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Utilizing 3D Open Source Software to Facilitate Student Learning of Fundamental Engineering Knowledge: A Quasi-Experimental Study*

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This study explored the effect of Google SketchUp on students' learning achievements in spatial visualization. A quasi-experimental with pre-test and post-test design was used to conduct the research. Eighty-four fifth graders from a public elementary school in Taiwan voluntarily participated in the study. Students from different classes were divided into three instructional modules: Google SketchUp (with full features), Google SketchUp (with limited features), and traditional instruction (hand-held objects). Students in each of the three experimental groups were instructed to manipulate various 3D objects that were created by a class teacher. A criterion test was developed to measure students' understanding about basic concepts of spatial visualization. The educational experiment was completed within three weeks. The results showed that Google SketchUp (with full features) was an effective learning tool to support students in developing spatial visualization skills ($F = 8.20$, $p < 0.01$).

Keywords: spatial visualization; Google SketchUp; open source software; K-12 engineering education

1. Introduction

1.1 Spatial visualization skills in engineering education

Spatial visualization skills refer to the ability to mentally process and manipulate two-dimensional (2D) or three-dimensional (3D) visual objects [1]. From an educational psychology perspective, spatial visualization skills contain two major constructs: mental rotation and mental transformation, which implies that objects are entirely or partially transformed in learners' mindsets [2]. Due to the significance in engineering professions, engineering educators [3, 4] contended that spatial visualization skills were emphasized in all engineering disciplines and not limited to graphic design-related disciplines. These skills are particularly important for architectural, manufacturing, and electronic engineers [5].

Previous research studies have shown that students equipped with well-developed spatial visualization skills can succeed in several engineering-related learning tasks [6]. Moreover, spatial visualization skills as fundamental engineering knowledge can be a strong indicator that predicts engineering students' learning achievements [7]. Thus, with available assessments (e.g. Purdue Spatial Visualization Test) to measure students' spatial visualization skills, many American engineering colleges require engineering freshmen to complete the spatial visualization assessment as a precautionary measure in order to enhance students' success in future engineering learning [e.g. 8].

K-12 engineering education is regarded as one of the emerging research topics for engineering educators and administrators [9]. Exploring K-12 students' preliminary contact with engineering subjects provides an understanding of how young learners engage in engineering learning [10]. In Taiwanese K-12 education systems, a conceptual framework regarding spatial visualization is developed and included in mathematics learning units for fifth graders at elementary schools. Early exposure to this fundamental engineering knowledge allows children to develop a positive attitude towards engineering. In the current study, computer applications in classrooms may offer elementary students an advanced technology tool to facilitate their engineering learning regarding spatial visualization.

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1.2 3D Multimedia tools in developing spatial visualization skills

Spatial visualization skills are not innate ability; however, they can be learned through systematic instructional training [2]. Mathematics scholars have proposed that since spatial visualization is related to mathematic computing, visual aids for learning is an effective instructional strategy to support students in developing spatial visualization skills [11, 12]. Generally speaking, visual aids for learning, based on information process theory, allow learners to comprehend large amounts of information and understand abstract concepts in an efficient way [13, 14].

Due to the advances in computer technologies, traditional hand-held visual aids in supporting spatial visualization skills have been replaced by 3D multimedia tools. They may provide additional learning opportunities for learners and attract their attention [15, 16]. For example, Christou et al. [17] contended that features of 3D multimedia tools motivated students to manipulate virtual visual objects on the computer screen and resulted in better learning outcomes. Similarly, Wu and Shah [18] considered that animations embedded in 3D multimedia tools clearly demonstrated spatial concepts and effectively lowered learners' cognitive learning loads.

While integrating 3D multimedia tools into classroom instruction, past studies have reported empirical evidence on positive learning outcomes for developing spatial visualization skills. For instance, Accascina and Rogora [19] investigated the paid software Cabri 3D for teaching geometric concepts. They indicated that the tool supported students in learning difficult mathematic solutions. Obara [20] employed the paid software called Geometer's Sketchpad to support students in calculating surface areas of a pyramid and cone, and found that teaching with technology helped students grasp important concepts. However, those studies tended to use non-experimental methods to collect data and adopt commercial 3D multimedia tools for class instruction.

Google SketchUp developed by Google Company is a 3D multimedia tool that allows students to design and develop 3D visual objects. Being open source software, Google SketchUp has been widely used for creating 3D building models in architectural engineering, interior design, and civil engineering [e.g. 21]. Kurtulus and Uygan [22] and Erkoc and Gecu [23] were pioneers who explored the use of Google SketchUp in mathematics classes. However, even though they employed an experimental method to examine the effect of Google SketchUp on students' geometric learning performances, a major problem was that student participants in these studies were asked to draw 3D models rather than manipulating visual objects. Training students to create visual models in limited time may pose a severe threat to the external validity of experimental design [24].

1.3 Purpose of the study

Based on the abovementioned information, the current study aimed to investigate how elementary school students employed Google SketchUp to support their mathematics learning regarding spatial visualization. An educational experiment was conducted in three fifth-grade classes where 84 student participants manipulated various types of 3D geometric models (computer-based vs. hand-held objects) created by one class instructor. One major research question was as follows:

- Did significant differences exist on learning achievements in spatial visualization for students manipulating different types of 3D geometric models?

According to the research question, the research null hypothesis of the study was:

- There was no significant difference on learning achievements in spatial visualization for students manipulating different types of 3D geometric models.

2. Research method

2.1 Research design

In the study, a quasi-experimental with pre-test and post-test design was adopted to explore the effect of Google SketchUp on students' learning performances. The independent variable was the type of 3D geometric models manipulated by students. The dependent variable was students' learning achievements in spatial visualization. Table 1 lists the research design of the study.

According to Clark and Mayer's [25] study, students tended to be motivated by emerging learning technologies and performed well on learning

Table 1. Quasi-Experimental Design

Treatment	Pre-Test	Experiment	Post-Test
Treatment 1 (Class A)	O_1	X_1	O_2
Treatment 2 (Class B)	O_3	X_2	O_4
Treatment 3 (Class C)	O_5	X_3	O_6

X_1 : Students using Google SketchUp (with full features) to manipulate virtual 3D objects.
X_2 : Students using Google SketchUp (with limited features) to manipulate virtual 3D objects.
X_3 : Students using their hands to manipulate cardboard-made 3D objects.
O_1~Q_6 : Criterion test on spatial visualization.

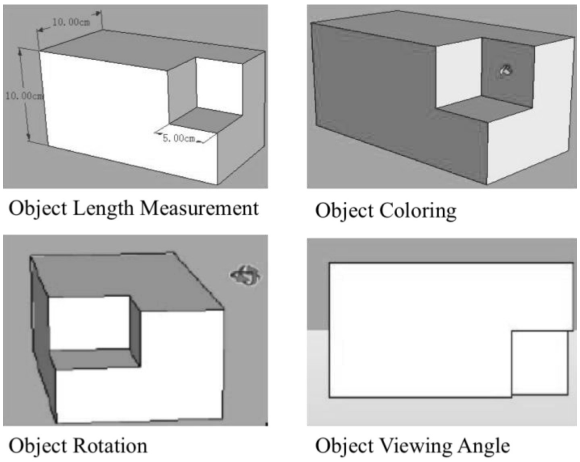

Fig. 1. Treatment 1—Google SketchUp (with full features) to manipulate 3D models.

achievement tests. Therefore, in the study, three different treatments were used to investigate Google SketchUp's influential effectiveness. Students in Treatment 1 (Class A) employed Google SketchUp with full features to manipulate virtual 3D objects (see Fig. 1). In Treatment 2 (Class B), one major feature (object transformation) in Google SketchUp was disabled (see Fig. 2). Students only used limited features in Google SketchUp to manipulate virtual 3D objects. Treatment 3 (Class C), used as a control group, provided each student with a package of cardboard-made geometric objects to practice spatial visualization skills (see Fig. 3). One week before and after the implementation of the study, students received a pre-test and a post-test on spatial visualization.

2.2 Experimental control

In order to minimize the threats to internal validity of experimental research [26], several experimental controls were administered during the implementation of the study. Table 2 summarizes the experimental controls used in the study.

2.3 Research instruments

2.3.1 Google SketchUp

In the study, virtual 3D objects were created in Google SketchUp. These geometric models served

Fig. 3. Treatment 3—Cardboard-made geometric objects.

Table 2. Summaries of Experimental Controls

Potential Threat	**Measure**
Class instructor	The same instructor in three experimental groups
Class time	The same class time students received
Learning contents	The same instructional design on materials
Class setting	In the same computer lab
Test implementation	Pre-test and post-test administered on the same school day
Prior knowledge	Pre-test adopted in three experimental groups
3D objects	All 3D models created by one class instructor

as computer-based visual aids that supported students in comprehending important concepts of spatial visualization. In Treatment 1 and Treatment 2, participants were not responsible for developing 3D objects through Google SketchUp. Students in the Treatment group employed five major features in Google SketchUp to manipulate 3D geometric objects that were created by an instructor. Table 3 illustrates these five major features. In contrast to 3D multimedia objects, students in Treatment 3 used their hands, color pens, and rulers to manipulate cardboard-made objects.

2.3.2 Criterion test

A criterion test was developed to measure students'

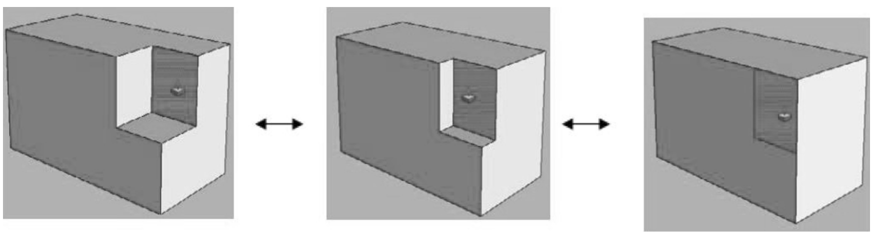

Fig. 2. Treatment 2—one feature (object transformation) disabled in Google SketchUp.

Table 3. Five Major Features in Google SketchUp

Feature	Function
1. Object rotation	Rotating 3D models
2. Object viewing angle	Changing the viewing angle of 3D models
3. Object coloring	Coloring the surface of 3D models
4. Object transformation*	Transforming 3D models into different shapes
5. Object length measurement	Measuring the length of a side in 3D models

* Object transformation was disabled in Treatment 2.

understanding about basic concepts of spatial visualization. The test contained 18 multiple-choice questions. The test items were directly related to these three major constructs: spatial comparison (similar to spatial rotation), spatial measurement, and spatial transformation. Higher scores in the measurement represented students' higher learning achievements. The score range of the test was between 1 and 18.

Three procedures were adopted to ensure the reliability and validity of the measurement. First, four experienced mathematics teachers reviewed the contents of 24 originally designed test items. Unclear descriptions and inaccurate items were removed during this time. Second, the modified test was sent to 30 fifth graders for completing item analysis of which discrimination index decreased test items from 24 to 18. Finally, Kuder-Richardson 21 (KR21) coefficient of reliability was calculated as 0.9.

Table 4. Profile of Research Participant

Class	Experiment	Number of Students
Class A	Virtual 3D objects (full features in Google SketchUp)	28
Class B	Virtual 3D objects (limited features in Google SketchUp)	29
Class C	Hand-held objects	27

2.4 Research participants

Eighty-four fifth graders from a public elementary school in Taiwan voluntarily participated in the study (Class A: 28; Class B: 29; Class C: 27). Overall, students in Google SketchUp groups had medium-level computer literacy since they received computer knowledge at computer courses. Table 4 presents the profiles of the research participants.

2.5 Research procedure

One mathematics-learning unit regarding geometric objects was selected as the main instructional content. The educational experiment lasted for three weeks; in each week, students received various instructional treatments within one hour. In Treatment 1 and 2, the course teacher taught mathematics through oral presentation, demonstrated 3D objects in Google SketchUp, and allowed students to manipulate 3D objects by using five features in Google SketchUp. In Treatment 3, in addition to class lecture, the course teacher also demonstrated hand-held objects and asked students to practice with cardboard-made visual aids. The learning schedule of a weekly class in three experimental groups is reported in Table 5.

2.6 Data analysis

In order to reduce the potential effect of the pre-test in the study, one-way analysis of covariance (ANCOVA) was used for data analysis. When the significance value was realized, a post-comparison method was used to compare mean differences among experimental groups. The significance level was set to 0.05 in the study.

3. Research result and discussion

3.1 Mean difference among experimental groups

Table 6 summarizes the results of descriptive statistics regarding the pre-test and post-test. Table 7 reports the ANCOVA results for each of the three experimental groups.

The information in Table 6 showed that students in the three experimental groups all improved their

Table 5. Learning Schedule of a Weekly Class

Learning Schedule	Treatment 1	Treatment 2	Treatment 3
1. Class lecture (25 minutes)	Instruction via Powerpoint and blackboard	Instruction via Powerpoint and blackboard	Instruction via Powerpoint and blackboard
2. Demonstration* of visual aids (5 minutes)	Demonstration of virtual 3D objects (with full features in Google SketchUp)	Demonstration of virtual 3D objects (with limited features in Google SketchUp)	Demonstration of physical 3D objects
3. Practice with visual aids (30 minutes)	Manipulation of virtual 3D objects (with full features in Google SketchUp)	Manipulation of virtual 3D objects (with limited features in Google SketchUp)	Manipulation of physical 3D objects

* Before the implementation of the study, students in Treatment 1 and 2 were taught to operate Google SketchUp.

Table 6. Summaries of Pre-Test and Post-Test Results

		Pre-Test		Post-Test	
Experiment Group	**N**	**Mean**	**S.D.**	**Mean**	**S.D.**
Treatment 1	28	6.68	3.50	11.71	4.59
Treatment 2	29	5.48	4.29	7.31	4.45
Treatment 3	27	6.52	4.01	8.96	5.50

Table 7. ANCOVA Results for Experimental Groups

Source	SS	DF	MF	F
Between	259.56	2	129.78	8.20**
Within	1265.71	80	15.82	
Total	1525.27	82		

** $p < 0.01$.

Table 8. Post-Comparison Results

Group	Modified Mean	Post-Comparison
A: Treatment 1	11.70	A > B**, A > C**
B: Treatment 2	7.54	B < A**
C: Treatment 3	8.74	C < A**

** $p < 0.01$.

spatial visualization skills after receiving various instructional methods. Compared to the pre-test, students in the Treatment 1 group earned more points (mean differences: 5.03) in the post-test. After removing the effect of the pre-test, the data in Table 7 indicated that there was a significant difference among the three experimental groups ($F = 8.20$, $p < 0.01$). Thus, a post-comparison test was performed to compare mean differences in the post-test. Table 8 lists the comparison results.

The results in Table 8 showed that a significant difference existed between Treatment 1 and 2 ($p < 0.01$) and between Treatment 1 and 3 ($p < 0.01$). However, no significant difference was found between Treatment 2 and 3. Therefore, after excluding the effect of the pre-test, students in Treatment 1 group performed significantly better than the other two groups.

According to the data in Table 7 and Table 8, the effect size revealed that Cohen d is 0.98 between Treatment 1 and 2; Cohen d is 0.54 between Treatment 1 and 3. According to Cohen's [27] definition, Cohen d between Treatment 1 and 2 can be regarded as large effect size; Cohen d between Treatment 1 and 3 is medium effect size.

3.2 Discussion

After the implementation of a three-week experiment, students' spatial visualization skills in three experimental groups were increased through various instructional models. From a starting point (pre-test), students in the Google SketchUp (with full features) group achieved a better learning improvement in the post-test. In contrast, students' post-test performances in Google SketchUp (with limited features) and traditional instruction groups grew by a small margin. By removing the effect of the pre-test, a significant difference was still found among the three experimental groups. This finding indicated that the students' starting behaviors were almost the same. Students' prior knowledge about spatial visualization would not influence learning performances in the post-test.

Regarding group comparison, there was a significant difference between Google SketchUp (with full features) and Google SketchUp (with limited features) and between Google SketchUp (with full features) and traditional instruction (hand-held objects). This finding showed that Google SketchUp (with full features) is the best instructional solution in developing elementary students' spatial visualization skills. While engaging in Google SketchUp (with full features) group, students might use five main features to manipulate virtual 3D objects to obtain full understandings of basic concepts in spatial visualization. The result supported previous research, which reported that 3D multimedia tools could support students in learning mathematics concepts [17, 18]. In other words, Google SketchUp (with full features) can be an effective visual aid in enhancing students' learning development about fundamental engineering knowledge [19, 20].

Compared with the other groups, students with limited features strengthened their knowledge base in the post-test but, no significant learning benefits were identified. Their learning performances were lower than those that received traditional instruction (hand-held objects). In Treatment 2, Google SketchUp lacked one major feature (object transformation) for students to manipulate 3D virtual objects. Limited learning gains resulted from the effect of the computed-based visualization tool being blocked. This phenomenon can be attributed to the role of object transformation being disabled in the group. In theory and practice, object transformation allows students to change 3D objects' formation into different shapes. When provided such a learning opportunity, students might effectively grasp basic concepts of spatial rotation and spatial transformation. In other words, without the feature of object transformation, students might not be able to easily link their prior knowledge received in their class lectures [28].

In the study, traditional instruction (hand-held objects) served as a comparison group to reflect the function of the other treatment groups. However, the findings showed that students under traditional instruction still performed well. Although there was no significant difference between Treatment 2 and 3, students' learning performances in traditional instruction surpassed those in Google SketchUp (with limited features) group. In other words, a learning value indeed exists for physical contact with cardboard-made objects. Manipulating these hand-held objects also supports student learning in spatial visualization [12]. This finding was consistent with past studies that reported that physical objects exhibited a positive effect on students' development of spatial visualization skills [29, 30].

4. Conclusion

This study explored the effect of Google SketchUp on students' learning achievements in spatial visualization. Based on the statistical results identified above, the research null hypothesis was rejected. A significant difference in students' learning achievements was found among three experimental groups. Compared to two other groups, students in Google SketchUp (with full features) group achieved a better learning outcome. Moreover, a medium to large effect size was identified for the Google SketchUp (with full features) group. Therefore, Google SketchUp (with full features) can be an effective learning tool to support students in developing spatial visualization skills.

Even though students in the Google SketchUp (with limited features) group used computers to facilitate their mathematics learning regarding spatial visualization, students' learning outcomes were the lowest among the three experimental groups. From a statistical perspective, Google SketchUp (with limited features) and traditional instruction (hand-held objects) achieved similar learning outcomes. When one major feature (object transformation) was disabled, Google SketchUp might not effectively benefit student in learning fundamental engineering concepts.

Although the study was conducted in a K-12 learning context, the findings of the study may still provide an implication for engineering educators at higher educational institutions. In engineering colleges, when given an opportunity to adopt advanced technologies in classrooms, instructors tend to choose commercial-based software and spend time developing specific tools for classroom instruction. From the results of our study, Google SketchUp as open source software showed its benefits in engineering learning. While developing visualization-training programs becomes popular in higher education, Google SketchUp may offer an alternative instructional solution to support engineering students in developing spatial visualization skills.

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