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Geometry Wall: An Embodied Gesture-based Game for Supporting Spatial Ability

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***Abstract*—Research has shown that interaction design based on embodied cognition has a significant effect on the understanding of abstract concepts. Spatial ability as one of the core literacies in mathematics education can be difficult to train. On this basis, we have designed and developed a gesture-based spatial skills game training system, which allows students to manipulate objects synchronously with gestures to complete game tasks, thereby practicing spatial skills. We then invited 20 students to conduct a pre-experiment and recorded the changes in spatial ability, operational data during the learning process, and the acceptance of the technology through questionnaires and system logs. The results showed significant improvements in all dimensions of spatial ability through this game training system, with two processual characteristic sequences reflecting the status of problem-solving strategies used by participants with different styles. In the technology acceptance survey, there were some issues with ease of use, but overall satisfaction with the game system as a whole was high.**

Keywords—spatial ability, embodied cognition, interaction design, game-based learning, virtual environment.

I. Introduction

Much empirical evidence has strongly proven that training spatial ability can improve efficiently students' mathematical performance [1]. Spatial skill as an essential part of physical and mental development has been explored further. Recently with the influence of embodied cognition increasingly popular, we are more interested in how bodily motion by motor and sensory systems shape our mind unconsciously. In the process of embodied interaction grounded in embodied cognition theory, suitable physical gesture representation can positively project more understandable cognitive schemas to cope with complicated tasks.

But noticeably, In many current projects that use embodied cognition for spatial skills training, there are obvious gaps in the connection between spatial thinking skills and bodily representations. For example, in Lee-Cultura's core interaction design, the actions are only superficially related to the task and the student's internal cognitive processing during problem-solving [2], which is still not connected to the interactive actions indeed. Thus our concentration is not only limited to concrete operational movement but is required to relate to abstract cognitive symbols [3]. Namely, the design of gestures ought to be in coordination with implications extracted from the relation between content and body. Or the more amount of integrated gestures without correspondences, the more overloaded our brains suffer. Conversely, it might impede learners' cognitive processing.

In addition, the design of spatial skills systems based on embodied theory is mostly presented as intuitive spatial geometry tasks, without much modification in the design of task contexts and task requirements. The spatial thinking skills, which are known for their abstraction, may be more effective in contextualized learning [4].

Therefore, based on the two critical problems above, we designed a spatial skills training system based on game-based learning and embodied theory. Importantly, we especially emphasize the consistency between gestures display and core operation commands beneficial to absorption and internalization of cognition of spatial skills. Our game's task points are more abstract and comprehensive spatial skills instead of simple object recognition or judgment. Besides, we integrated some game-based learning strategies and a cute pedagogical agent with the whole game content, which makes spatial ability training more enjoyable and interactive.

Overall, the system is to explore the critical issue of how action representation and internal cognitive processing are connected in spatial ability training and incorporates gamification mechanisms to help achieve better learning outcomes.

II. Related Work

Spatial ability is the embodiment of cognitive skills in the interaction between human beings and the environment [5], which is significantly embodied in many disciplines. According to Lohman [6], there were three main spatial factors: spatial visualization, spatial orientation, and speeded rotation. Embodied cognition emphasizes the co-development of mind and body in terms of the mechanics of cognitive processing during learning. Among these interpretations of embodied cognition theory, R. A. Wilson and Foglia thought the features of the physical body play a fundamental role in cognitive processing [7], namely the job of solving problems is not processed by the brain solely. But the consequent question is how our body influences our brain. Keehner et.al. indicated that some sort of construction of

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explaining cognitive problems is relevant to our bodily properties [8]. Our brain will work out cognitive processing with the aid of the nature of the body. The different property of embodies cognition theory has widely applied to various domains. The field of education technology mainly probes into how to simplify cognitive thinking by our body when surrounded by a digital and immersive environment. Interaction design based on embodied theory emphasizes the interaction between the brain and the body, while spatial skills include the acquisition and utilization of elements of the spatial environment. The application of embodied interaction in spatial ability had a great promotion effect on the cognitive management of abstract concepts [9].

In the interaction design based on embodiment theory, Johnson-Glenberg, M. C et, al. emphasizes three key factors in judging the level of embodied learning: the amount of motoric engagement, gestural congruency, and immersion. Among them, gesture coherence emphasizes the need for gesture design in embodied activities to be closely related to the current learning content in the form of concrete learning structures[10].

In the current study, the relationship between the physical representation of the action and the trained thinking ability is generally ignored in the design of the interaction, e.g., in Lee-Cultura's use of a motion-based game to train students' spatial abilities, the gestures were designed to simply match the affiliation [2], and the matching was only the final decision-making stage in the problem-solving process. The most valuable cognitive processing of thinking ability was not much tied to the gestures involved. Therefore, it is crucial to address the issue of consistency between physical representations and learning content in the game design process.

III. GAME DESIGN

A. Overall Design

Geometry Wall is an educational game combining gesture-based interaction with game-based learning strategies for training spatial skills. Besides, an interactive agent serves the role of tutoring, monitoring, and accompanying during the whole play. The primary goal of this geometry-filling game is to select and rotate virtual objects according to the targeted shape of the incomplete wall. Rotational hand gestures could effectively contribute to the exchange of spatial thinking between realities in spatial skills training [11], so we implemented gestures as a kind of embodied tool that enables learners to interact with virtual objects. Significantly, we elaborated the game design precisely based on the instruction from mapping between game features and spatial abilities [12] in Table I. Specifically, participants need to perform mental rotation spatial processing when rotating objects at different angles, reflecting spatial visualization in the mapping of different spatial dimensions, and feeling spatial perception in being stimulated by various spatial objects with different depths of field and angles in the environment. Additionally, we added another new but critical dimension "Spatial Updating" of spatial abilities [13].

To achieve the goal of every filling task, players should first be familiar with the basic gestural operation and game mechanics by completing the tutorial part. Then the formal training spatial skills module just kicked off. Once the game started, players need to choose one suitable geometry according to the shape of the moving wall. Subsequently rotating this geometry by four directional gestures until making sure the current object's parallel projection was matching with the missing part of the wall. Of course, we offered reselecting mechanics if players would want to exchange another geometry among alternative objects when they found the current object was impossible to rotate expecting angle. Within certain time limits, completing correctly would receive congratulatory feedback or else frustrating feedback. Furthermore, an animated learning agent called " Tuan Tuan" would offer instruction guidance, emotional support, and learning monitoring throughout the whole play.

TABLE I. SPATIAL ABILITIES AND CORRESPONDING GAME FEATURES

Spatial Abilities	Game Features
Mental Rotation	Object Rotation (Gesture-based Rotation for Selected Geometry)
Spatial Visualization	2D to 3D Projection, 3D to 2D Projection (Reasoning Right 3D Geometry from 2D Shape of the Wall / Reasoning Right 2D Projection from Different Angles of 3D Geometry)
Spatial Perception	Spatial Characteristic (Characteristics of Every Observed Geometry / Position Perception to the Moving Wall Forward)
Location Matching	Shape Matching (Filling the Missing Part of the Wall)
Spatial Updating	Trial and Error (Reselecting Other Geometry after Failing to Rotate)

Through the functionally dividing of the game modules, this part mainly introduces design thought of the several modules of the framework, including gesture-based interaction design, learning assistant interaction design, and game-based learning strategies design.

B. Specific Design

As a type of embodied educational game based on gesture interaction, hand gesture design undoubtedly determines whether cognitive information processing during playing can promote the realization of assimilation and accommodation of spatial thinking or not. Therefore, we proposed a set of design principles to instruct our gesture design, including simplicity, congruency, and sensitivity. Simplicity refers to avoiding increasing extraneous cognitive load before processing a game task. The design of gestures reasons to be easily memorized and less redundant. Congruency is the precondition that the intention of gesture design must have a high connection with induced feedback displayed from the virtual environment. For example, drawing the route in the mid-air with a finger is much better than directly pointing the finger to the destination when executing a task moving from start point to end. Considering the limited affordance of Leap Motion inherently, the sensitivity of gestural implementation needs to be taken into consideration. Terrible user experience easily leads to evoke negative feelings like boredom and irritability. Here's a specific gesture design based on listed key principles in our game playing as follows.

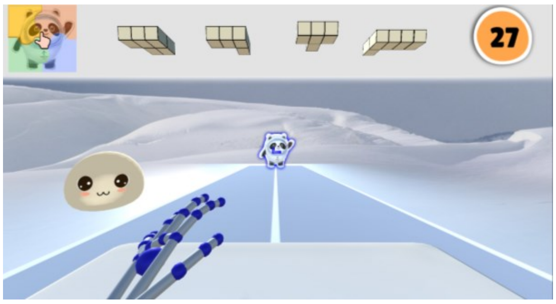

Fig. 1. First Round: Select the right object from above to the platform by gesture, rotate it to the right Angle, and check (at the beginning of the game)

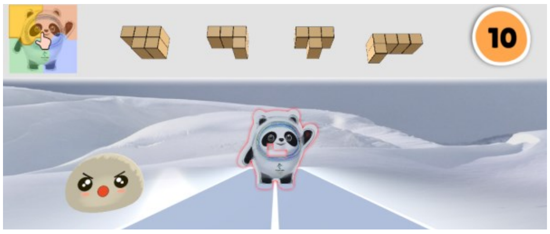

Fig. 2. First Round: Select the right object from above to the platform by gesture, rotate it to the right Angle, and check (time almost ran out)

1) Gesture of Selecting Object

The first session of playing is to choose a suitable object among four rotating geometries by observing the missing shape of the wall before time runs out. Four geometries are placed in a row above the virtual spatial environment at the beginning of the game and every one of them is in autorotation to easily get an overall perspective to players. Based on alternative object placements and users' motion preferences, We designed a gesture to indicate the object selection by moving the right hand to the left or the right. The gesture that moves left and right is in good accordance with simulating the virtual condition of selecting objects from left to right. Players can raise their right hand in front of the screen where the Leap Motion device was placed. They can only move their right hands to the left or right within range of what we predefined and they will stay at the edge of the screen if the hand position is out of range. To clearly and rapidly locate the position in which their hands are, a tiny hand icon will move as hands move. It seems like a kind of indicator to help players to identify the positional relationship between the virtual world and the real physical environment.

2) Gesture of Confirming or Reselecting Object

During the process of selecting a suitable object, the corresponding geometry will glow red with external contours as soon as the ray given off by the moving hand meets the certain object. According to the missing shape of the wall, players will choose considered answers by moving their hands. While the geometry they're expected to choose is in a state of glowing red, we designed a gesture to indicate object confirmation by griping the right-hand fist. Wu et al. [14] suggested that the gesture of opening a hand into a fist could well represent grabbing the imagined clothes in an immersive VR shopping environment. It indicated a sense of making sure of dragging the object I wanted to target place. Similarly, our targeting behavior is a kind of ascertaining way of placing selected objects on the operation platform. Thus, gripping the right hand is a simple and accurate way of gesture design for confirming an object. On the other hand, when players confronting with supposing to exchange another object during several failures of rotating the current object, we exactly designed an opposite gesture to indicate the object's reselection by griping the left-hand fist. This is not a behavior about object operation but a switch between two different game formats (regain the state of selecting the object), so it doesn't entail any learning implication.

3) Gesture of Rotating Object

When it comes to gestures of rotating an object or operationalization of mental rotation, most of the studies based on Leap Motion generally tended to twist the hand to indicate object rotation. However, some inevitable problems were exposed in the application process. The biggest problem of all is attributed to the affordance of sensitivity to recognizing twisted hands. Because the angular change of a twisted hand during rotation is not obvious, which easily leads to confusion and tiredness when players use these gestures [15]. What we expect is to minimize the negative effect brought by our interference. After accessing previous research on the interpretation of mental rotation, we found an interesting argument that motor processes exert an important influence on the transformations of mental images. The findings revealed that reaching better compatibility between mental images and bodily movement is necessary to make sure the directions of the two rotations are correlated [16]. Based on that we designed a more sensitive but simple gesture to indicate object rotation by swiping in four basic directions (left, right, up, and down).

The gesture of swiping is called a usual applied way of browsing the Web page in our daily life. Leap Motion recognizes the distinction of plane position much more accurately than that of space angle in practice. But unchangeably, the direction of swiping gesture is equally highly related to the direction in which mental images rotate. It's essential that making two sides are well-matched for the congruency of internal relations. To be specific, we design two pairs of rotating relations including X-rotation and Y-rotation for avoiding the effect of Gimbal Lock as much as possible. Within each pair of rotating relations, the presence of clockwise and counterclockwise makes "left-right" or "up-down" two symmetry directions represent them. Among them, swiping left indicates rotating objects towards the clockwise Y-axis; accordingly swiping right means toward the counterclockwise Y- axis. So it is with "up-down" gestures as well except for differing axis.

C. Game-based Learning Strategies Design

In developing learning abilities, for people who are playful and prefer to visualize the learning process, trying out implementing game-based learning strategies in the learning environment is a recommended way that is more relaxing to absorb the knowledge. Jabbar et al. concluded four gaming elements effectively improve learners' engagement and learning outcomes including multimedia elements, fun elements, interactive elements, and motivational elements [17]. In our embodies system applied to game-based learning strategies, the agent's text, voice, expression, and movement as multimedia elements are to draw attention to game content; predefined storyline and virtual animated agent character as fun elements are to promote a playful and enjoyable experience; conversational module, role-play and game objective as interactive elements are to enhance players' involvement and participation; lastly puzzle collection and different kinds of visual feedback as motivational elements are to increase the meaning of learning during gameplay.

For increasing the interactivity and learnability of the play system, we brought an animated pedagogical agent called "Tuan Tuan" into our virtual environment. To enrich the multi-model features, our agent embodies four kinds of external information channels including dialogue text, sound effects, facial expression, and body movement It takes on different assisting tasks throughout the whole gameplay. On the aspect of function, it is generally divided into three functions which are tutorial guidance, emotional support, and behavioral monitoring. When players enter into the training part before the game starts, the agent severed as the role of instruction guide helping them to get knowledge about how to use correct gestures and what the game objective is.

IV. Method

The scare of images of different perspectives of abstract 3D geometry during rotating has bothered lots of students who often lose confidence in math learning. Our goal of the game system was aimed to help them improve their spatial abilities through a series of spatial stimulation based on gestures in the embodied environment and to arouse their passion along with easing fear. Therefore, we conducted a study on users' learning outcomes and experiences. We invited 20 college students (8 male,12 female) who never trained in spatial thinking before from a university in central China to participate in our experiment. Their ages ranged from 22 to 24.

Before entering into the training system, participants spent 10 minutes filling out the Spatial Reasoning Test (including three dimensions of Mental Rotation, Spatial Perception, and Spatial Visualization) to measure their initial spatial abilities. Subsequently, they learned how to control game elements by suitable gestures in the process of completing a tutorial with the aid of an assistant if they had any misunderstandings. Then they formally played the game to pass four rounds. The Next round was more complicated than the previous round, and they would collect successfully one more missing puzzle of the subject character if passed the current round. They finally achieved the goal until collected all the missing puzzles. After playing, they were required to fill out the posttest, the Technology Acceptance Test (including three dimensions of Perceived Ease of Use, Perceived Usefulness, and Attitude toward Using) to indicate how useful, user-friendly and likable they thought this game system was, and the Cognitive Load Test to evaluate the extent to which their cognitive processing would suffer during playing. We additionally asked them several random questions about what they felt and whether there were any suggestions for improvement of the system.

Besides, we also recorded in-game operational data to reflect behavior changes that they completed every task from the beginning to the end. It concluded the completion time, the number of failures, and the sequence of rotation operations. Completion time recorded how much time they consumed to complete every round. The number of failures recorded how many times they repeated the current round to success. Differing from the number of rotations used for measuring what they performed during playing in most of the previous studies, we applied the measurement of the sequence of rotation operation to record dynamic behavior change.

V. Results

Because measurements of spatial ability (concluding three sub-dimensions) didn't conform with normal distribution under a Shapiro-Wilk Test, we applied Wilcoxon Test to verify the significance of the differences between the pretest and protest. We found various degrees of significant difference of pre-test and post-test in the mental rotation ($Z=-2.19$, $p=0.028$), spatial perception ($Z=-2.58$, $p=0.010$), spatial visualization ($Z=-3.28$, $p=0.001$) and spatial ability ($Z=-3.65$, $p=0.000$). As shown in Table II, participants using the game system performed better than before in the enhancement of the aspect of spatial abilities (Pre-test: M=8.65, Post-test: M=11.45, the total points of three dimensions is 15 points). Through experiencing the game system, scores of three dimensions of mental rotation (Pre-test: M=2.80, Post-test: M=3.65, the total points of each dimension is 5 points), spatial perception (Pre-test: M=3.40 Post-test: M=4.40), and spatial visualization (Pre-test: M=2.45 Post-test: M=3.40) separately improved significantly.

TABLE II. Wilcoxon Analysis of the Spatial Abilities (N = 20).

Measurement	Group	Mean	Std. Deviation	Z	p
Mental Rotation	Pre-test	2.80	1.06	-2.19	.028*
	Post-test	3.65	.99		
Spatial Perception	Pre-test	3.40	1.64	-2.58	.010*
	Post-test	4.40	.75		
Spatial Visualization	Pre-test	2.45	1.00	-3.28	.001**
	Post-test	3.40	1.19		
In All	Pre-test	8.65	2.89	-3.65	.000***
	Post-test	11.45	2.16		

TABLE III. Descriptive Analysis of the Technology Acceptance

Measurement	N	Mean	Std. Deviation
Perceived Ease of Use	20	3.83	.60
Perceived Usefulness	20	4.23	.56
Attitude toward Using	20	4.23	.47
Cognitive Load	20	2.33	.47

During game playing, the general change trend of recorded three critical measurements to represent distinctive performances was as follows. Most participants often failed in the first round along with various rotation operations including different objects or different rotational angles. Completion time tended to decrease as the number of failures increased. The sequences of rotation operations displayed two kinds of orders during completing every task: one was a decisive sequence that only had rotation operations of the right object; the other was a tentative sequence that had rotation operations of four objects.

Table III reflected that on the aspects of technology acceptance and cognitive load, participants generally thought this game system was useful (Perceived Usefulness: M=4.22, SD=0.56) to help understand the abstract spatial relationship and develop the spatial ability in a certain way in the case of keep practicing. And most of them held a relatively positive attitude (Attitude toward Using: M=4.23, SD=0.47) to this game experience and even would expect to apply it in other fields of learning. However, they felt it was complicated and inaccurate (Perceived Ease of Use: M=3.83, SD=0.60) somehow when operating objects using gestures in practice, and the score of the cognitive load was slightly higher (Cognitive Load: M=2.32, SD=0.47).

VI. Discussion

This game system for supporting spatial ability significantly exerted a positive effect on improving students' spatial thinking.

But there was some difference in initial performance and changing intensity of perspective spatial dimension. Through pretest before tutored, we got to know about students' performance on spatial visualization and mental rotation was not as well as their performance on spatial perception. Nevertheless, after playing, the improvement of spatial visualization was more significant than those of mental rotation and spatial perception. The reasons for this were likely that mental rotation and spatial visualization focus on the more abstract and comprehensive thinking ability of perspective or dimensional changing of objects, so our students who never intentionally trained before often only reach a medium level compared to well-experienced spatial perception accessibly stimulated by the outer world. However spatial visualization is more focused on the correspondence between shape part-whole relationships than mental rotation [18], which is in line with the core tasks trained in this game system. Although the participants strengthened their mental rotation ability by manipulating the rotating objects through gestures, the improvement was slower in a short period compared to spatial visualization. Probably due to the short training period of the game and the fact that periodic testing was not attempted.

From the recorded operational data, the high number of failures in the first level may be because participants may still be somewhat unfamiliar with gestural operations after the tutorial, and as the first level is completed, the failures in the later levels may be related to the difficulty of the task. Of the two sequences we have summarized, participants in the decisive sequence mostly adopted a more deliberate-careful strategy in task completion; they tended not to adopt gestures at the beginning of the game, but rather determined the target object and general direction through observation and reflection before performing gestures. In contrast, participants in the tentative sequence began to perform various manipulations of objects at the beginning of the game, and they tended to solve the problem through a trial-and-error strategy.

In addition, participants' feedback on the perceived usefulness and attitude towards using was generally high, indicating that the game system achieves a good balance between learnability and fun. The slightly high cognitive load may be related to the manipulation of gestures, which may be related to the deficiencies of the Leap Motion.

VII. Conclusion

For the effective application of embodied theory in spatial thinking skills training, we designed a gestural spatial ability game training system based on Leap Motion, aiming to allow students to link embodied gesture manipulation with abstract spatial thinking elements, and thus improve spatial ability in a fun game. The experimental results show that the system is effective in improving students' spatial thinking skills, with significant improvements in mental rotation, spatial visualization, spatial perception, and a high level of satisfaction with the system in general.

Therefore, a preliminary exploration was given on the key issue of how action representation and internal thought processing were connected in current spatial ability training, in which we tried to combine different teaching strategies to facilitate learning outcomes. However, the small number of participants in this study and the desktop motion capture device used have some limitations, and further optimization considerations in technology selection and experimental subjects may be made in subsequent studies.

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