Effects of different embodied scaffoldings on students' spatial abilities in digital game-based learning

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Abstract: Adding embodied scaffolding to the teaching process can be effective in improving students' spatial abilities. However, few studies have been conducted to explore the effects of different embodied scaffoldings on students' spatial abilities. Therefore, the purpose of this study was to investigate the effects of different embodied scaffoldings on students' spatial learning. Three types of embodied scaffoldings were designed: controllable animation scaffolding (CA), instructional gesture plus animation scaffolding (GA), and physical object scaffolding (PO). Based on this, we conducted a quasi-experimental study in which 197 elementary school students were randomly divided into three groups to learn geometry in a game-based learning context and measured their knowledge learning, spatial ability, and flow experience. The results showed that although there were no significant differences in spatial ability among the three groups, students in the PO group performed significantly better in knowledge transfer than the other two groups, while students in the PO group also had the lowest level of flow experience. In addition, we investigated the influence of students' prior proficiency on the effects of different embodied scaffoldings. The results showed that students in the low proficiency group performed better in the PO condition and the CA condition than those in the high proficiency group.

Keywords: Spatial ability; Game-based learning; Embodied cognition; Scaffolding

1. Introduction

Spatial ability can be defined as a human's capacity to understand, reason over, recall and manipulate the spatial relations among objects or in space, consisting of three factors: mental rotation, spatial perception, and spatial visualization (Linn & Petersen, 1985). As one of the basic human cognitive abilities, spatial ability is important for people to recognize their own environment and solve spatial problems (Duffy, Sorby, & Bowe, 2020; Gardner, 1983). Spatial ability levels not only directly affect learners' understanding, representation, and solution of science, technology, engineering, and mathematics (STEM) problems, (He, et al., 2021; Hodgkiss, et al., 2018) but also predict learners' career achievement and career choices in STEM fields (Yoon & Mann, 2017).

In the current pedagogical community, game-based learning is widely adopted by many educators. Numerous studies have shown that educational game is effective in enhancing learners' learning performance (Cerra, et al., 2022), self-efficacy (Kuznetcova, et al., 2023), and motivation (Fadda, et al., 2022). In addition, educational games can provide students with visual representations of objects in a three-dimensional form, and students can master spatial relations in the process of interacting with games, which also has a positive impact on spatial ability (Uttal, 2000). Therefore, some researchers have tried to integrate digital game-based learning into the teaching and learning process of spatial ability and have confirmed the effectiveness of educational games in improving students' spatial ability (Hou, et al., 2021; Chai, et al., 2019; Lin & Chen, 2016).

However, current educational games for developing students' spatial ability pay less attention to the essential features of spatial cognition and neglect the importance of embodied cognition for spatial ability. Evidence from several studies suggests that there is a link between the body, action, and spatial cognition and that physical movement plays an active role in spatial cognition (Lozano, Hard, & Tversky, 2007; Morsella & Krauss, 2004). By offloading mental processing to physical actions, it may help to improve students' understanding of spatial relationships. Some studies have been conducted to design teaching activities for spatial abilities based on the perspective of embodied cognition, and the results have shown that students who use embodied scaffolding achieve better learning outcomes (Kwon, et al., 2023; Rabattu, et al., 2023; Burte, et al., 2017). Therefore, given the value of scaffolding for student learning, educators may consider introducing embodied scaffolding to support students' spatial development.

Currently, few existing studies have explored the best practice of designing embodied scaffolding to enhance spatial ability in digital game-based learning. Therefore, this study aims to investigate and compare the effects of three different types of embodied scaffolding on students' spatial learning, with further consideration of the influencing factor, students' initial proficiency.

2. Literature Review

2.1 Embodied scaffolding in digital game-based spatial ability learning

The theory of embodied cognition states that the process of knowledge construction is inseparable from the physical interaction of the learner with the learning environment (Ioannou & Ioannou, 2020). By expanding learning from visual cognitive activities to physical movement, the researchers believe that this allows students to engage in multimodal interactions that help students process learning content at a deeper level (Anastopoulou et al., 2011) and understand abstract scientific concepts. In addition, several studies have shown that embodied learning enhances students' spatial thinking skills (Burte et al., 2017) and that the embodied element is positively associated with mathematical proof performance, insight, and intuition (Nathan et al., 2021).

Based on this, a growing number of researchers have attempted to apply embodied cognition theories to instructional design. Some studies encourage students to increase physical movement as an aid to cognitive processes (Rollinde, et al., 2021), while others incorporate the idea of embodied cognition into scaffolding to support their learning (Rahimi, et al., 2022). This scaffolding, which is provided during instruction to help students offload cognition onto the body or external objects, is referred to as embodied scaffolding. Embodied scaffolding transforms sensory experience into cognition and reduces cognitive load through physical movement (Zhang, et al., 2022) to help learners integrate abstract concepts with the learning environment and achieve better learning outcomes (Rahimi, et al., 2022).

Embodied scaffolding can be represented in many forms, and there are also differences in the motor nerves that can be mobilized by various embodied scaffoldings. Controllable animation is one of the most common embodied scaffoldings. Controllable animation scaffolding is a less embodied form of learning support in which learners can use finger tracking to control the animation with tools such as virtual sliders to achieve embodied cognition. For example, Johnson-Glenberg et al. (2016) designed animations that can control the speed of a round ball through a virtual slider to assist students in learning physics. In addition, some researchers have pointed out that gestures can act as a cross-modal prime (Hostetter & Alibali, 2008), providing learners with additional memory codes, thereby strengthening memory representation, increasing retrieval cues (Johnson-Glenberg & Megowan-Romanowicz, 2017) and reducing the cognitive load of learners (Goldin-Meadow, 2014). Therefore, some research has also attempted to combine instructional gestures with animation to mobilise more motor nerves while promoting students' embodied cognition. For example, in Merkouris et al. (2019) 's study, students remotely manipulated programmed robots with the help of instructional gesture scaffolding and animation scaffolding. Besides, physical object scaffolding is a highly embodied learning support in which learners can gain a deeper tactile experience by interacting with teaching aids, joysticks, force feedback devices, etc., and offload their cognition to the physical object. For example, Zohar et al. (2021) used a haptic device that applied force feedback to help students learn about chemical bonding.

In summary, researchers have designed rich embodied scaffolding in different disciplines to support students' embodied learning. However, few studies have attempted to investigate embodied scaffolding for spatial ability learning, leaving a certain gap in this area. In addition, most of the existing research has been situated within traditional teaching approaches, and no research has attempted to explore the effect of different embodied scaffoldings in the context of game-based learning.

2.2 Effect of initial proficiency on embodied learning

When designing embodied interventions, it is necessary to fully consider the relevant factors of the learners themselves, such as prior knowledge or ability (Conley et al., 2020; Post et al., 2013). Chi and Glaser (1985) noted that the level of expertise of the learner is a key factor in determining what information is relevant to the learner and what information to focus on. As learners increase in proficiency, their embodied learning styles may change somewhat. Novices, for example, often use their fingers when engaging in abstract number tasks, but as students' expertise increases, mental representations become more abstract and simplified (Pouw et al., 2014), so experts prefer to solve problems in an intangible way. The Expert Reversal Effect also points out that instructional guidance that is essential for novices may negatively affect more experienced learners, meaning that learners with less domain knowledge are more likely to benefit from an environment with a large number of sources of information and instructional support, while the opposite is true for learners with higher domain knowledge (Kalyuga et al., 2003).

There is empirical evidence of the effects of initial proficiency on embodied learning. Pouw et al. (2016) found that children with lower math skills benefited more from using augmenting instructional animations with a body analogy (BA) compared to children with higher math skills. Similar evidence was found in statistical disciplines (Conley et al., 2020) and computational thinking (Merkouris & Chorianopoulos, 2019) that participants with low prior knowledge may benefit most from higher levels of embodied experience, while participants with high prior knowledge prefer disembodied and abstract learning content. However, there are studies that have come to the opposite conclusion. Swart et al. (2017) found that students with lower initial proficiency benefited more from playing the deictic gesture (pointing) version of the game, while students with higher initial proficiency benefited more from the iconic gesture (metaphorical, enactive, symbolic) version of the game. Therefore, students' proficiency also need to be considered when designing embodied scaffoldings.

2.3 The Present Study

The above studies have discussed the effects of embodied scaffoldings on digital game-based spatial ability learning. However, few studies have focused on the effects of different embodied scaffoldings on improving spatial ability. In addition, little or no research has considered the influence of learners' prior proficiency. For this reason, a quasi-experimental study was conducted to assess the effects of different embodied scaffoldings on students' spatial ability learning and to examine the effects of learners' prior proficiency on embodied learning. Three common types of embodied scaffoldings were selected for this study: controllable animation (CA), instructional gesture plus animation (GA), and physical object (PO). The following two research questions were explored:

1. What is the effect of different embodied scaffoldings on students' learning of spatial ability?
2. Do students with various proficiency perform differently with each embodied scaffolding support?

3. Method

3.1 Participants

The participants were 197 fourth graders (100 females, M_{age} = 10.09, SD_{age} = 0.86) from three classes in one public primary school in Sichuan, China. All students had not been exposed to the learning content and the ANOVA analysis of three classes' math final exam grades of last academic semester showed no significant difference ($F(2, 191) = 0.437$, $p = .647$, $\eta_p^2 = 0.005$). Previous studies have confirmed the correlation between spatial ability and mathematical ability (Geer et al., 2019), so we concluded that the initial spatial ability of the students in the three classes was similar. The classes were randomly assigned to use three embodied scaffoldings: CA condition (32 females, 33 males) to learn using the controllable virtual three-dimensional simulation, GA condition (35 females, 31 males) to learn using the simulation plus instructional gestures, and PO condition (33 females, 33 males) to learn using physical objects. Each class was taught by the same two instructors with extensive teaching experience.

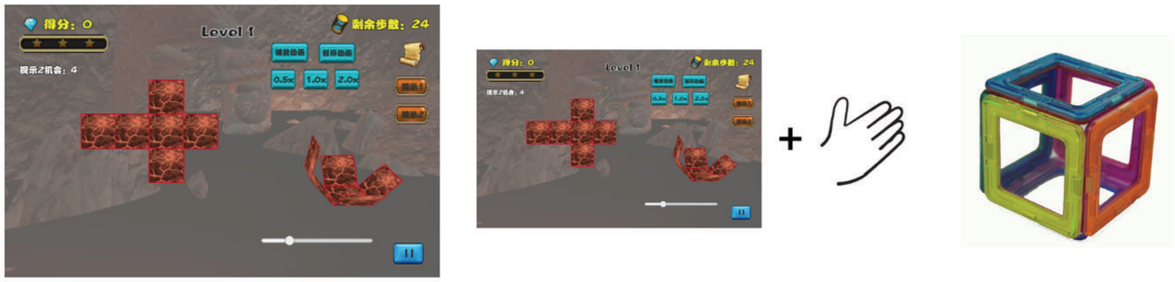
3.2 Procedure

The experiment was conducted as an 11-day experiment. All students took a three-day lesson (40 min per day) about mental folding from day 8. A ten-minute basic concept instruction was given in the first class and then students used the digital game environment on tablet to learn by themselves, with instructors providing learning supports. Thirty-two-minute pre-, post-tests were administered to students on the first and the last day of the experiment, respectively. Furthermore, students completed the flow questionnaire after the last lesson.

3.3 Materials

The digital educational game was called *Cube Elimination*, which focused on spatial visualization ability training and math geometric content learning of the cube nets fold and unfold. The *Cube Elimination* game was designed to help students form spatial representations, build an understanding of the cube and net concepts, and construct the association between three- and two-dimensional objects. Specifically, students were required to complete three main challenges presented in the game: 1) Given a net with the same pattern on each side, and find the opposite sides of the shaped cube; 2) Given a net marked with bottom/top surface, and find the front and top/bottom surface of the formed cube; 3) Given a cube, find the corresponding net from a figure. None of the students had prior experience with *Cube Elimination*.

The embodied learning resources varying in scaffolding were as follows. In the CA condition, the game provided the student with a three-dimensional cube that can be rotated and viewed, as well as a dynamic animation of the transition between the cube and the net. The student can control the speed, progress, and so on of the animation (see Figure 1a). In the GA condition, students were not only exposed to the three-dimensional cubes and dynamic animations in the game, but were also guided to use gestures that represented the transition process (see Figure 1b). In the PO condition, the student would get the physical magnetic square pieces (see Figure 1c).



(a) (b) (c)

Figure 1. CA condition (a), GA condition (b), and PO condition (c).

3.4 Measures

The pre-tests and post-tests included questions assessing two categories of variables: spatial ability (mental folding and mental rotation) and knowledge learning (retention and transfer). Students' knowledge learning status can reflect their understanding of objective knowledge in the process of spatial ability cultivation, so it was also measured in this study. Moreover, the flow questionnaire contained items collecting data on students' learning experiences.

3.4.1 Spatial ability

The spatial ability test included mental folding test, which was the ability that students were trained directly in the game, and mental rotation test, which was the transfer ability that students were not trained directly. For the mental folding test, the Paper Folding Test from the Kit of Factor Referenced Cognitive Tests (Ekstrom et al., 1976) was used, containing 20 items. In this test, students were given a square paper that had been folded and punctured in a series, as well as five figures showing the position of the holes when the paper was fully unfolded. They were asked to find the correct number from among the five figures. Each correct answer was worth one point, while each incorrect or no answer was worth 1/5 of a point, on a scale from -4 to 20.

The Mental Rotation Test was administered using the Vandenberg & Kuse Mental Rotation Test (Peters et al., 1995) and contained 24 items. Each test contained a target figure as well as four stimulus figures, and students were asked to select the rotated version of the stimulus figure that matched the target figure. If the correct stimulus figure was found, one point was given, on a scale from 0 to 24.

3.4.2 Knowledge learning

The knowledge learning test contained questions from the retention test and the transfer test, with each including ten questions, a total of 20 points. The knowledge test lasted 20 minutes. The retention test measured students' understanding of cubes and nets. For example, given a numbered network, students were asked to find the opposite side of the number two. The transfer test evaluated students' application of knowledge in new situations, such as asking students to find shapes that cannot be folded into cubes. On both the retention test and the transfer test, each correct answer received one point, while each incorrect or no answer received zero point. Pre-test and post-test questions were different, but the content and difficulty were similar. In addition, the knowledge test was tested by two experienced math teachers and a math teaching expert, with good expert validity.

3.4.3 Flow experience

The Short Flow State Scale-2 (SFSS-2) developed by Jackson, Ecklund and Martin(2008) was used as a flow experience questionnaire to measure the intensity of flow experience in students in game-based embodied learning. The scale consisted of nine items corresponding to the nine-dimensional conceptualization of convection by Csikszentmihalyi (1990). SFSS-2 was rated on a six-point Likert scale ranging from 1 (strongly disagree) to 6 (strongly agree), with higher scores indicating stronger feelings of flow. The reliability of SFSS-2 was α=0.77 (Jackson et al., 2008).

3.5 Data analysis

The data was analyzed in SPSS v.28 (IBM Corp, 2021). To answer RQ1, analyses of variance (ANOVAs) were conducted to assess differences between conditions in post-test scores. As the result of an ANOVA showed that there was a significant difference between conditions in the pre-test for mental folding ability (F (2, 194) = 3.646, p = .028*, η_p^2 = 0.036), a univariate analysis of covariance (ANCOVA) was employed to account for mental folding pre-test scores. All variables met the assumption of homogeneity of variance given the results of Levene's tests, except the flow experience. Thus, Welch's ANOVA was used for the analysis of the flow variable. Table 1 presents the descriptive statistics for all variables.

To answer RQ2, a median split was adopted to assign students in each condition to distinct levels of prior proficiency (Bobek & Tversky, 2016). Based on students' pre folding test scores, they were divided into low- and high-proficiency groups. Table 2 sets out the descriptive statistics for each group in three conditions on all variables. There were significant differences between the low and high prior proficiency groups in each condition (CA: F (1, 56) = 164, p < .001***, n_p^2 = 0.745; GA: F (1, 51) = 88.0, p < .001***, η_p^2 = 0.633; PO: F (1, 58) = 185, p < .001***, η_p^2 = 0.762). To compare each group's improvement from the pre-test to the post-test, we calculated the learning gain by subtracting the pre-test score from the post-test score. ANOVAs were employed to examine differences in learning gains between groups under each condition. All variables met the assumption of homogeneity of variance or had equal group sizes.

4. Results

4.1 Embodied scaffolding

With respect to the effect of embodied scaffolding on knowledge learning after classes, the three conditions did not significantly differ in their retention scores, F (2, 194) = 0.673, p = .511, η_p^2 = 0.007, whereas the analyses revealed a significant effect of condition on transfer scores, F (2, 194) = 3.603, p = .029*, η_p^2 = 0.036. The follow-up LSD comparisons showed that students in the PO condition performed better in the transfer test than students in the CA condition, MD = 0.88, SD = 0.374, p = .019*, and students in the GA condition, MD = 0.85, SD = 0.372, p = .024*, respectively.

Regarding the effect of embodied scaffolding on spatial abilities after classes, the analyses did not find a significant effect of condition on mental folding ability, F (2, 193) = 1.578, p = .209, η_p^2 = 0.016, nor on mental rotation ability, F (2, 194) = 2.967, p = .054, η_p^2 = 0.030.

Regarding the effect of embodied scaffolding on students' flow experience during learning, the analyses revealed a significant effect of condition on flow scores, F (2, 127.42) = 8.807, p < .001***, ω_p^2 = 0.061. The results of follow-up analyses indicated that students in the PO condition had a lower feeling of flow than those in the CA condition, MD = 0.53, SD = 0.137, p < .001***, and students in the GA condition, MD = 0.31, SD = 0.137, p = .027*.

Table 1. *Descriptive statistics for pre-, and post-tests*

Variable	CA Condition (N=65)		GA Condition (N=66)		PO Condition (N=66)	
	Pre	Post	Pre	Post	Pre	Post
	M(SD)		M(SD)		M(SD)	
Retention	3.46(2.13)	6.88(1.97)	3.70(2.00)	6.83(2.50)	3.82(1.89)	6.45(2.39)
Transfer	4.65(1.92)	5.65(2.19)	4.55(2.06)	5.68(2.19)	4.92(1.86)	6.53(2.04)
Folding	4.97(4.46)	7.85(4.57)	4.64(3.81)	6.51(4.38)	6.55(4.68)	8.22(4.56)
Rotation	6.28(3.15)	7.63(3.53)	7.17(2.88)	8.73(3.54)	7.39(3.00)	9.15(3.96)
Flow		4.76(0.65)		4.54(0.90)		4.23(0.78)

4.2 Prior proficiency

With respect to the pre-post test learning gain, the analyses of knowledge retention data showed that there was no significantly greater gain between the low proficiency group and the high proficiency group (CA: $F(1, 56) = 0.0118$, $p = 0.914$, $\eta_p^2 = 0.000$; GA: $F(1, 51) = 1.16$, $p = 0.286$, $\eta_p^2 = 0.022$; PO: $F(1, 58) = 0.00$, $p = 0.999$, $\eta_p^2 = 0.000$). Regarding the knowledge transfer, the results still failed to reach statistical significance (CA: $F(1, 56) = 0.118$, $p = 0.732$, $\eta_p^2 = 0.002$; GA: $F(1, 51) = 0.0798$, $p = 0.779$, $\eta_p^2 = 0.002$; PO: $F(1, 58) = 0.407$, $p = 0.526$, $\eta_p^2 = 0.007$).

With regard to the mental folding ability, the analyses showed that the low proficiency group achieved a significantly greater gain than the high proficiency group in the CA condition, $F(1, 56) = 11.5$, $p = .001^{**}$, $\eta_p^2 = 0.171$, as well as in the PO condition, $F(1, 58) = 9.72$, $p = 0.003^{**}$, $\eta_p^2 = 0.144$. In the GA condition, although the low proficiency group had a numerically greater gain than the high proficiency group, the results failed to find a statistical significance, $F(1, 51) = 1.32$, $p = 0.257$, $\eta_p^2 = 0.025$. Regarding the mental rotation ability, results showed that there was no significant greater gain between the low proficiency group and the high proficiency group (CA: $F(1, 56) = 1.46$, $p = 0.232$, $\eta_p^2 = 0.025$; GA: $F(1, 51) = 1.12$, $p = 0.295$, $\eta_p^2 = 0.021$; PO: $F(1, 58) = 2.34$, $p = 0.131$, $\eta_p^2 = 0.039$).

Table 2. *Descriptive statistics for low and high proficiency groups in three conditions.*

Variable	Proficiency	CA (N_{Low}=27, N_{High}=31)		GA (N_{Low}=21, N_{High}=32)		PO (N_{Low}=29, N_{High}=31)	
		Pre	Post	Pre	Post	Pre	Post
		M(SD)		M(SD)		M(SD)	
Retention	Low	2.78(1.74)	6.26(2.14)	3.38(2.33)	6.14(2.69)	3.34(1.61)	5.83(2.49)
	High	4.00(2.24)	7.42(1.63)	4.00(1.72)	7.53(2.18)	4.52(2.00)	7.00(2.29)
Transfer	Low	4.11(2.01)	4.96(1.95)	3.67(1.71)	4.67(1.96)	4.62(1.80)	5.90(1.72)
	High	5.16(1.88)	6.23(2.29)	5.13(1.91)	6.31(2.04)	5.39(1.93)	7.03(2.29)
Folding	Low	0.71(2.02)	5.56(3.80)	0.91(1.25)	3.14(2.56)	2.12(2.67)	5.52(3.30)
	High	8.81(2.69)	10.25(3.89)	7.66(3.13)	8.71(4.58)	10.63(2.16)	10.75(4.34)
Rotation	Low	5.51(2.68)	7.22(3.50)	7.19(2.50)	8.05(2.82)	6.79(2.60)	7.55(3.00)
	High	7.13(3.41)	7.97(3.69)	7.56(2.71)	9.38(3.75)	7.71(2.95)	9.94(3.82)

5. Dicussion

5.1 Effects of embodied scaffolding on spatial ability learning

This study assessed students' spatial ability, knowledge learning, and flow experience after game-based instruction in three conditions. In terms of spatial ability learning, the main results showed that while students' spatial ability improved significantly in all three embodied scaffolding conditions, there were no significant differences in scores on mental folding and mental rotation in the three conditions. This may verify the importance of incorporating embodied scaffolding in teaching spatial ability (Kwon, et al., 2023; Rabattu, et al., 2023; Burte, et al., 2017), regardless of the form of scaffolding.

For geometry knowledge learning, the main results showed that there was no significant difference in knowledge retention scores between the CA condition, the GA condition, and the PO condition, while students in the PO condition performed significantly better in the transfer assessment of geometry knowledge. The results showed that all three types of embodied scaffolding were able to support students' learning of geometry while also demonstrating the advantages of object embodied scaffolding in terms of knowledge transfer. This is consistent with previous studies suggesting that engaging in higher levels of embodied learning activates sensorimotor codes that enhance memory traces and help learners learn content faster and in greater depth (Johnson-Glenberg et al., 2020). As physical object scaffolding is a relatively high-embodiment scaffolding, students would gain more diverse memory cues when using it, which may help them to extract knowledge more quickly on transfer tests.

In terms of students' flow experience, the main results showed that the scores of flow experience were significantly lower in the PO group than in the other two groups. The reason may be that students in the PO group had to switch frequently between electronic devices and magnetic square pieces during the learning process, and this shift in attention may have affected the students' flow experience.

5.2 Performance of students with different proficiency in embodied scaffolding

To investigate whether students with different proficiency would perform differently with each embodied scaffolding support, this study divided students into high and low proficiency groups based on the pre folding test scores. Analysis of the learning performance of the two groups revealed that there was no significant difference in the learning gain in terms of knowledge retention, knowledge transfer and mental rotation ability between the two groups, regardless of the embodied scaffolding used. As for the mental folding ability, there was a significant difference in the learning gain between students in the high proficiency group and students in the low proficiency group in both the CA condition and the PO condition, with both showing greater progress for students in the low proficiency group. The reason may be that students in the CA group and the PO group were able to get clear feedback from the scaffolding during the learning process, while students in the GA group were unable to determine whether their movements were consistent with the real folding process. On the other hand, imagining the process of folding the cube out of thin air also tests students' spatial thinking skills, which may not be applicable to students with low initial spatial ability.

6. Conclusion

Our study investigated the effects of different embodied scaffoldings on students' learning of spatial ability. The results showed that students in the CA group, the GA group, and the PO group were able to learn geometry and enhance their spatial abilities, indicating the effectiveness of incorporating embodied scaffolding in enhancing spatial abilities. For the transfer assessment of geometric knowledge, the PO group scored significantly higher than the other two groups, although this group also scored significantly lower than the other two groups for flow experience. This suggested that we should not only explore the cognitive value of object scaffolding, but also pay attention to its negative impact on flow experience. In addition, we further analyzed the possible effects of students' proficiency in different embodied scaffolding conditions and showed that students with lower proficiency were more suitable for CA scaffolding and PO scaffolding with clearer feedback. We hope that our work will help educators to better initiate the teaching of spatial ability and apply appropriate embodied scaffoldings to enhance students' spatial ability.

Acknowledgements

We would like to acknowledge Ruonan Hu, Zhiyong Li, Yu Li, Xiaoqi Wei, Yuxi Wei, Hua Tian, Songjiang Chen, Yongguo Wang, Yanjun Cao, Jing Feng, Yingyong Jin, Jing Zhao, Hailing Tang, Jing Li for their help with experiment conducting and data collection.
Foundation: Key Project of The Beijing 14th Five Year Plan in 2021 for Education Science, "Research on the Cultivation of Learning Ability based on Learning Sciences and Game-based Learning"(No.CEFA21067)

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