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Whose Spatial Ability Benefits from Learning with 3D Design? From the Perspective of Learning Analysis

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ABSTRACT: Three-dimensional (3D) design can improve students' spatial ability, but the research on the differences of spatial ability development after 3D design training for students with different initial spatial ability is not unified. The ability-as-enhancer hypothesis and the ability-as-compensator hypothesis explain the performance differences of students with different initial spatial abilities in different situations. However, the existing research has not formed a consistent conclusion, which makes students lack of fine guidance, and it is difficult to achieve good spatial ability training effect. This study first explored the differences of students' performance under different educational interventions, and verified the value of process data in the cultivation of spatial ability. Then, we collected more students' data, discussed the improvement of students' spatial ability by 3D design with different initial spatial ability, and tried to explain the difference of students' performance by students' 3D design behavior. We found that different educational interventions can affect students' task participation, and then the effect of spatial ability training. Students with different initial spatial abilities still have significant differences in spatial ability after 3D design, but there is no significant difference in the improvement of spatial ability, and no difference in the data of 3D design operation process. Through cluster analysis, this study also found five types of students in the process of 3D design. There are significant differences in the pre-test, post-test only among some types of students. This study provides a reference for the training effect evaluation of students with different initial spatial abilities.

Keywords: 3D design, Spatial ability, Learning analysis, Ability difference

1. Introduction

Human beings live in the space environment, and their survival and development are carried out through the exchange of material and energy with the space environment. In contact with the environment, people must have the ability to judge spatial orientation and determine the spatial relationship and structure of geographical things. As one of human's basic intelligence, spatial ability plays an important role in human survival and development. Many studies have shown that spatial ability are highly correlated with the performance of science, technology, engineering, and mathematics (STEM) subjects (Lubinski, 2010; Sorby et al., 2013). Although spatial ability is one of the most researched factors of human cognitive function (Carroll, 1993), the concept of spatial ability has not been unified yet, and the measurement and testing methods of spatial ability cannot fully measure spatial ability (Höffler, 2010). Spatial ability has always been of secondary interest in the research of human intelligence.

Many studies have found that no matter how students' previous skills, experience, grades, etc. are, their spatial ability can be improved after training (Šafhalter et al., 2020). Ability-as-enhancer hypothesis and ability-as-compensator hypothesis are often used to explain differences in students' spatial ability improvement. Mayer and Sims (1994) believe that students with high spatial ability should benefit from animation in particular because they have sufficient cognitive ability to construct a mental model. Hays (1996) believe that students with low spatial ability should benefit from explicit graphical representation because it is difficult for them to construct their own visualization psychologically. Due to the lack of a perfect theoretical framework and the diversity of teaching design, there is a certain contingency in the research, so that it is impossible to form an effective and generalizable teaching practice strategy. Existing research is still more about exploring the universal laws of education through collective teaching, but students' cognitive characteristics or differences have not received enough attention. The students' spatial ability tendency, learning preference, motivation and environment are interfering with each other (Hays, 1996). According to the Aptitude-by-treatment interaction theory (ATI), there are complex interactions between students and teaching strategies. While some teaching methods are generally effective, they may not be effective for students with other characteristics (Mcleod et al., 1977). Students with different spatial abilities have different cognitive loads, prior knowledge, learning styles, learning interests, etc. They also have different behavioral characteristics when solving spatial tasks. After students with different spatial abilities use 3D design, can their spatial abilities be improved? Are there any differences in their improvement values? Is there any difference in 3D design behavior for students with different initial abilities? Are there any differences in the improvement of spatial ability among students of different learning types?

2. Literature review

2.1. Spatial ability and its development

Linn and Petersen defined spatial ability as a skill involving representation, transformation, generation, and extraction of symbols and non-verbal information, and they proposed three factors of spatial ability: spatial perception, mental rotation, and spatial imagination (Linn & Petersen, 1985). However, there is no consensus on whether the improvement of students' spatial ability is durable and transferable through training (Heckman & Masterov, 2007; Sims & Mayer, 2002).

At present, the spatial ability of students is mainly measured by methods such as mental rotation test, origami test, mosaic pattern test, etc. The reliability and effectiveness of measurement need to be improved. For one thing, there is no unified definition of spatial ability, and there is no comprehensive measurement scale for each element of spatial ability and comprehensive experience in use. For another, the difference between spatial ability test tools and test environment will also affect students' performance. For example, computer-based spatial ability test can eliminate the male advantage in mental rotation test (Monahan et al., 2008). Regarding whether there are gender differences in the cancellation of the time limit of the mental rotation test, different researchers have found different results (Masters, 1998; Vandenberg & Kuse, 1978). However, when the test time is further shortened, women will use the method of guessing questions to complete the test task, and the gender advantage of men will be more significant (Voyer et al., 2004). Last but not least, Larson pointed out the difference between the dynamic real world and the two-dimensional static test. Paper-pencil test and standardized test restrict the exploration of spatial ability (Larson, 1996). Moreover, different spatial problems have different solutions, and so does the teaching environment. In turn, the differences in cognitive processes and task-solving strategies (Chien & Chu, 2018) also pose challenges to the consistency research of spatial ability diagnosis.

Gender differences, age differences, and strategy differences in spatial ability have been extensively studied, but the reasons for the differences have not been fully explained. Teaching interventions based on differences in spatial ability cannot be widely promoted. The spatial ability test only provides the test results, ignoring the students' efforts and the improvement of logical thinking ability in the task-solving process, and cannot show the problems of students' learning input, learning strategies, knowledge and skills application, etc. Moreover, the teaching intervention focuses on the evaluation and feedback of the overall performance of the students, ignoring the diagnosis and personalized feedback of the individual behavior of each student.

2.2. Spatial ability difference and its intervention

In the early studies of spatial ability, psychologists and educational researchers found gender differences in spatial ability (Baenninger & Newcombe, 1989; Voyer et al., 1995). However, gender differences in spatial ability are also heterogeneous (Linn & Petersen, 1985; Voyer et al., 1995). Men have a dominant advantage in mental rotation (Deno, 1995; Linn & Petersen, 1985; Voyer et al., 1995), while women are more dominant in spatial positioning and perception speed.

In recent years, the role of students characteristics or individual differences in spatial ability training has attracted more and more attention (Höffler & Leutner, 2011; Meijer & Broek, 2010). The ability-as-enhancer hypothesis believes that students with high spatial ability can use less time to extract spatial information and can gain greater gains from 3D design (Huk, 2010). The ability-as-compensator hypothesis believes that 3D design can help students with low spatial ability build a 3D model, without affecting students with high spatial ability or increasing their irrelevant load (Höffler & Leutner, 2011; Hays, 1996; Huang & Lin, 2017; Lee & Wong, 2014). However, the improvement of different spatial ability elements of students is also different. At present, researchers have a consensus that stereotypes in spatial ability will affect students' spatial task performance (Ortner & Sieverding, 2008; Sharps et al., 2010). For example, when there are gender differences in the process of guided mental rotation tasks, the gender differences in performance on mental rotation tasks will increase (Ortner & Sieverding, 2008).

When students receive correct, immediate and personalized feedback in the process of spatial problem solving, they tend to be more motivated to participate in learning activities (Kleij et al., 2012). Compared with paper and pencil tests, procedural data can provide feedback on the thinking process for students and teachers (Whitelock, 2009). Automated data tracking, collection, and storage can avoid the Hawthorne effect of students and the expected effect of teachers. It also avoids standardized tests that rely on language and mathematical logic skills, as well as the restrictions caused by controlled experiments, data reasoning and induction, making it easier to convert the evaluation results into implementable, generalizable, and replicable teaching suggestions.

2.3. 3D design and spatial ability

The 3D virtual environment has unique advantages in simulating the authenticity, interactivity, and visibility of the objective world. 3D design through in-depth integration with traditional education, builds a personalized, interesting, and open comprehensive innovative practical teaching mode. 3D design can make abstract knowledge concrete and help students master science, technology, engineering, mathematics and other knowledge. Different from the methods of training spatial skills such as engineering drawing and sketch training, 3D design provides students with clearer object visualization (Blikstein et al., 2017). Not only can it help students spend less time creating models and improve the accuracy and completeness of the models (Snyder et al., 2014), but it can also help students learn how to solve problems (Blikstein et al., 2017) and cultivate students' creativity (Eisenberg, 2013). In the 3D design process, the choice of graphics, the splicing of graphics, the combination of graphics, and the rotation of graphics all reflect the students' spatial ability. Many scholars have proved that 3D modeling can improve students' spatial ability (Gerson et al., 2001; Koesa & Karakus, 2018).

3D design is not only a tool and means for cultivating spatial ability, but also an important scenario for spatial ability evaluation. In addition to traditional spatial ability evaluation methods such as observation, interviews, questionnaire surveys, and self-evaluation, methods such as work design schemes, operation logs, and screen records have also been applied (Wu et al., 2018). Operating habits such as the number of 3D design operations and operating time are also commonly used to evaluate the teaching effects of 3D design (Al-Ahmari et al., 2018; Barber et al., 2016). 3D design can not only be used for spatial ability training, 3D design process data is also the explicit data of students' spatial thinking, which can be used to evaluate students' spatial ability (Wu et al., 2020). Therefore, we plan to use 3D design tools to cultivate students' spatial ability, and diagnose the improvement of different types of students' spatial ability based on process data, and provide support for teaching decision-making and students' personalized intervention.

2.4. Research hypothesis

The basic assumption of this study is that in the process of 3D design, students' operation behavior can be divided into many types, and different types of operation behavior will get different spatial ability training effect. Students with high initial spatial ability and students with low initial spatial ability will produce different operation behavior data in 3D design, so as to achieve different spatial ability promotion. Specifically, we will ask the following questions:

Research question 1: Compared with paper materials, will 3D printed models affect the training effect of 3D design on spatial ability? Will different educational interventions affect students' behavior?

Research question 2: What is the difference between the 3D design behavior of students with high spatial ability and students with low spatial ability? Is the improvement of space capacity related to operational behavior?

Research question 3: In 3D design, according to the 3D design operation behavior, what types can we divide students into, and what are the improvement differences, in spatial ability, for these students?

3. Methods

3.1. Participants

We conducted two experiments on 22nd May 2020 and 20th October 2020. Prior to the study, we obtained ethical review approval, and participants obtained informed consent and voluntarily signed the consent form.

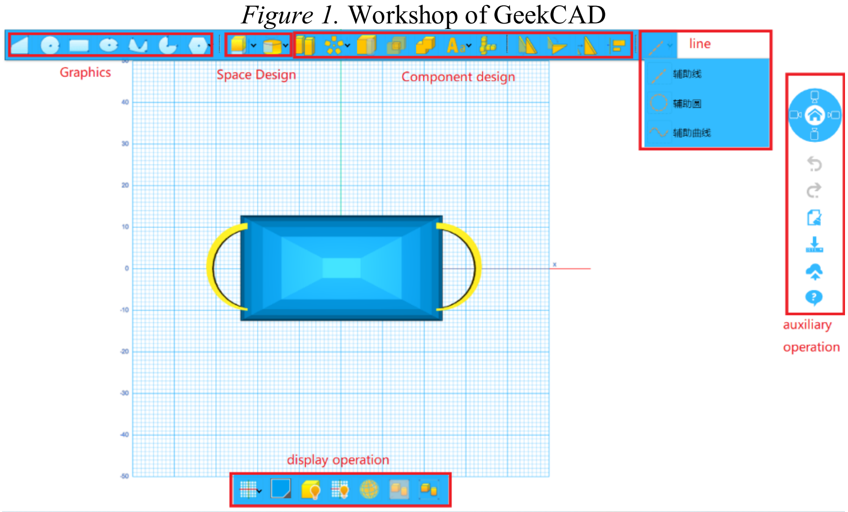
This study does not require prior knowledge or computer skills of the participants. In the first round of the experiment, we selected two classes in grade one of a middle school in Lanzhou City, Gansu Province, China. A total of 97 students participated in the experiment, including 51 students in the experimental group and 46 students in the control group. In the second round of experiment, we conducted this research in two classes of the first grade in a middle school in Lanzhou, China. A total of 88 students participated in this experiment. The students who do not participate in this experiment will use separately assigned accounts to participate in the course normally, but the operation process of the two students will not be recorded and analyzed.

This course was taught by an experienced male information technology teacher. All students completed the research tasks. However, it needs to be explained that because the object of this study cannot represent the level of high school students, the purpose of this experiment is to explain the differences in the operation of different types of students, and the research results need to be further verified to extend to all high school students.

3.2. Materials

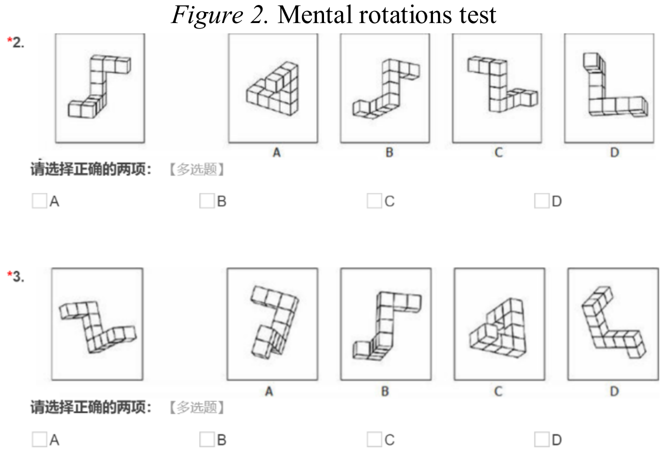
Considering the ease of use and difficulty of 3D design software, geekCAD, a browser-based 3D design tool, was selected for this research. As shown in Figure 1, geekCAD includes seven areas, the commands related to 3D object operation are at the top, and the other areas are system auxiliary functions. When students are designing in 3D, all their operations on the platform will be recorded.

Figure 1. Workshop of GeekCAD



We choose the mental rotation test score as the student’s spatial ability, and use the mental rotations test (Vandenberg & Kuse, 1978) shown in Figure 2 for testing. Each question includes a total of five graphics, of which the first graphic is the original graphic. Students need to determine which two of the following four graphics (labeled with ABCD) can be obtained by rotating the original graphic. There are two correct options for each question, and only the students who choose two correct answers will get one point. Checking one answer or selecting zero answers is counted as zero points. Each student has six minutes to complete the test.

Figure 2. Mental rotations test



3.3. Research procedure

Referring to Boucheix and Schneider (2009), we designed two rounds of experiments to explore the differences of students' operation behavior under different educational intervention conditions and the behavior differences of different types of students in 3D design.

The process and duration of the two experiments are consistent with each other. All participants completed the task in four steps. First (10 minutes), the teacher described the test process and organized the students to participate in the mental rotation test. Then (15 minutes), the teacher explained the function and operation method of geekcad. The students tried to make a water cup and get familiar with the operation method of geekcad. Then (80 minutes), the teacher asked the students to design Zhongshan Bridge. Zhongshan Bridge is a famous scenic spot of the Yellow River in China. After confirming that the students have no problem with the task, ask them to complete the design task independently. Students can consult the materials provided by teachers at any time during the design process. Finally (15 minutes), the teacher commented on the students' works and invited them to participate in the mental rotation test again. The first round of experiment was divided into experimental group and control group. The knowledge of the experimental group and the control group are the same, including the introduction of Zhongshan Bridge and three view drawing. 88 students participated in the second round of experiment. The only difference is that in the first round of experiment, we provided the 3D model of Zhongshan Bridge for the experimental group and the paper three view data for the control group. In the second round, we provided all the students with 3D models.

The first round of experiments proved the value of operational behavior in spatial ability evaluation. However, due to the small number of participants in the first round of the experiment, the classification of students may lack credibility. Therefore, in order to further explore the differences in learning performance of different types of students, we carried out a second round of experiments under the same educational intervention. The task of different difficulty and different situation will affect students' learning state. We only measure students' spatial ability, but not their academic performance (Hegarty & Sims, 1994). However, it should be noted that the order of questions before and after the mental rotation test is confused, which avoids the students' practice effect.

3.4. Data collection

In this study, xAPI specification is used to automatically collect students' click stream data during 3D design on geekcad. Each click of students will generate a series of relevant data, including operators, coordinate points, operation objects, operation commands, results, etc. For example, when coloring a model, xAPI can automatically collect data such as which student added which color to which object at what time, and record the mouse or keyboard input data in the process. For xAPI data collection mechanism and students' 3D design behavior specification, please refer to research results of Wu et al. (2020). Response latency, response frequency, and invested time are performance factors often considered in dynamic spatial ability test (Contreras et al., 2007). Furthermore, referring to the research on learning behavior engagement in online learning (Fredricks et al., 2004; Kim et al., 2016), we identified three types of students' 3D design behavior, including nine indicators, such as the number of operations, the type of operations, the duration of investment, and the maximum time interval. The explanation of each type of learning behavior indicator is shown in Table 1.

What needs to be explained and distinguished is that the operation mentioned by CZ and CZZL, as shown in Table 1, refers to the command buttons on the right and low sides of geekcad, as well as the operation of mouse and keyboard light. MLZL and MLCZ refer to the 3D interactive operations on the top of geekcad, such as graphic selection, stretching, rotation, scaling.

Table 1. 3D design learning behavior indicators

Indicator	Explanation
Number of operations (CZ)	Accumulated operation times of mouse, keyboard, platform auxiliary function, etc
Number of operation types (CZZL)	Accumulated operation types of mouse, keyboard, platform auxiliary function, etc
Login duration (DLSC）	The time interval from the first operation to the last operation
Number of commands types (MLZL)	Cumulative number of types of 3D design commands such as rotate, stretch, align and crop
Number of command operations (MLCS)	Cumulative usage of 3D design commands such as rotate, stretch, align and crop

Interaction duration (JHSC)	The number of minutes in which the number of operations of 3D design command is greater than zero
Maximum operations per minute (ZDZ)	Maximum operations per minute
Maximum time interval (ZDT)	Maximum duration of zero operations per minute. Long time interval is considered as non learning state.
Efficient interaction time (YXZ)	The cumulative time that the number of clicks per minute exceeds the average number of clicks in the class

4. Result

4.1. Difference analysis of 3D design operation behavior in different situations

4.1.1. The influence of 3D model on students' 3D design

The full score of students' mental rotation ability test is 24. The pretest scores of the experimental group ranged from 2 to 18 points (M = 8.33, SD = 3.14, median = 8), while the pretest scores of the control group ranged from 0 to 18 points (M = 8.54, SD = 3.89, median = 9). By independent sample t-test, there was no difference between the experimental group and the control group (p = .085 > .05).

The pretest and posttest of each group were analyzed. As shown in Table 2, there were significant differences between the pretest and posttest of each group. Whether the experimental group or the control group, the students' spatial ability has been significantly improved after using 3D design.

Table 2. Pre- and post- test analysis of experimental group and control group

Group	Pre-test		Post-test		t-test		
	M	*SD*	*M*	*SD*	*MD*	*t*	*p*
Control group	8.54	3.89	12.74	5.42	-4.20	-7.55	.000**
Experimental group	8.33	3.14	13.92	4.85	-5.40	-7.38	.000**

Note. $^{**}p < .01$.

After analyzing the posttest and promotion value of the two groups, it is found that, as shown in Table 3, there is no difference in the posttest value between the experimental group and the control group, that is, there is still no significant difference in the spatial ability of the two groups after the experiment. However, the improvement of spatial ability in the experimental group was significantly higher than that in the control group (p = .026 < .05).

Table 3. Comparative analysis of experimental group and control group by pre-test and post-test

Indicator	Control group (N = 46)		Experimental group (N = 51)		t-test		
	M	*SD*	*M*	*SD*	*MD*	*t*	*p*
Pre-test	8.54	3.89	8.33	3.14	0.21	0.291	.085
Post-test	12.74	5.42	13.92	4.85	-1.182	-1.13	.309
Improvement	4.20	3.77	5.59	5.40	-1.393	-1.46	.026*

Note. $^{*}p < .05$.

Table 4. Comparative analysis of experimental group and control group by learning behavior indicators

Indicator	Control group (N = 46)		Experimental group (N = 51)		t-test		
	M	*SD*	*M*	*SD*	*MD*	*t*	*p*
CZ	294.09	83.905	301.08	86.286	-6.991	-0.404	0.687
CZZL	8.13	2.613	10.43	2.532	-2.301	-4.402	0.000**
DLSC	30.13	14.896	37.27	16.096	-7.144	-2.261	0.026*
MLZL	7.89	2.601	8.84	2.453	-0.952	-1.855	0.067
MLCS	68.11	42.536	81.24	35.334	-13.127	-1.659	0.100
JHSC	16.78	7.357	20.82	7.326	-4.041	-2.707	0.008**
ZDZ	81.91	37.457	63.67	36.773	18.246	2.419	0.017*
ZDT	8.67	9.825	10.47	10.542	-1.797	-0.866	0.389
YXZ	5.28	2.605	5.84	2.292	-0.561	-1.127	0.262

Note. $^{*}p < .05$; $^{**}p < .01$.

Self-directed learning (Chou, 2013), interest (Scarborough & Dobrich, 1994) and other characteristics will affect the quality and quantity of students' participation in space tasks, and then affect the growth of space ability. It is a feasible way to explore the difference of ability promotion from the perspective of behavior. It can be seen from table 4 that CZZL, DLSC and JHSC of the experimental group are significantly higher than those of the control group. However, the ZDZ of the control group was significantly higher than that of the experimental group.

4.1.2. Performance differences of students with different initial spatial abilities when using 3D models for 3D design

Similar to the first round experiment, students' spatial ability has been significantly improved after using 3D design. We will focus on the differences of learning performance among different types of students. There are many ways to distinguish high and low ability students. The median score (Boucheix & Schneider, 2009), the average score (Hu et al., 2017), and 50% of the total score (Hegarty & Steinhoff, 1997) are the three common dividing points. In this study, we choose the median of students' mental rotation test pretest score as the cut-off point. Students whose pre-test score is less than or equal to 8 will be marked as low spatial ability students, and students whose pre-test score is higher than 8 will be marked as high spatial ability students.

Through the homogeneity test of variance, we found that the variance between the high spatial ability group and the low spatial ability group was equal. Furthermore, independent sample *t*-test was performed for pretest, posttest and promotion values. As shown in Table 5, we find that there is a significant difference between the pre-test and post-test data of students' spatial ability. That is to say, the score of mental rotation test of high spatial ability students is significantly higher than that of low spatial ability students before and after training. But there is no difference between the two groups, that is, high spatial ability students and low spatial ability students' spatial ability has made the same improvement.

Table 5. Spatial ability differences between the high-and low- spatial ability students

Indicator	High spatial ability (N = 49)		Low spatial ability (N = 39)		*t*-test		
	M	*SD*	*M*	*SD*	*MD*	*t*	*p*
Pre-test	5.82	2.01	11.03	2.35	5.21	11.03	$.00^{**}$
Post-test	11.47	4.85	16.95	3.44	5.48	6.19	$.00^{**}$
Improvement	5.65	4.61	5.92	3.30	0.27	0.32	.76

Note. $^{*}p < .05$; $^{**}p < .01$.

A total of 32,657 pieces of data were collected in this experiment. The data generated by each student ranged from 199 pieces to 857 pieces (M = 371, SD = 104.71, median = 359). As shown in Table 6, the operation types, command types, command usage times, interaction time, maximum time interval and maximum operation times of high spatial ability students are slightly higher than those of low spatial ability students. But there is no significant difference between the two kinds of students. However, it is worth noting that the effective interaction time of low spatial ability students is slightly higher than that of high spatial ability students.

Table 6. Behavioral differences between the high-and low- spatial ability students

Indicator	Low spatial ability (N = 39)		High spatial ability (N = 49)		*t*-test		
	M	*SD*	*M*	*SD*	*MD*	*t*	*p*
CZ	291.43	74.850	301.59	94.903	10.161	.562	.576
CZZL	9.41	2.879	9.49	2.846	.079	.129	.898
DLSC	30.80	14.947	37.15	16.496	6.358	1.893	.062
MLZL	8.08	2.465	8.85	2.729	.765	1.378	.172
MLCS	72.47	37.546	78.56	41.025	6.095	.726	.470
JHSC	18.31	6.941	20.18	8.571	1.873	1.133	.260
ZDZ	68.67	38.107	73.21	37.321	4.532	.559	.577
ZDT	7.78	9.601	10.41	9.563	2.635	1.281	.204
YXZ	5.63	1.997	5.51	2.910	-.120	-.229	.820

Note. $^{*}p < .05$; $^{**}p < .01$.

4.2. Behavior clustering and ability improvement

4.2.1. Cluster analysis of 3D design behavior

Because the student behavior data includes time, times and other data of different dimensions, and there are extreme values between the student behavior data. We first standardize the data, and then use k-means algorithm to cluster the behavior data of students, and get five types of students, as shown in Figure 3.

Cluster5: excellent students. A total of 3 students, accounting for 3.41% of the total number of students. In addition to the maximum number of clicks and the maximum time interval, all the data such as the type of operation, the number of operations and the length of login are the highest among the students, and this type of students are the best students to participate in learning.

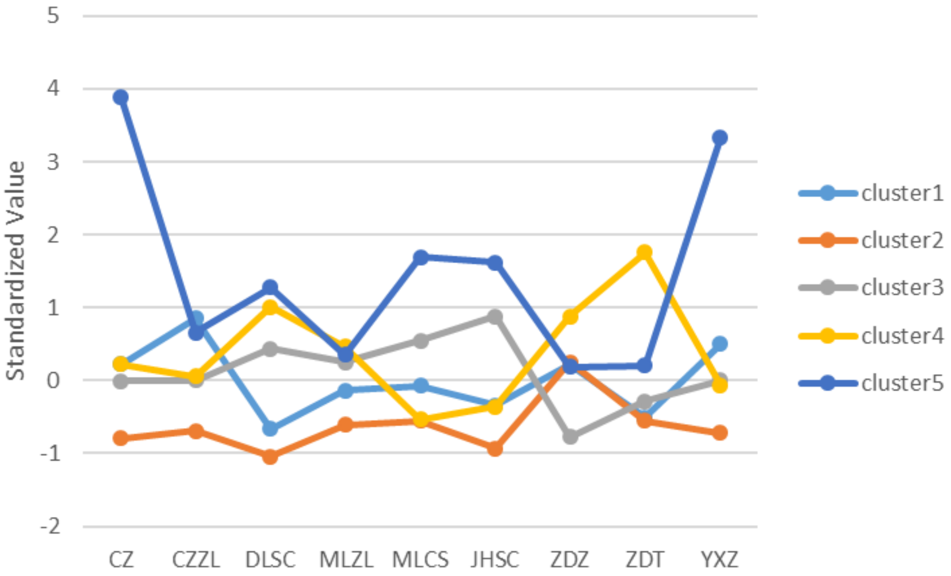
Cluster3: ordinary students. A total of 31 people, accounting for 35.23% of the total number. All the data are in the middle of all the students, and are basically above the average level.

Cluster2: risk students. A total of 23 people, accounting for 26.14% of the total number. In addition to the maximum number of clicks, all the data such as the type of operation, the number of operations and the length of login are the worst among the students, and there is a huge gap with the average level. This type of students is the worst in learning participation.

Cluster1: tasters. A total of 15 people, accounting for 17.05% of the total number. The operation types and effective interaction time are above the average level, but the operation times and command types are below the average level, and the login time is relatively short. This type of students spend more time using some platform operations and 3D design operations in less login time.

Cluster4: task quitting. A total of 16 people, accounting for 18.20% of the total number. Although online for a long time, the maximum time interval is particularly large, that is, the middle of a particularly long time did not participate in 3D design. It is considered that the students once gave up their study in the middle of the course.

Figure 3. Comparison of five types of students' operation behavior



4.2.2. Differences of spatial ability among different types of students

As shown in Table 7, there are no significant difference in the pre-test (p = .145 > .05) and post test (p = .285 > .05) of the five types of students. After analyzing the five types of students, we can find that there is no difference between the five types of students in the post test. But in the pretest, there is significant difference between cluster1 and cluster5. On the whole, there is no significant difference in improvement of the five types of students (p = .053 > .05), but there was significant difference between cluster 2 and cluster 1, cluster 3, Cluster 4.

Table 7. Differences of spatial ability among different types of students

Indicator	Types	*M*	*SD*	*F*	*Sig.*
Pre-test	Cluster 1	6.73	2.915	1.757	0.145
	Cluster 2	8.39	4.076		
	Cluster 3	7.90	3.070		
	Cluster 4	8.81	2.857		
	Cluster 5	11.67	3.512		
Post-test	Cluster 1	14.33	4.865	1.279	0.285
	Cluster 2	12.17	5.622		
	Cluster 3	13.97	4.902		
	Cluster 4	15.25	4.754		
	Cluster 5	17.00	2.646		
Improvement	Cluster 1	7.60	4.067	2.444	0.053
	Cluster 2	3.78	3.357		
	Cluster 3	6.06	4.676		
	Cluster 4	6.44	3.140		
	Cluster 5	5.33	1.155		

5. Discussion

5.1. The influence of 3D model on students' spatial ability

Through paired sample *t*-test of students' mental rotation ability before and after the test, it is found that no matter what kind of teaching intervention materials are provided, 3D design can significantly improve students' spatial ability. That is, with the help of 3D design technology, students' spatial ability has been significantly improved, which is consistent with the research of Uttal et al., 2013. The improvement value of spatial ability of the experimental group was significantly higher than that of the control group, which seems to indicate that compared with paper materials, providing 3D model in the process of 3D design can improve students' spatial ability more effectively. However, it is worth noting that there is no difference between the pre-test and posttest of spatial ability between the experimental group and the control group. From the final results, we cannot conclude that 3D model intervention can improve students' spatial ability more effectively. 3D design operation data can let us interpret this phenomenon more accurately.

DLSC, CZZL and JHSC of the experimental group were significantly higher than those of the control group, while ZDZ of the control group was significantly higher than that of the experimental group. 3D model teaching intervention can make students spend more time on the platform and use more commands unrelated to 3D design for 3D design tasks, so that the 3D model education intervention training achieved significantly higher than the paper material education intervention value. However, although the 3D interaction time is long, there is no difference in the types of 3D design operations between the experimental group and the control group, so there is no difference in the post test of spatial ability between the experimental group and the control group. Similar to Scarborough and Dobrich (1994), 3D model intervention may enhance students' interest in learning, make students spend more time, carry out more operations, and achieve greater value of spatial ability improvement. However, because the novelty of 3D model will also enhance students' interest in learning, in the long-term experimental environment, students' novelty or interest in learning may change. We also need to verify students' differences in different educational intervention situations according to different task difficulty.

5.2. The differences of spatial ability training among students with different initial levels of spatial ability

Similarly, through the second round of experiments, we also found that using 3D models to carry out 3D design can significantly improve students' spatial ability. Through paid matched samples *t*-test on students' mental rotation before and after test scores, we found that 3D design can significantly improve students' spatial ability. Furthermore, we find that after 3D design, high spatial ability students and low spatial ability students have the same improvement. This finding is different from the ability-as-enhancer hypothesis and ability-as-compensator hypothesis. It is also possible that 3D design enables students to operate 3D objects intuitively, which reduces students' cognitive load and makes no difference between students.

However, after 3D design training, the mental rotation performance of high spatial ability students is still better than that of low spatial ability students. However, the experiment we set up is relatively simple, and ignores the individual differences of motivation and interest besides the differences of learners' abilities, and does not use a variety of educational interventions to ensure the diversity of learning environment design (Höffler, 2010). This conclusion needs more extensive verification. In the 3D design training, teachers should get rid of the stereotype in spatial ability and carry out teaching activities equally.

Therefore, our research no longer focuses on the performance of students with different initial spatial abilities in different teaching situations, but explores the performance differences of students with different initial spatial abilities from the perspective of learning analysis. Due to the short research cycle and low difficulty of the task, the research results need to be further verified in order to promote. In addition, this study uses 3D design to train students' spatial ability, but still uses traditional MRT to measure students' spatial ability. Although most of the existing studies also use this method (Koesa & Karakus, 2018), the effectiveness of the measurement results needs to be further verified.

5.3. Behavior differences of students with different spatial levels

At present, there are many studies on building block activities, computer-aided design, sketch, 3D modeling and other activities on the cultivation of spatial ability, but there is no research on the effect of spatial ability cultivation based on students' behavior data. In the field of online learning, many scholars regard interaction as the most important part of all learning environments (Woo & Reeves, 2007). Many scholars extract students' behavior variables from the system log data, and explore the behavior variables to predict students' performance (Macfadyen & Dawson, 2010; Morris et al., 2005). Similar to this study, Sherman and Martin proposed a method to capture student app inventor project snapshot and explore student development behavior (Sherman & Martin, 2015). Filvà collects the data generated in students' scratch interaction, detects students' behavior patterns, and supports teachers to provide implementation quality feedback (Filvà et al., 2019). We collected the data of students' operation times, login time, operation time interval in the process of 3D design, and analyzed the behavior data of high spatial ability and low spatial ability. We observed that high spatial ability students used more command types and operated more times in a longer time than low spatial ability students. Although most of the behavior data of high spatial ability is higher than that of low spatial ability, there is no significant difference between the two types of students.

The results of this study are not consistent with either the ability-as-enhancer hypothesis or the ability-as-compensator hypothesis. For one thing, ability-as-enhancer hypothesis and the ability-as-compensator hypothesis are mainly based on the cognitive load theory. And 3D modeling provides students with intuitive 3D space operation experience, which does not require students to convert abstract two-dimensional or text data into 3D objects for further operation, and will not cause cognitive overload of students with low spatial ability. For another, it is also possible that the task of this study is relatively simple, the difficulty of the task and the sense of achievement of the task can not meet the learning desire of the high spatial learners, which makes the 3D object operation become a low desire learning activity, and produce similar learning results and behaviors with the low spatial learners. The results also need to carry out a longer period of research in the complex teaching situation to verify.

5.4. The improvement of spatial ability of different types of students

Referring to the interaction behavior in the online learning environment, students' 3D modeling behavior is also related to students' ability to use specific learning tools and find the right information. These abilities will also affect students' 3D design operation, and further affect the cultivation of spatial ability (Hillman et al., 1994; Lust et al., 2012). In addition, learning situation, external motivation, instructional design and task setting also affect students' 3D modeling enthusiasm and their 3D modeling behavior. Regardless of students' internal and external motivation, it will be reflected in the 3D modeling behavior and affect the improvement of spatial ability. Therefore, only using the initial spatial ability to analyze students' 3D modeling behavior, there are still many uncertainties. In order to further explore the improvement of different students' spatial ability, we use k-means algorithm to cluster students' 3D modeling behavior, and get five types of students.

Novice designers often test their designs through trial and error, and experienced designers use different testing strategies according to their experience (Ahmed et al., 2003). Although we cannot fully refer to students' 3D modeling behavior data to evaluate students' spatial ability, behavioral data can provide a reference for the cultivation and improvement of students' spatial ability. Although there are only three students in cluster5, it is the most ideal type of learning. Cluster4 is in the state of not learning for a long time. It is possible that the students have completed the course task in a short time and have a long idle period. It is also possible that the students have not seriously participated in the course activities. Both cluster1 and cluster2 participate in 3D modeling, but both cluster1 and cluster2 are of poor participation type. Compared with cluster2, cluster1 tries more 3D modeling operations and has a longer interaction time. Cluster1 and cluster2 may be that the students have completed the course task in a short time, and then they are not interested in participating in the course. Cluster3 belongs to ordinary students, all behaviors are above the average, and the number of students is the largest.

From the perspective of pretest, there are some differences in 3D modeling behavior between students with low spatial ability and students with high spatial ability. Students with particularly low spatial ability may encounter great difficulties in the process of 3D modeling. Therefore, although they are more interested in 3D design, have tried the platform functions, and have relatively long interaction time, they do not continuously participate in the course activities and become tasters. Students with high spatial ability are more interested in 3D design and continue to participate in the course tasks. Only the students with very low spatial ability and very high spatial ability showed differences in 3D modeling behavior. There is no difference in the post test and spatial ability improvement between the two kinds of students. As long as students participate in 3D modeling, their spatial ability has been trained and improved. Although students' 3D modeling behavior is different due to internal and external motivation, it can be considered that students have similar spatial ability after the course. From the perspective of promotion, the promotion value of spatial ability of cluster2 is significantly less than that of cluster1, cluster3 and cluster4, but there is no difference with that of cluster5. Therefore, teachers should encourage and guide students to actively participate in 3D design, give more guidance to students with low spatial ability, and pay attention to personalized feedback of students with high spatial ability. Although we often choose a few students as representatives to praise in teaching practice, the relevant conclusion can only be a hypothesis, because the number of cluster5 is too small. More extensive research is needed to promote the experimental results.

6. Conclusion

The results of this exploratory study verify the following points: (1) On the whole, 3D design can improve students' spatial ability, regardless of their initial spatial ability. (2) 3D model can enhance students' interest in learning and encourage them to spend more time on 3D design. (3) Students with different spatial ability levels still have significant differences in their spatial ability after using 3D design, but there is no significant difference in the improvement value of spatial ability among students with different spatial ability levels.

We also found that: (1) Spending more time and exploring more 3D design functions can improve students' space ability more effectively. Teachers should take the initiative to set up educational intervention to enhance students' learning interest and motivation, so as to improve students' learning effect. However, in the long-term process of education, the impact of educational intervention on students' interest and the persistence of students' spatial ability need to be further explored. (2) The 3D modeling behavior data of high spatial ability students is better than that of slightly low spatial ability students. High spatial ability students spend more time using more command types and doing more operations, but low spatial ability students have longer effective interaction time. However, it should be emphasized that there is no significant difference in 3D modeling behavior data among students with different spatial ability levels. (3) There are many types of students' behavior data in 3D design, including excellent students, ordinary students, risk students, tasters and task quitting. The students with great differences in initial spatial ability also have differences in their operation behavior, but most of them have no differences in their operation behavior. There was no significant difference in the post test value of spatial ability among different types of students, but the students with the worst participation achieved the least improvement in spatial ability.

In order to explore the differences of students' 3D modeling behavior, we need to extract computable key indicators, and provide personalized guidance and timely feedback to students. Although the behavior data of 3D design in this study cannot predict the improvement of students' spatial ability. There are also other ways to predict the effect or promotion of students' spatial ability according to the initial level of spatial ability. For example, Xiao and Zhang (2021) through two years of continuous research, found that interest in space activities can significantly predict the development of spatial ability, but has nothing to do with the initial spatial ability. Turgut (2015) developed the Spatial Ability Self-Report Scale (SASRS) to evaluate the spatial ability of college students. Despite, the SASRS is not suitable for k1k8 students. However, it can be used for high school students. The automatic tracking, collection and storage of 3D design behavior data can avoid the Pygmalion effect and Hawthorne effect, which are often encountered in empirical research, and provide a path for the study of spatial ability improvement differences.

In short, we verify the spatial ability growth of students with different initial spatial abilities in 3D design, and explore the spatial ability growth of students with different initial spatial abilities and different types of students through behavioral data. It is a limitation of this study to choose mental rotation measurement as the basis of students' spatial ability. At present, there is no unified definition of spatial ability, and there is no perfect measurement scale of each part and comprehensive use experience. Mental rotation and other spatial ability scale can only measure part of the content of spatial ability. Moreover, spatial ability is trained by 3D design, but the typical mental rotation scale is only a simple graphic test, and the difference between measurement methods and training methods will also affect the credibility of the measurement results. Moreover, the results of mental rotation measurement are also affected by students' speech ability and logical reasoning ability. The choice of research objects is another limitation. Although the purpose of this study is to explore the growth of spatial ability of students with different initial spatial ability and different learning types, we can not extend the results to all middle school students because we do not consider the prior knowledge of students and the difficulty of this 3D design task to be low. In addition, although learning behavior data is the result of the comprehensive influence of students' internal and external motivation, different teaching strategies, different task scenarios and different operation tools may also have different effects on students' behavior data, and students' external motivation is still an important factor affecting the research results.

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