Platform Design and Fine-grained Data Collection

The game platform is designed modularly, allowing for flexible content. Game modules can be added or removed easily by communicating through documented APIs. The map of the dungeon maze can be modified through a single JSON file. The game platform collects player's in-game behavior in detail, which allows for the possibility of implementing adaptive learning. The completion time for each attempt is recorded for all levels of each game. Meanwhile, in-game behaviors are logged in great detail. Every single click, action, move is recorded. Using this data, the system can infer a player's problem-solving strategy and react by adjusting game difficultly or repeating failed challenges.

METHOD

To test our game platform in the field and validate our research hypotheses, we conducted a mixed-method study, in-game behavior analysis and qualitative interview, with participants from three entry-level engineering graphics courses at a large public university. All courses focus on the various aspects of engineering drawings where the spatial visualization skills are strongly emphasized.

Iterative Design & Development Process

Before the formal evaluation, we iteratively modified and improved our design. In an eight-week period, our team met with a group of testers weekly. With their valuable feedback, we adjusted the difficulty level for each game module and implemented a detailed tutorial system.

Participants

We sent out study invitations for a spatial visualization training game via email to students in three entry-level engineering graphics courses. All three courses share two learning goals: 1) to gain familiarity with the standards and conventions of engineering design graphics and 2) to gain exposure to computer aided design techniques. 10 students agreed to join our study. Five were male and five were female, and all had Freshman standing within an engineering major. Participants were compensated with 15 dollars for their participation at the end of the study.

Procedure

Before participants started the game, we tested their spatial visualization skills using the Revised Purdue Spatial Relations Test (PSVT:R) [49]. The PSVT:R test is widely used in assessing college students' spatial visualization skills [47, 48, 49]. The PSVT:R consists of 30 questions in order of increasing difficulty with a 20-minute time limit [49].

After participants finished taking the PSVT:R, research assistants installed the game on the participant's computers and went through the tutorial of each game module with them to make sure they understood the game objective and the basic controls. After that, participants were asked to play the game over a 3 days period and try to complete as many levels as possible. We estimated that it would take participants about 1.5 hours to complete the entire game. Considering participants' schedule, we believed 3 days was more than enough time for everyone to complete as much of the game as they could. At the end of game-playing period, research assistants collected in-game player behavior data through a network protocol. After finishing the gameplay session, participants completed a post-game survey in which they rated how fun, boring, easy, and frustrating they found the game and their opinion about the gaming platform overall.

In-Game Player Behavior Metrics

We collected a large amount of player behavior data from our participants. Data collected for each player focused primarily on three major aspects: 1) Game Progress, 2) Completion Time, and 3) Error Rate. Each of these player behaviors help us understand how players' spatial visualization skills are associated with game difficulty, and different types of player strategies. An explanation of the metrics follows below.

Game progress. For each game module, a player's Game Progress is the percentage of levels they completed. For the overall game, the game progress is the average game progress of all eight modules.

Average Level-completion Time. Average Level-completion Time measures the time in seconds taken to complete each level. For each game module, the player's completion time is the averaged across all levels in that game module. For the overall game, the completion time is the average level-completion time of all eight modules. If the player did not successfully complete a level, the time they spend in failure attempt did not count.

Average Error Rate. The Error Rate measures how many failed attempts (resets) a player made before they successfully completed a level. Due to the difference in game mechanics across the eight modules, error rate is calculated differently for each of them:

- *Block Builder*. In this game module, the Error Rate is calculated by dividing the number of incorrect addition/deletion actions by the total number of addition/deletion actions. An incorrect addition is defined by as adding a block that is not a part of the correct model. Meanwhile, an incorrect deletion action is defined as removing a correctly added block.

- *Constructive Solid Geometry / Flat Pattern*. In the Constructive Solid Geometry (CSG) and Flat Pattern game, the Error Rate is defined by the percentage of failed submissions out of all submission attempts. "Failed submissions" here counts both the number of failed submissions and how many times the player reset the scene.

- *Plane Exploration/ View Point / Transform Limitation/Shape Revolving/ Cube Shift*. The Error Rate in these game modules is the percentage of failed attempts out of total attempts.

For each game module, the player's Average Error Rate is the average Error Rate of all completed levels. The overall game's Average Error Rate is the mean of all eight modules' Average Error Rate.

Post-Game Survey

In addition to in-game player behavior data, we are also interested in what players thought of our game and whether they are motivated to use our gaming platform as a training tool after trying it out. We had players fill out a post-game survey rating their game experience on a 1-5 Likert scale (1 not at all to 5 very much) on the following measures:

Perception of the Game Platform. The Game Perception measure contained 4 items asking how easy, boring, frustrating, and fun the game was.

Willingness To Use the Game Platform. This measure contained 2 items asking players how they liked our game overall and whether they wanted to use our game as a tool to develop their spatial visualization skills in the future.

We also asked the participants to leave any comments or suggestions in a text box.

Hypotheses

We had the following three hypotheses for this user study.

H1: Players' existing spatial visualization skills will be correlated with their in-game behavior metrics. More specifically, players with lower level of spatial visualization skills will spend more time to complete a level and make more errors.

H2: Players with higher spatial visualization skills will explore and complete more game levels than players with lower spatial visualization skills.

H3: Players will be intrinsically motivated to use our platform to train their spatial visualization skills.

RESULT

The focus of our analysis was to determine if players' spatial visualization skills were associated with their in-game player behaviors and number of completed levels, and to assess player's impressions of our game platform. We performed a hierarchical two-stage correlation analysis, starting with the aggregate in-game player behavior metrics for the game as a whole and then looking into the in-game player behavior metrics for each game module.

Spatial Visualization Skills

Participants' average PSVT:R score was 19.8 out of 30 (SD=7.8) which is similar to previous findings in a large scale assessment of college students using the PSVT:R [20]. From the distribution of PSVT:R scores, we can see players' spatial visualization skills range from 8 to 30 and are not skewed to either direction. Consistent with previous research [3,20,47], we found a significant gender difference in test scores, with males (M=24.6, SD = 6.1) scoring higher than females (M=15.0, SD = 6.4); $t = 2.41$, $p < 0.05$.

Spatial Visualization Skills and Average Game Completion Time

The time spent on each level is a good indicator of how challenging the level is to the player. We looked into the relationship between players' spatial visualization skills and how much time they used to complete each level on average. There

In-Game Player Behavior Metrics	*Mean*	*SD*	*Correlation w/ PSVT:R Score*
Block Builder			
Average Level-completion Time (in seconds)	116.8	93.48	$-.97^{**}$
Error Rate	0.27	0.12	$-.87^{**}$
Constructive Solid Geometry			
Average Level-completion Time (in seconds)	61.24	32.59	$-.95^{**}$
Error Rate	0.50	0.20	$-.91^{**}$
View Point			
Average Level-completion Time (in seconds)	32.87	32.00	$-.94^{**}$
Error Rate	0.35	0.31	$-.89^{**}$
Transform Limitation			
Average Level-completion Time (in seconds)	33.49	21.08	$-.65^{**}$
Error Rate	0.31	0.14	$-.67^{**}$
Shape Revolving			
Average Level-completion Time (in seconds)	28.88	16.95	$-.51^{**}$
Error Rate	0.55	0.14	$-.91^{**}$
Plane Exploration			
Average Level-completion Time (in seconds)	32.19	32.83	$-.65^{**}$
Error Rate	0.46	0.24	$-.91^{**}$
Cube Shift			
Average Level-completion Time (in seconds)	9.06	2.15	$-.87^{**}$
Error Rate	0.12	0.11	$-.40^{**}$
Flat Pattern			
Average Level-completion Time (in seconds)	185.37	82.87	$-.97^{**}$
Error Rate	0.64	0.20	$-.96^{**}$

Table 2: Pearson's correlation between player's spatial visualization skills (PSVT:R Score) and in-game player behavior metrics for each game module. *Note. ** indicates p < .01.*

was a significant strong negative correlation between players' PSVT:R scores and Average Level-completion Time (M = 72, SD = 36), r = -0.94, n = 10, p < .01. The correlation holds for all eight game modules as well (Table 2).

This result suggests that players who have higher spatial visualization skills spent less time completing each level, which supports our hypothesis that our gaming platform utilizes player's spatial visualization skills. The result also aligned with established research that when solving spatial tasks, players who are lower at spatial visualization skills take more time to mentally visualize potential solution and to find the correct problem-solving strategy [37, 41, 42]. However, the time used in solving such question indicates potential learning effects [7]. Therefore, players with lower spatial visualization skills may benefit from the time they spent in solving those questions.

Spatial Visualization Skills and Error Rate

Next, we analyzed players' game actions. We expect that players with lower levels of spatial visualization skills made more mistakes, as the game is designed to train spatial visualization skills. Person's correlation test revealed that spatial visualization skill was negatively correlated with Average Error Rate(M = 0.36, SD = 0.13),r = -.97, n = 10, p < .01). Players with lower spatial visualization ability made more mistakes than those with higher spatial ability. This relationship also holds for all eight modules (Table 2).

Without a clear solving strategy, players with lower spatial visualization explore multiple potential strategies and experience more failure attempts [37]. Learning often happens in the process of exploring potential strategies. When players experience multiple failures, they either learn from the failure or give up. Our analysis on game progress shows no significant correlation between players' spatial visualization skills and their game progress which indicates that players with lower spatial visualization skills eventually acquire the strategy that leads them in the right direction.

Spatial Visualization Skills and Game Progress

We analyzed the relationship between players' spatial visualization skills and the percentage of game they completed. The average Game Progress was 85.6 % (SD = 9.1%). Pearson's correlation test revealed a positive but not significant correlation between player's PSVT:R score and the Game Progress, r = 0.58, n = 10, p > .05. The result did not support our hypothesis that players with lower spatial visualization skills will complete less game content than others.

Players' Impressions of the Game

We collected player's opinions in the post-game survey immediately after they finished playing the game. Overall, player's impressions were positive. Most of the participants found our gaming platform is interesting and moderately fun to play (M = 3.3, SD = 0.5). As two of our participants explained:

> *"There are many interesting types of spatial visualization and memory that I hadn't really used before. I'm not sure how much my skills have improved, but it was fun to complete the puzzles!"* (P1)

and

> *"I really enjoyed it! There [are] a ton of cool training tools there"* (P2)

Being fun and enjoyable is the key indicator of a good game. Our goal with *Cubicle* was to combine effective spatial skill training exercises with the entertaining aspects of traditional video games. We believe, therefore, that our game can attract and motivate students to voluntarily use our platform as a tool for training spatial visualization skills.

We also asked our players how much they liked our platform in general and whether they would want to use it in the future as a training tool. Most participants reported liking our platform (M = 3.5, SD = 0.5) and wanted to use it in the future (M = 3.8, SD = 1.1) (5-point Likert Scale). After analyzing their comments further, we found that players who had lower levels of spatial visualization skills (PSVT:R score lower than 18, N = 5) all expressed strong interests in training their spatial visualization skills via our platform (M = 4.2, SD = 0.8). For example, some players said,

> *"I think overall it is useful for helping to understand visual and spatial organization, and I'm glad to have this experience to learn what I'm good and not good at."*(P3)

and

> *"I wish there were more levels to improve my spatial visualization skills."*(P4)

Through our players' impression, we can see a great potential for the gaming platform to be deployed on a larger scale.

DISCUSSION

Our results indicate that our gaming platform, *Cubicle*, tapped into players' spatial visualization skills, supporting our hypothesis **H1**. We found that players with lower spatial visualization skills tend to spend more time on each level of the game and make more errors. In addition, participants exhibited a high level of willingness and enthusiasm to use Cubicle for future training, especially those with lower level of spatial ability, supporting our hypothesis **H3**.

However, our **H2** is not supported by the result that players' spatial visualization skills does not predict how many game levels they complete. Game progress can be used to infer how engaging players find our game [27]. The game allows players to make an unlimited number of attempts on each level, and we give our participants more than enough time to play the game. Therefore, as long as players are engaged in our game, they will achieve a similar level of game progress.Thus, one way to interpret this result is players were equally engaged in our game regardless of their existed spatial visualization skills.

Although the *Cubicle* has the feature that supports learning analytics, our analysis did not reveal any clear error patterns for players with different levels of spatial visualization skills. Our small sample size is a likely cause; learning analytics requires large scale data collection. However, our evaluation results suggest a bright future for our platform once deployed on a large scale.

Future Directions and Development

Our study demonstrated the potential of our gaming platform, *Cubicle*, as a tool for training college students' spatial visualization skills at scale. The design of the platform allows fine-grained in-game player behavior collection which creates the possibility of multiple learning analytics. We envision the following future directions.

Data-Driven Adaptive Learning Trajectory

A data-driven method can be implemented to achieve adaptive learning trajectories. Adaptive learning has been researched in different contexts and has been shown to promote learning [5, 17]. However, hindering implementation of adaptive learning at large scale is the problem of how to automatically detect the student's current learning progress and what the next step should be. With the in-game behavior data collected in our platform, a learning model could be built for each player by comparing their problem-solving strategy with those of past players. For example, based on a player's in-game behaviors, the system can infer their level of spatial visualization skills and provide the most effective materials for players with the a similar level of spatial ability. As the player progresses in the game, the storyline and game modules can evolve to give the player the most effective gaming content for their skill level.

The player's problem-solving strategy can also be captured by the platform, which can analyze the player's strategy to provide personalized guidance. For example, the system can help a player who exhibits incapability in mental rotation by analyzing which specific part of the problem-solving strategy (e.g. using the wrong reference point while rotating the subject) is the issue and guide the player to the best strategy found by previous players.

Hint systems are prevalent in all kinds of games and are designed to adjust the game difficulty for individual users [46]. A good hint system could reduce a player's frustration and increase their engagement [9, 46]. In an educational game, the hint system can be designed as an instruction system that helps players learn more efficiently. The design of our game platform allows for the possibility of personalized hints. With sufficient in-game player data, our system can classify player mistakes into different categories and generate hints accordingly. If the player is stuck in the middle of a game, hints can be provided automatically and adaptively, which will help the user to gain a deeper understanding of the best problem-solving strategies and increase learning efficiency.

Comprehensive Feedback System

People learn from the feedback they receive from a game. A good feedback system can provide the player with more useful information beyond merely telling them whether what they did was right or wrong. It is even better if the feedback not only tells the player what they did wrong but also provides information on how to solve the problem. In our game platform, all in-game behavior data was stored in a large database that allows knowledge discovery. Future work could enable a comprehensive feedback system that deconstructs a player's performance and problem-solving strategies and provides a comparison with other players. With such a feedback system, the player could gain more insight about how to solve such problems in the future.

Large Scale Collaborative Game Module

Large scale collaborative learning has been examined in multiple studies as an effective way to increase player engagement and create a better learning environment [1, 30]. Our gaming platform was built using the Unity game engine, which allows us to compile it as a WebGL application. Hosting it on web allows players all over the world to use our platform to train their visualization skills. Meanwhile, with more players' in-game behavior data, our platform can better engage those learning analytic methods we mentioned above.

Because of its modular design, *Cubicle* can add more game modules designed for collaborative learning. For example, we can extend the Block Building module to allow players to collaborate and build together. This would allow players to learn from each other. With such large-scale collaborative features, we believe our future platform can benefit a wider range of audiences and promote more effective learning.

Limitations

Our current study has several limitations. First, although all current gaming modules were adapted from an existing spatial visualization workshop, we have not yet tested whether the training effects of the workshop was preserved. In addition, training spatial visualization skills is a long-term process that our short evaluation in this study could not capture. Therefore, we plan to deploy our gaming platform with more content in the future within an actual classroom environment and examine its training effectiveness. Lastly, players found several bugs while playing the game in our study. Although we fixed them as soon as possible, they may have negatively impacted players' engagement with the game.

Conclusion

Certain in-class or online workshops have been empirically shown to train spatial visualization, a set of cognitive skills tightly linked to future success in STEM disciplines. However, current methods of training students' spatial visualization skills face two main problems : scalability and engagement. In this study, we gamified an existing online platform and created a modular educational gaming platform, *Cubicle*, to train players spatial visualization skills while addressing the problems of scalability and motivation. A user study of 10 participants with varied level of spatial ability showed a strong correlation between performance in *Cubicle* game modules and players' existing spatial skills. Players reported a strong willingness and motivation to keep using our platform as a tool of training spatial visualization skills in the future. In addition, our platform is capable of implementing intelligent learning features, such as data-driven adaptive learning trajectories, a comprehensive feedback system, and large scale collaborative game modules. Therefore, we believe *Cubicle* is a great educational gaming platform with bright future potential for helping students to engage spatial visualization skills training and prepare them for STEM coursework and future careers.

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