



## The Effectiveness of Using Stereoscopic 3D for Proportion Estimation in Product Design Education

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### ABSTRACT

In product design education, identifying proportion and manipulating proportional relationships are important practices in form-giving training. However, using conventional 2D displays with monocular depth cues to train students with different spatial abilities remains a great challenge. Although, some literature has indicated that stereoscopic 3D (S3D) displays were helpful for depth-related tasks, whether S3D is helpful for proportion estimation is an open question. Therefore, the objective of this research was to study whether using S3D for design department students could assist them in improving their ability to interpret the proportions of products. The independent variables of the experiment included spatial ability, task complexity, and display mode. Spatial ability was a between-subject variable. Students aged 20–25 years were recruited as participants and were categorized into high-, moderate-, and low-performance groups depending on their score on a spatial ability scale. Task complexity and display mode were within-subject variables. In the experiment, three chair styles were used as samples. Digital models of three chairs with distinct proportions were displayed in two conditions: 2D mode with monocular depth cues and S3D mode. Participants were asked to compare the proportions of a physical chair and three digital chairs and then select the digital chair with the correct proportions in the 2D and S3D modes. The dependent variable were the score of selecting the 3D digital models with correct proportions compared to the physical objects. The result indicated that students could perceive proportions more accurately in the S3D mode than in the 2D mode. In particular, when using S3D, participants with low spatial ability demonstrated overall performance that was equal to that of participants with high spatial ability.

**Keywords:** product design education, proportion estimation, spatial ability, stereoscopic 3D (S3D)

### INTRODUCTION

#### Product Design Education and Spatial Ability

The primary goal of design education is to improve designers' proficiency. The curriculum content includes creative thinking, design methods, ergonomics, psychology, aesthetics, graphics, mechanics, material, manufacturing processes, and other professional knowledge and practical abilities that designers must acquire (Yang, You, & Chen, 2005; Phillips, De Miranda, & Jinseup, 2009).

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#### **Contribution of this paper to the literature**

- In product design education, identifying proportion and manipulating proportional relationships are important practices in form-giving training.
- This paper demonstrates that S3D, which has disparity depth cues, is helpful for the training of proportion estimation in product design education.
- When using S3D, participants with low spatial ability demonstrated performance equal to participants with high spatial ability.

In the curriculum of design and engineering education, teaching dimensions, proportions, and spatial composition through 2D images with monocular depth cues is a critical introductory course. In addition, teaching the perspective method of constructing 3D spaces is critical. During the learning process, students often encounter tasks that require 3D spatial visualization skill, and learning performance is dependent on the spatial ability of students (Marunić & Glažar, 2014). Therefore, spatial ability plays an important role.

Spatial ability, including spatial cognition and spatial intelligence, is the ability to comprehend image variations, and the concept was originally studied in the field of psychology. Thurstone (1938) defined spatial ability as the ability to mentally memorize, twist, and move an image before comparing the mentally changed image with the original image. Lohman (1984) argued that spatial ability is not a single ability but a structured combination of the ability to move, combine, analogize, preserve, and transform abstract visual images. McCormack (1988) divided spatial ability into four types: spatial perception, spatial memory, logical spatial thinking, and creative spatial thinking. Furthermore, the abilities of understanding spatial relations, spatial orientation, and spatial visualization were critical factors affecting designers' performance in 3D product design (Liao, 2017).

In an application study on spatial cognition involving 37 high school students, Donelson (1990) determined that the participants with high spatial ability significantly outperformed those with low spatial ability in aspects such as information encoding, spatial thinking, and reaction time. Sorby (2007) indicated that 3D spatial ability is a key factor to succeeding in engineering and other technical fields. In particular, the ability to imagine object rotation in space is most crucial. Poor 3D spatial ability affects designers' performance in engineering graphics. Therefore, spatial cognition refers to the ability of a person to accurately observe and identify objects, memorize visually received images in the brain, and mentally imagine the received image subsequently. As an indicator of intelligence, the level of spatial ability is positively correlated with learning, reasoning, and creativity. In addition, design training had positive effects on spatial ability performance (Lin, 2016). The students with design training tended to use the holistic strategy, however the students without design training tended to use the analytical strategy.

Roth (1993) claimed that the creative thinking, problem solving, and concept formation practiced in design concept development entail spatial ability. Lacking spatial ability hinders perceiving the 3D spatial concepts represented in 2D images, thereby decreasing learning effectiveness.

However, in the curriculum of product design or architecture design education, some teaching materials for demonstrating and discussing case studies have always been presented in 2D images with monocular depth cues such as motion parallax, occlusion, shadow (or shading), relative size, texture gradient, linear perspective, and accommodation. Identifying these depth cues relies on learners' individual experience and on their complex spatial cognition of relative object attributes in the image.

For novice students, their capabilities of graphic drawing, observation, and spatial imagination still undergo continual training. If the capabilities of observation and spatial imagination are not well developed, teaching professional knowledge with these 2D images would lead to communication gaps between instructors and students. The gap increases with the complexity of the image (Mukai, Yamagishi, Hirayama, Tsuruoka, & Yamamoto, 2011; Guedes, Guimarães, & Méxas, 2012).

Therefore, in order to reduce the gap, some research groups have tried to use virtual reality (VR) and augmented reality (AR) technologies (Kaufmann, Steinbügl, Dünser, & Glück, 2005). In order to improve the spatial ability (i.e., spatial relations, spatial visualization, and spatial orientation) of new engineering students, VR and AR were used in a training experiment (Roca-González, Martín-Gutiérrez, García-Domínguez, & Carrodeguas, 2017). Recently, stereoscopic 3D (S3D) displays, which have binocular disparity, have been used to present teaching materials for product design education or architecture design education (Smith et al., 2005; Chen, Cheng, Chu, & Sandnes, 2015). However, given the contributions from many research groups, some literature has still reported that the existing VR systems were not suitable to support the learning process of industrial design students and it was necessary to develop a designer-oriented VR system (Liang et al., 2016).

### Applications of S3D Displays

Unlike a traditional 2D display, an S3D display increases the composite of monocular and binocular depth cues.

For example, since both spatial thinking and spatial ability can be improved through training (Newcombe & Stieff, 2012), stereoscopic vision has been used in teaching descriptive geometry, which is relatively difficult in spatial geometry (Kaufmann et al., 2005; Kaufmann, 2009). With two lateral-shift images, one for the left eye and the other for the right eye, the students were able to perceive additional depth cues from the S3D teaching materials.

Regarding S3D applications, tour guide or interpretation systems in museums were pioneering S3D applications (Styliani, Fotis, Kostas, & Petros, 2009). Recently, applications for medical education have gradually increased (van Beurden, IJsselsteijn, & Juola, 2012). For example, 3D holographic displays have been used to demonstrate anatomy and infection scenarios at the single-cell level. S3D streaming of surgeries has been helpful for collaborative e-learning. S3D has fostered the ability to represent anatomical details for biological e-learning. For neuroanatomy lectures, students considered the S3D approach superior in spatial understanding, applicability in future anatomy classes, effectiveness, and enjoyableness (Kockro et al., 2015).

In addition to education, 3D displays have been used successfully for video conferencing. A research team developed an S3D system that enabled collaboration and telepresence among team members by allowing automobile models to be rotated through two-point touch (Edelmann, Gerjets, Mock, Schilling, & Strasser, 2012).

In addition, Lin, Cheng, & Wang (2015) reported that stereoscopic displays were helpful for the performance of depth-related tasks. These tasks included judging absolute and relative distances, finding and identifying objects, performing spatial manipulations of objects, and navigating. However, the accuracy of distance judgment was influenced by the angle of declination while estimating depth in a projection-based stereoscopic virtual display.

Most studies on S3D displays have verified that user perception of 3D scenes and objects was improved with such technologies. Furthermore, these technologies enhanced the users' ability to memorize and recall 3D scenes and objects and increased the effectiveness of learning spatial and environmental relationships (Patterson, Cristino, Hayward, & Leek, 2012). Regarding the completion time of spatial cognition tasks, stereoscopic presentation methods were more efficient and accurate than conventional 3D methods for estimating depths (Price & Lee, 2010).

For medical applications, some research has reported that S3D displays were beneficial over monoscopic 3D displays for relative position judgment tasks in a medical visualization setting (Escobar et al., 2015). However, some experiments have concluded that S3D viewings offer no significant advantages over monoscopic 3D viewings (McIntire & Liggett, 2014). If the presence of monocular depth cues was sufficient to complete the tasks, the binocular depth cue offered by S3D was not necessary.

In addition, some research has reported that the effects of S3D on science learning were related to the spatial ability of the viewer (Price, Lee, Plummer, SubbaRao, & Wyatt, 2015). Participants with different levels of spatial abilities perceived stereoscopic images differently. Recently, a study about virtual molecule manipulation

has demonstrated that S3D did not benefit participants with high spatial ability, while it did benefit those with low spatial ability (Barrett & Hegarty, 2014).

Given the potential advantages and limitations of S3D, determining if a stereoscopic viewing approach is effective for all students or if its efficacy depends on the characteristics of the tasks or the levels of spatial abilities of the students deserves in-depth study. Also, given that in product design education, identifying “proportion” and manipulating “proportional relationships” are important practices in form-giving training (Rampino & Gorno, 2011), determining whether S3D is helpful in form proportion training is another research issue addressed in this research.

## METHOD

### Research Design

The objective of the present study was to understand whether using an S3D as a teaching tool for design department students can assist them in improving their ability to interpret the dimensions and proportions of objects. The independent variables of the experiment included spatial ability, task complexity, and display mode. Spatial ability was a between-subject variable. Students aged 20–25 years were recruited as participants and were categorized into high-, moderate-, and low-performance groups depending on their score on a spatial ability scale. Task complexity and display mode were within-subject variables. The participants interacted with 3D digital models in 2D and S3D display modes before judging an object’s proportions. In order to control the task complexity, the deformation of the digital models changed sequentially from differences of 20%, to 10% and then to 3%. The dependent variable were the score of selecting the 3D digital models with correct proportions compared to the physical objects.

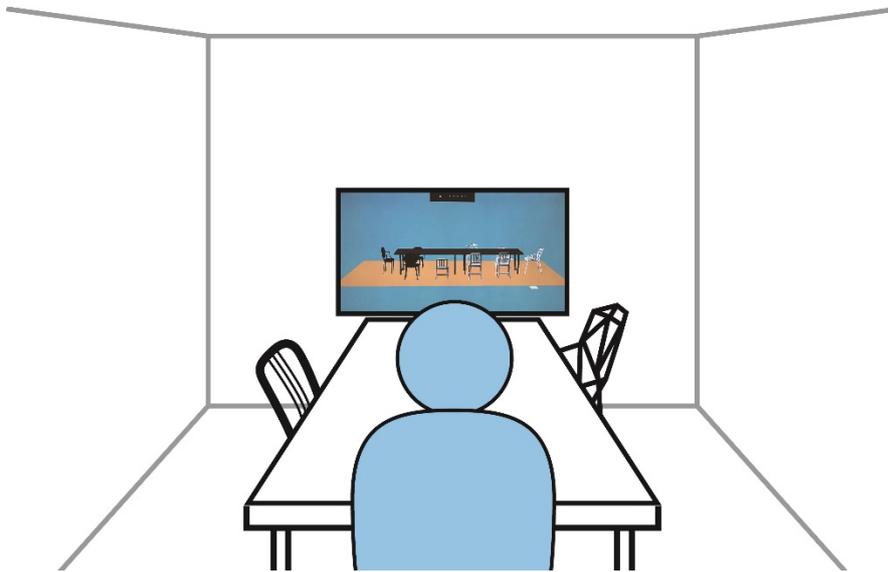
### Stimuli and Apparatus

In order to construct a system for experiment, Visual C++ 2013 and Direct3D 11.1 were employed as the development tools. The Direct3D S3D sample and Visual Studio 3D Starter Kit were modified and integrated to construct a platform for importing 3D models in FBX format and displaying these models in either S3D or 2D mode. The program ran on a Windows 8 operation system installed in an Acer desktop computer with a GT640 graphic card. The images were displayed on a 50-inch 3D TV and viewed through passive glasses. In addition, the experiment system allowed users to adjust the effect of disparity for S3D display mode. The investigator could switch between 2D display and S3D display modes. The pilot test of such a system was carried out previously with 30 participants (Chen et al., 2015). The system could help participants perform the tasks of identifying image differences and locating ergonomic or design problems.

To offer minimal interactivity, the users could change the mode of model rotation. At the beginning of program execution, the 3D models rotated in 1.0 rpm with respect to the vertical axis. The user could use the left button on the computer mouse to stop or start rotation.

The computer-based test displayed 2D and S3D images in a laboratory. Only the participant and the recorders stayed in the experimental site, thus minimizing external interference (Figure 1). The lighting of the experimental site was dimmed to minimize lighting interference on the testing results. The participants were video-recorded as they completed the computer-based test. The recorders used interviews to understand the participants’ perceptions of 2D and S3D modes.

The computer-based test in this study referenced the triangulation cupping method adopted in the World Cup Tasters Championship to facilitate questionnaire responses. A cup taster must determine the correct cup of coffee among three similar samples. Similarly, three chair styles (i.e., Chair One, Emeco Kong, and Navy 1006 chairs) that the design department students were familiar with were used as the samples. For each chair style, two chairs with distinct length–width ratios in addition to a chair with the correct length–width ratio were prepared. The participants were asked to pick the correct one from the three chair examples. Similar to the triangulation



**Figure 1.** The equipment and the experimental site planning

Deformation rate	2D Display Mode	S3D Display Mode
20%		
10%		
3%		

**Figure 2.** The 2D and S3D modes with different deformation rates from 20% to 3%

cupping method, in which the difference among the three cups of coffee diminishes and the difficulty increases gradually, the deformation of the chair dimensions in this study changed sequentially from differences of 20% to 10% and 3% to increase the difficulty.

The computer-based test comprised two stages: the 2D and S3D modes (**Figure 2**). In both tests, the three chair styles were used as the samples. For each style, three chair examples with distinct dimensions were displayed. For each chair style, the participants were asked to select the chair with the correct dimensions and proportions. Each correct answer received 1 point, and the full score for each test was 3 points. Each participant received three cycles of testing in completing the computer-based test.

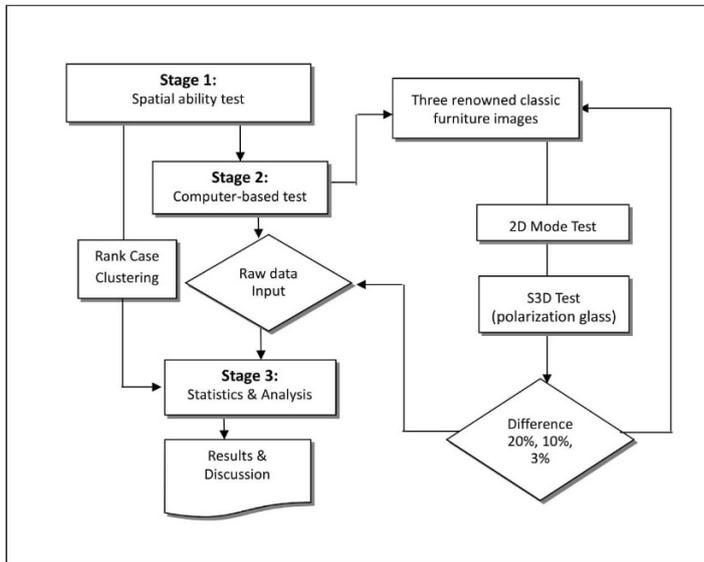


Figure 3. Research design and the experiment flowchart

### Procedure

This study was carried out in two stages. In Stage 1, all participants completed a spatial ability test to determine their spatial ability. Stage 2 involved a computer-based test. The test objects were renowned classic furniture that the students were familiar with. The participants first observed interactive 3D furniture models displayed in a 2D mode and completed the questionnaire. Next, they wore S3D glasses to observe interactive 3D models and answered related test questions. Finally, analysis of the differences between 2D and S3D modes were conducted to determine the learning effectiveness from employing an S3D to identify proportions. A flow chart of the experiment is shown in Figure 3.

### Spatial ability test

At Stage 1, all participants completed a spatial ability test. A total of 41 design department students aged 20–25 years participated in this study. The 30-item questionnaire for the spatial ability test was based on Revised Purdue Spatial Visualization test: Visualization of Rotations. The validity and reliability of this test in measuring spatial ability had been proved in the literature (Maeda et al., 2013). One point was received for each correct answer, i.e., the full score was 30 points. The participants were requested to complete the test in 20 minutes.

The purpose of this test was to identify the participants’ spatial ability levels. The authors used the rank cases function in SPSS software to divide the 41 participants into three groups with low, moderate, and high spatial ability ( $N_{low} = 13$ ,  $N_{moderate} = 13$ , and  $N_{high} = 15$ , respectively). Descriptive statistics such as means and standard deviations of the scores of each group are shown in Table 1.

Table 1. The rank cases clustering for spatial ability test

Spatial Ability Groups	N	Mean	Std. Deviation
Low	13	17.62	0.96
Moderate	13	21.85	1.41
High	15	27.20	1.66
Total	41	22.46	4.24



**Figure 4.** The computer-based test

### *Computer-based tests*

After the spatial ability test, the participants rested for a few days before taking the computer-based test in Stage 2. The participants were allowed to take the test whenever they wanted. In Stage 2, the participants were provided with actual chairs to enable them to perceive the correct chair dimensions and proportions, thus facilitating their responses and comparisons (Figure 4). The participants were permitted to note or sketch the chair dimensions and proportions that they perceived.

In the 2D test, the participants were asked to watch images on a television screen. The screen presented three chair styles that the participants could rotate, thus freely selecting a view angle. Three examples were provided for each chair style. Therefore, the screen showed nine chairs at the same time. For each style, only one chair had the correct dimensions and proportions; the other two had a ratios of difference compared with the actual chair. The difference was relatively large at the beginning (20%). The participants had to identify the chair with the correct dimensions and proportions. Since three chair styles were presented concurrently, the participants had to choose three chairs in each test. A correct answer for a style earned 1 point for each participant.

After the 2D test, the arrangement of the chairs was randomly altered before the participants performed the S3D test wearing polarized glasses. Similarly, the participants could rotate and customize the view angle freely while picking the correct three chairs from the nine chairs. For each style, 1 point was received for a correct answer. Figure 4 shows the testing scenario, with the participant viewing 3D images while wearing polarization glasses.

After the first test, the participants relaxed their eyes for 10 minutes. The same cycle of 2D and S3D image viewing was repeated with the proportional difference decreased to 10%, which increased the difficulty of the spatial identification. Subsequently, the participants took another break before the last cycle, which had a proportional difference of 3%, further increasing the difficulty of the spatial identification. The entire computer-based test and the two breaks were completed in 40 minutes.

**Table 2.** Descriptive statistics for computer-based test with different deformation rates

Deformation rate	Group	n	2D		S3D		Total	
			M	SD	M	SD	M	SD
20%	L	13	1.385	0.506	3.000	0.000	2.192	.100
	M	13	1.692	0.480	2.923	0.277	2.308	.100
	H	15	2.000	0.655	2.867	0.352	2.433	.093
	Total	41	1.707	0.602	2.927	0.264	2.311	.057
10%	L	13	1.000	0.707	2.385	0.506	1.692	.118
	M	13	1.538	0.519	2.692	0.480	2.115	.118
	H	15	1.267	0.594	2.733	0.458	2.000	.110
	Total	41	1.268	0.633	2.610	0.494	1.936	.066
3%	L	13	0.231	0.439	1.769	0.832	1.000	.124
	M	13	0.615	0.506	2.231	0.439	1.423	.124
	H	15	0.800	0.561	2.133	0.640	1.467	.116
	Total	41	0.561	0.550	2.049	0.669	1.297	.070

M = mean, SD = Standard Deviation

**Table 3.** Analysis of variance (ANOVA) results

		SS	df	MS	F	Sig.
2D 20%	Between	2.642	2	1.321	4.237*	.022
	Within	11.846	38	.312		
	Total	14.488	40			
2D 10%	Between	1.885	2	.942	2.528	.093
	Within	14.164	38	.373		
	Total	16.049	40			
2D 3%	Between	2.313	2	1.156	4.491*	.018
	Within	9.785	38	.257		
	Total	12.098	40			
S3D 20%	Between	.124	2	.062	.887	.420
	Within	2.656	38	.070		
	Total	2.780	40			
S3D 10%	Between	.977	2	.488	2.114	.135
	Within	8.779	38	.231		
	Total	9.756	40			
S3D 3%	Between	1.554	2	.777	1.806	.178
	Within	16.349	38	.430		
	Total	17.902	40			

## RESULTS AND DISCUSSION

Descriptive statistics for the computer-based test are shown in **Table 2**. The mean scores clearly show that the difficulty in selecting the correct chair increased as the deformation difference decreased. The overall mean decreased from 2.311 to 1.297 points. Regardless of the participants' spatial ability, they attained substantially higher average scores when in the S3D test than they did in the 2D test. This result confirmed that S3D is conducive to identifying proportions. This beneficial effect was increasingly significant as the difficulty increased.

Analysis of variance (ANOVA) results for these data are shown in **Table 3**. When the participants were in the 2D test, the level of spatial ability affected response accuracy. For instance, the participants exhibited a significant difference in means at the 20% deformation rate ( $F(2,38) = 4.237, p = .022$ ) and the 3% deformation rate ( $F(2,38) = 4.491, p = .018$ ). However, when the participants conducted the S3D test, no significant difference was observed in the mean scores of the three testing cycles, regardless of the participants' spatial ability. For instance,

at the 20% deformation rate, the groups with distinct levels of spatial ability showed no significant difference ( $F(2,38) = .887, p = .420$ ). As the deformation rate decreased to 10% and 3%, the results still showed no significant difference. These preliminary results verified that the S3D mode assists in mitigating gaps between students' spatial abilities.

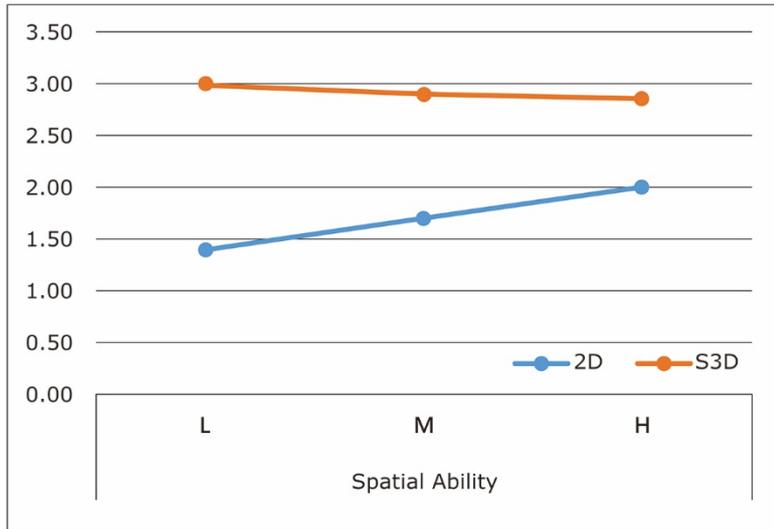
To determine the relationship among the experimental variables in the three testing cycles, two-way ANOVA of repeated measures was conducted. In the 20% deformation test, an analysis of the main effect of the two independent variables showed no significant differences among the total scores of groups with distinct levels of spatial ability ( $F(2,38) = 1.553, p = .225 > .05$ ). However, the two within-subject sample means of 2D and S3D tests exhibited a significant difference with a between-group effect of  $F(1,38) = 260.532, p = .000 < .05$ . This result verifies that wearing polarization glasses significantly improved the participants' spatial cognition in selecting the correct chairs.

According to this result, although the group with high spatial ability exhibited a high total mean at the 20% deformation rate, no significant difference was observed between the groups. The authors inferred that the participants with low spatial ability experienced no difficulties during tests because the difference in deformation rate was considerable.

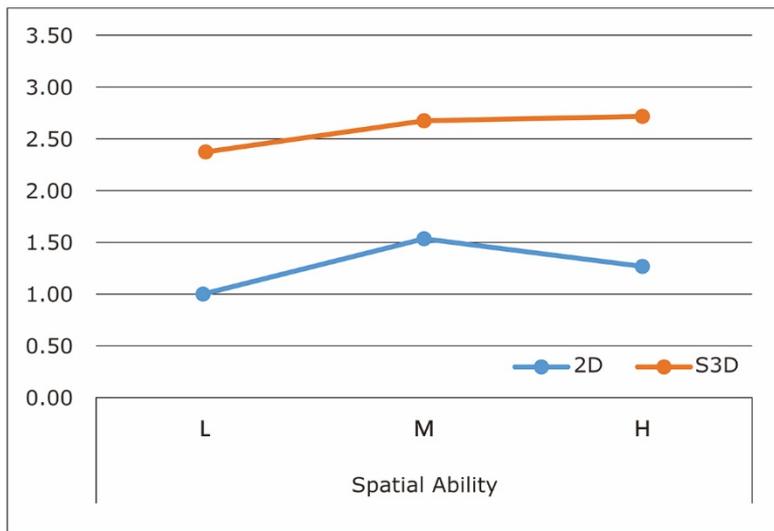
In the second cycle, the test difficulty increased by decreasing the deformation rate to 10%. Analysis of the main effect of the two independent variables showed that the total mean scores between the groups with distinct spatial ability levels reached a significant difference ( $F(2,38) = 3.473, p = .041 < .05$ ). This result indicates that when the deformation rate reached 10%, the level of spatial ability generated a significant difference. The two within-subject sample means also demonstrated a significant difference with a between-group effect of  $F(1,38) = 149.400, p = .000 < .05$ . This result indicates that the S3D mode had a more significant effect on picking the correct chairs than the 2D mode did.

In the third cycle, the difference among chairs of the same style declined to 3%, considerably increasing the difficulty of picking the correct chair. Analysis of the main effect of the two independent variables revealed that the groups with distinct spatial ability levels showed a significant difference in total mean scores ( $F(2,38) = 4.424, p = .019 < .05$ ). This result indicates that when the deformation rate decreased to 3%, the mean scores of participants with distinct spatial ability levels still showed a significant difference. In addition, the between-group effect of the two sample means for whether the participant in the S3D mode reached significance ( $F(1,38) = 160.331, p = .000 < .05$ ), validating that the S3D mode was significantly conducive to spatial cognition.

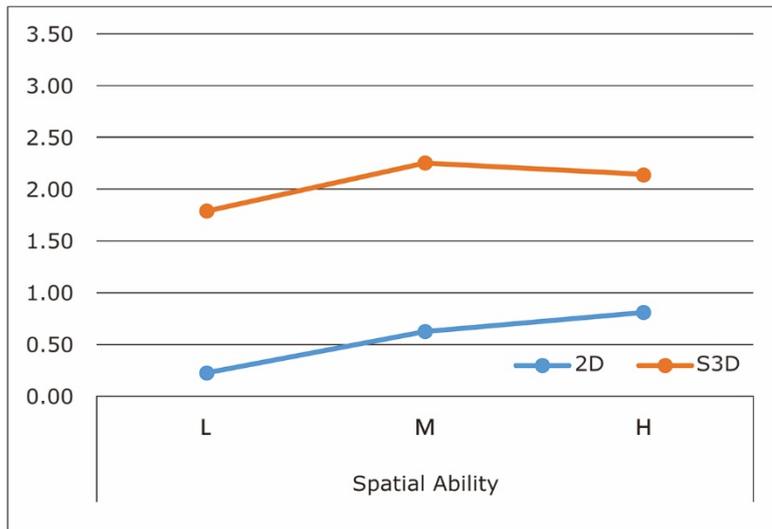
Finally, a post hoc comparison was conducted, and line charts were plotted for analysis. The  $y$ - and  $x$ -axes represent mean score and spatial ability, respectively. The 2D and S3D use are expressed in individual lines. **Figures 5-7** show the relationship of the three testing cycles involving deformation rates of 20%, 10%, and 3%, respectively. Clearly, the three line charts demonstrate nonparallel lines, indicating that an interactive effect existed between spatial ability and the S3D mode. In other words, the mean scores of the three spatial ability groups were moderated by S3D use, exhibiting a significant difference.



**Figure 5.** The performance line chart for the 20% deformation rate



**Figure 6.** The performance line chart for the 10% deformation rate



**Figure 7.** The performance line chart for the 3% deformation rate

The effect of S3D use on the scores of the three groups differed. For example, the participants with low spatial ability occasionally exhibited scores higher than those of the participants with high ability. A fixed order could not be determined from the three cycles of experimental data. This result was possibly caused by approximating the spatial ability of the three groups after they conducted the S3D test, thereby mitigating the gap between the spatial ability levels of the participants in the 2D test. In other words, the group that originally scored highest in spatial ability on the 2D test did not necessarily score highest on the S3D test. This result again proved that the S3D mode effectively assists students in design education.

While most literature focused on the techniques and tools for improving the abilities of spatial relations, spatial visualization, or spatial orientation (Alqahtani et al., 2017; Nagy-Kondor, 2017; Roca-González et al., 2017), the present study focused on training the synthesis ability of proportion estimation. Furthermore, the experimental S3D system provided users with binocular depth cue, overcoming the limitation of traditional Virtual Reality or Augmented Reality systems that offered only monocular depth cues. The binocular depth cue could stimulate self-regulated reflections while comparing the virtual models and physical objects in the training sessions.

## CONCLUSION AND SUGGESTIONS

The ANOVA results of the experiment clearly indicate that the S3D system assists students in identifying the proportions of objects. This effect became particularly pronounced as the test difficulty increased. For example, in the testing cycle with a 20% deformation rate, the mean score of the 41 participants increased from 1.7 to 2.9 points (nearly a full score of 3 points), a 70% increase. In the most difficult cycle (3% deformation rate), the mean score for the 2D test was 0.56 points; however, the mean score reached 2.05, a 266% increase, when the participants conducted the S3D test. This result was unexpected and showed that, in contrast with the 2D mode, the S3D mode was more beneficial for design department students in interpreting the proportions of objects in spatial compositions.

As shown by the differences among the three groups of participants with low, moderate, and high spatial ability, S3D use was most beneficial to the participants with low spatial ability. In the 2D test, differences existed among the three groups in identifying proportions. The group with low spatial ability exhibited test data significantly different from those of the other groups in the three testing cycles. At a deformation rate of 3%, the group with low spatial ability attained an average score of only 0.23 points. However, the mean scores stratified by

spatial ability showed no significant difference in any of the three S3D testing cycles. Moreover, the participants who scored lowest on the 2D test scored the highest on the S3D cycle with a deformation rate of 20%. In the most difficult cycle (3% deformation rate), the participants who had moderate mean scores on the 2D test achieved the highest mean scores on the S3D test. Thus, the S3D mode maximized the spatial ability of participants with low spatial ability and benefitted them the most.

The aforementioned results indicate if S3D were introduced in design teaching activities, students could more accurately perceive proportions. Regardless of the spatial ability of the students, they could achieve significant progress. In particular, participants with low spatial ability demonstrated excellent overall performance when using S3D that was equal to the participants with high spatial ability. Hence, students with low spatial ability require similar equipment to improve their ability to identify proportions.

The test results indicate that technological advancement has provided a novel solution to a conventional design education problem. The S3D system enables students to perceive the third axial direction (i.e., depth), whereas the conventional 2D teaching model relies only on monocular depth cues. The S3D system enables students to easily discern the relationship between object proportions during the learning process, in addition to strengthening their self-reflection and self-regulation in training, compensating for gaps in spatial cognition. Thus, their learning effectiveness can be substantially improved.

Although the proposed test achieved satisfactory outcomes, whether the S3D can be introduced into design practice with designers operating 3D digital contents over long periods was not investigated in the present study. For example, some literature has indicated that participants might experience eyestrain and fatigue, due to long-term exposure to S3D (McIntire & Liggett, 2014). Future studies should consider including such a topic in their experimental planning.

#### ACKNOWLEDGEMENT

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