British Journal of Educational Technology Vol 45 No 4 2014 666–675
doi:10.1111/bjet.12059

Motion controllers for learners to manipulate and interact with 3D objects for mental rotation training

Shih-Ching Yeh, Jin-Liang Wang, Chin-Yeh Wang, Po-Han Lin, Gwo-Dong Chen and Albert Rizzo

Shih-Ching Yeh is an assistant professor in the Department of Computer Science and Information Engineering at National Central Unversity, Taiwan. Jin-Liang Wang is currently a PhD student in the Department of Computer Science and Information Engineering at National Central University, Taiwan. Chin-Yeh Wang is an assistant research scholar in the Research Center for Science and Technology for Learning, National Central University, Taiwan. Po-Han Lin is a PhD student in the Graduate Institute of Learning and Instruction, National Central University, Taiwan. Gwo-Dong Chen is a professor in the Department of Computer Science and Information Engineering at National Central University, Taiwan. Albert Rizzo is a research scientist and research professor in the Institute for Creative Technologies and in the Department of Psychiatry/School of Gerontology, University of Southern California. Address for correspondence: Dr Chin-Yeh Wang, The Research Center for Science and Technology for Learning, National Central University, 300 Jhongda Rd., Jhongli City, Taoyuan County 32001, Jhongli, Taoyuan 32001, Taiwan. Email: chinyea@db.csie.ncu.edu.tw; chinyea871@hotmail.com

Abstract

Mental rotation is an important spatial processing ability and an important element in intelligence tests. However, the majority of past attempts at training mental rotation have used paper-and-pencil tests or digital images. This study proposes an innovative mental rotation training approach using magnetic motion controllers to allow learners to manipulate and interact with three-dimensional (3D) objects. Stereovision allows learners to perceive the spatial geometric form of a 3D object. This approach allows learners to perceive 3D objects in space through stereovision and make mental rotation visible from each intrinsic and invisible mental rotation step using motion-interaction methods. This study examines the effects of user training performance and perceptions. The results indicate that the proposed approach can improve user mental rotation ability effectively. Learners expressed high degrees of concentration toward the mechanism that included direct control and immediate feedback. The results also suggest that female testers perceive greater degrees of playfulness toward the mechanism and improve more through training than male testers.

Introduction

Mental rotation belongs to the category of spatial cognition and refers to the ability to mentally rotate objects in two- or three-dimensional space. This ability significantly impacts learning activities across multiple disciplines, including geometry, physics, mirror image refraction and reflection, and chemical structures. People with superior mental rotation abilities grasp these concepts more rapidly than others (Moe & Pazzaglia, 2006). This ability is therefore indispensable for mathematicians, chemists, engineers and artists.

The current method of judging the strength of a person's mental rotation ability is based on the degree of accuracy and time spent on a mental rotation test. Early mental rotation training was performed primarily through continual practice on paper tests or engaging in educational activities involving puzzles. Later, the popularization of personal computers allowed for the use of computer games, such as Tetris, to improve mental rotation abilities. In recent years, with

Practitioner Notes

What is already known about this topic

- The majority of past attempts at training mental rotation have used paper–and-pencil tests or digital images.
- Women's mental rotation ability might not show as well as men on paper-and-pencil tests.

What this paper adds

- This study uses an innovative mental rotation training mechanism that integrates motion control and three-dimensional (3D) stereovision technology, allowing learners to perceive 3D geometric shapes of objects through stereovision. It also allows visibility of mental rotation from each intrinsic and invisible mental rotation step using motion-interaction methods. This system then provides real-time rotation results through stereovision to the user with visual cues for necessary adjustments for the next step of space rotation.
- Women showed a greater degree of improvement in learning performance and expressed significantly higher perceived playfulness than men when using the mental training system with motion control and stereovision.

Implications for practice and/or policy

- This study tries to use motion controllers and 3D stereovision technology for mental rotation training. This approach can put into practice to increase students' mental rotation ability. Students can perceive more playfulness and pay more attention while operating the 3D objects through motion controllers.
- This research could be a good reference for other researchers while adopting motion controllers or 3D stereovision technology for learning.

developments in relevant technology, novel technologies led to more realistic, concrete and interesting three-dimensional (3D) mental rotation training activities, such as the use of 3D images and interactive technologies, to provide situational or authentic learning. Constructed 3D virtual learning environments can improve learning motivation through the creation of learning environments and activities that are closer to knowledge and situations encountered in daily life. Moreover, students can become active participants in learning processes, and their motivations may shift from extrinsic to intrinsic rewards (Bruner, 1961).

This study uses an innovative mental rotation training mechanism that integrates motion control and 3D stereovision technology, allowing learners to perceive 3D geometric shapes of objects through stereovision. It also allows visibility of mental rotation from each intrinsic and invisible mental rotation step using motion-interaction methods. This system then provides real-time rotation results through stereovision to the user with visual cues for necessary adjustments for the next step of space rotation. This process is continually repeated to complete training.

Related work

The first part of this section introduces current mental rotation training approaches. The second part describes how current training systems increasingly focus on providing playfulness for the learners. When learners experience more playfulness, they have more positive attitudes, consequently involving themselves more deeply in the task. This study focuses on the effects of training performance along with the user's perception of playfulness of the system.

Mental rotation training approaches

In traditional mental rotation training, participants complete a seven-piece puzzle or play Tetris. Cooper (1976) proposed using some two-dimensional (2D) images for mental rotation training, including incongruent representations and diverse rotation angles. Results showed that participants who received mental rotation training showed a significant improvement in mental rotation abilities. De Lisi and Wolford (2002) allowed participants to undergo training by playing Tetris. After training, the participants exhibited improved performance on mental rotation tests. Participants who obtained a high score in Tetris also obtained higher scores on the mental rotation test. Rafi, Samsudin and Ismail (2006) had participants use engineering drawing software as a mental rotation training tool; the results indicated that interactions between the user and the training tools resulted in enhanced performance on a mental rotation task. Rafi and Samsudin (2009) used computers as tools for participants to decide how to rotate objects to match the targets. This approach provides participants with opportunities to experiment with methods and use reflective thinking. In a constructivist interpretation system (Dalgarno, 2001), participants were required to compare two pictures of 3D objects to determine how to rotate them. Results indicated that the 3D environment was more appreciative and better facilitated the imagination of the participants while comparing with the 2D setting. Although many approaches have been proposed, few training environments support the immersion to allow participants to control 3D objects directly through stereo observation.

Immersive environment

Previously, learners have typically used a keyboard and mouse to interact with a computer. During the learning process, they received immediate and useful feedback that promoted interest and assisted in concentration, thereby improving learning outcomes. Recent technological developments such as 3D virtual environments and somatosensory interfaces allow users to interact intuitively with highly realistic simulation environments. Thus, they can focus on learning objectives and training for specific tasks in realistic situations, without the need to learn how to navigate a complex user interface. Furthermore, intuitive interfaces provide a greater level of control than that offered by a keyboard and mouse. Examples of such systems include flight simulation and surgical training systems that employ immersive virtual environments that users can operate intuitively. Learning with these technologies is potentially more convenient and efficient. The potential for these systems has been enhanced by the development of interfaces such as Nintendo Wii, Sony PS Move and Microsoft Kinect (for Xbox or PC), which allow people to experience gesture-based computing in their households. Sophisticated hand-held computing systems are also being developed. Furthermore, the price of hardware and software required to implement the discussed virtual technologies has become economically feasible for classroom environments; thus, the application of visual 3D stereo images with intuitive control has become potentially viable.

To create an immersive environment, Cruz-Neira, Sandin and DeFanti (1993) proposed a room-sized virtual reality (VR) system named the CAVE. They employed high-resolution stereoscopic projection and 3D computer graphics to develop a sense of presence in a virtual environment. Their system integrated a motion capture interface to record the user position in real time. The CAVE was used to build narrative-based, immersive, constructionist/collaborative environments for children, which encouraged exploration and experiential learning (Roussos *et al*, 1997). Users constructed and cultivated simple virtual ecosystems that incorporated complex models with numerous variables and behaviors that children typically have difficulty visualizing. This shows that immersive environments have been applied effectively to reduce complex models to simpler qualitative representations for learning. Chen (2006) employed 3D VR technology to create an immersive environment for training novice driver training. Their study presented 3D representations and dynamics of road scenarios that significantly reduced learners' needs to use their existing spatial processing schemas and showed that learners with VR experience achieved significantly higher gain scores for the VR-based test than those without similar experience.

Currently, commercial companies employ stereoscopic 3D display systems that present users with highly detailed and realistic environments. Furthermore, tracking systems have also been incorporated so users can move 3D images and interact with them. However, the design and development of practical applications for specific learning objectives requires intensive interdisciplinary collaboration to realize the potential of gesture-based computing in immersive environments. Such research would provide an effective analysis to assist in identifying specific causalities that would enhance the design of the discussed technologies.

Playfulness

Playfulness (Barnett, 1990), treated as a motivational characteristic of users, also plays an important role in modern learning systems. Martocchio (1992) showed that the cognitive playfulness of participants significantly affects microcomputer training performance. Moon and Kim (2001) found that participants might focus more and feel more enjoyment in a playful learning environment. They also extended the technology acceptance model (Davis, Bagozzi & Warshaw, 1989) of an individual's Internet acceptance behavior by adding perceptions of playfulness as an intrinsic motivation factor. The results showed that perceived playfulness, perceived ease of use and perceived usefulness have a significant influence on attitude; attitude has a significant influence on behavioral intention to use and actual usage. Roca and Gagne (2008) also confirmed that the influence of playfulness is stronger than perceived usefulness. Woszczynski, Roth and Segars (2002) found that playfulness allowed participants to immerse themselves in a learning environment.

Therefore, when evaluating a training system, the demands of playfulness are as important as learning outcome. This study adopts a kinesthetic sensation technique to create an immersive learning environment in which participants can actively control 3D objects. The kinesthetic sensation technique may increase the participants' intrinsic motivation and playfulness.

Method

The participants recruited for this study comprised 79 university students in Taiwan who were placed into two groups (experimental and control) based on pretest scores to evaluate differences in their perceived playfulness and improvement.

Participants

The 79 university students that participated in this study comprised 37 men and 42 women who majored in Chinese Literature, Finance, Business Administration, Information Management, Electrical Engineering, as well as Computer Science and Information Engineering. Three female participants were excluded due to their extreme z-score (above 2.5) in initial pretest. The excluding criterion followed the specified z-score suggested by Vanselst and Jolicoeur (1994; see also Cousineau & Chartier, 2010 for review). Students were in the ages between 21 and 44, with a mean score of 25.02 years old (mode = 23 years, SD = 4.96 years).

Procedures

The experiments were conducted over 2 weeks and included two training activities. The weekly learning time totaled 90 min and comprised an introductory film (10 min), as well as two activities (40 min each).

To ensure that the experimental and control groups had identical initial average mental rotation abilities, the mental rotation abilities of participants were pretested using the original mental rotation test proposed by Vandenberg and Kuse (1978), which comprised 24 test items. Participants were presented with four geometric forms and awarded one point if they identified a match with a target object (scores ranged from 0 to 24) and were allocated evenly into two groups based on the pretest results. Following the training process, participants were immediately posttested in a manner that was identical to the pretest (test items were reordered).

Experimental group

Mental rotation training comprised the following two learning activities: (1) users rotated or moved a controllable object using a magnetic motion controller until the object was superimposed over a target object (ie, position and orientation). For this activity, we adapted 48 trials from the 24 items of Vandenberg and Kuse's mental rotation test (Vandenberg & Kuse, 1978); and (2) users rotated a controllable object using the abovementioned magnetic sensing controller, although the objects could not be moved. Users rotated the controllable objects to determine whether they matched the target objects. For this activity, we also adapted 96 trials (48 matching objects and 48 nonmatching objects) from Vandenberg and Kuse's mental rotation test (Vandenberg & Kuse, 1978).

The testing method in this study was based on that which was employed by Shepard and Metzler (1971). Participants were required to compare various 3D geometric shapes to determine whether they were identical. Two adjacent 3D objects were projected simultaneously onto a 100-inch projection screen. Users could not rotate or move the target object, although they could freely rotate and move the controllable object (Figure 1).

Control group

For the control group, stereovision and motion-interaction controls were not provided for either learning activity. Both learning activities were identical to the experimental group trials, although they were presented using animated films. The activities are detailed as follows (1) one of the two objects was automatically moved and rotated until superimposed over the other object; and (2) one of the objects was rotated automatically, and participants evaluated whether the other object matched the preceding geometric shape.

After completing the second training activity, the Vandenberg and Kuse mental rotation test (Vandenberg & Kuse, 1978) was employed for posttesting. Participants also completed questionnaires to evaluate perceived playfulness (Martocchio, 1992).

Results

This section presents the participants' performance results as well as their perceived playfulness. Playfulness was evaluated using a questionnaire (7-point Likert scale; 1 = *strongly disagree*, 7 = *strongly agree*) following the 2-week training activities and posttest.

Testing of hypotheses 1 and 2

H_1: Learners using the motion controllers to interact with 3D objects showed higher levels of perceived playfulness than those in control group.

A *t*-test was conducted to compare the effects of the two modes of training. Participants in the experimental group had significantly greater perceived playfulness than those in control group, $t(74) = 4.156$, $p < 0.001$. This finding indicates that learners using motion controllers to interact with 3D objects have better perceived playfulness than those in control group (Table 1).

H_2: Is there any difference of perceived playfulness between woman and men while using the motion controller to manipulate and interact with 3D objects?

We performed a two-way analysis of variance (ANOVA) test with both gender and conditions as between-subject variables to identify any significant differences between women and men's perceived playfulness. The results show a significant difference in perceived playfulness between men and women, $F(1, 72) = 8.361$, $p < 0.01$, partial $\eta^2 = 0.104$, power = 0.814 as well as a

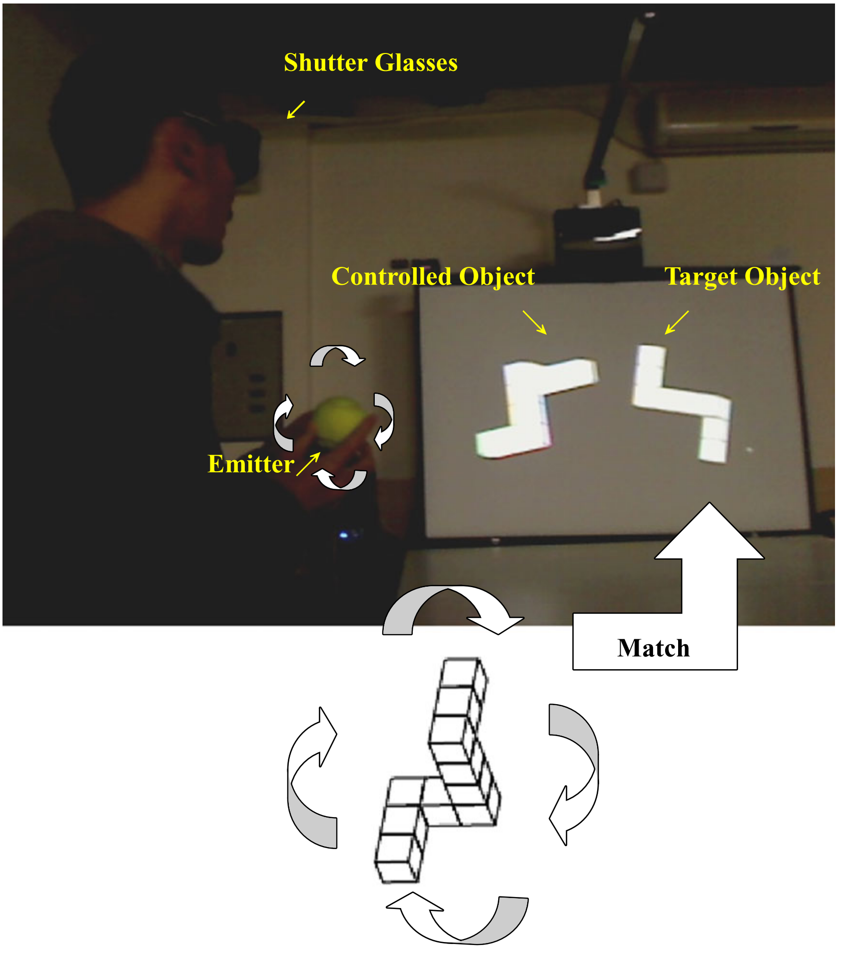

Figure 1: Motion control 3D object training system screenshot

Table 1: Perceived playfulness t*-test results by group*

Condition	n	*Mean*	*SD*	t *value*
Experimental	36	38.06	7.119	4.159**
Control	40	31.50	6.621	

$^{**}p < .001$.

significant main effect of groups, $F(1, 72) = 19.561$, $p < 0.01$, partial $\eta^2 = 0.214$, power = 0.992, which indicates that the mean score of playfulness in the experimental condition is significantly higher than the mean score in the control condition. To further examine the source of variances in between genders across and within conditions, post hoc comparisons of using the Scheffe test are employed. It shows that the mean scores of the women in the experimental group were significantly higher than those of the control group ($p < 0.001$), and the mean scores of the women in the experimental group were also significantly higher than those of men in the experimental group ($p < 0.001$). The descriptive statistics for the playfulness scores are illustrated in Table 2.

Table 2: Mean (SD) perceived playfulness scores by genders across conditions

	Women	*Men*
Experimental group	41.44 (5.382)	34.67 (7.146)
Control group	32.38 (6.232)	30.53 (7.066)

Table 3: Improvement t*-test results by group*

Condition	N	*Mean*	*SD*	*t value*
Experimental	35	3.47	2.348	0.659
Control	41	3.23	2.496	

Testing of hypotheses 3 and 4

H_3: Learners using motion controllers to manipulate and interact with 3D objects will have evidence of better training than those in control group.

This section defines the difference between the pretest and posttest scores as "improvement." This is used to indicate the effectiveness of the training activities. A *t*-test was conducted to compare the effects of the two modes of training. There is no significant difference between the two groups' pretest, $t(74) = 0.473$, $p = 0.638$, indicating the initial spatial abilities of the two groups are similar. We then conducted a *t*-test to compare the improvement. The results show that both groups improved significantly following training, $t(150) = -4.852$, $p < 0.001$ (collapsed between genders for examining the effect of test phases). No significant difference was found in the overall degree of improvement between the two groups, $t(74) = 0.443$, $p = 0.659$. The statistical comparison between the experiment and control group means is shown in Table 3.

H_4: Is there any difference of training performance between woman and men while using the motion controller to manipulate and interact with 3D objects?

Although no difference in the overall improvement between the experimental and control groups were found in the initial *t*-test, it is possible that our training manipulation might have differential effects on men and women. Previous evidence had suggested that similar enhancement training or aids on mental rotation task has a differential effect across genders (eg, McWilliams, Hamilton, & Muncer, 1997; Parsons *et al*, 2004; Wiedenbauer & Jansen-Osmann, 2008). In particular, the marked gender difference in mental rotation performance can be reduced after training or aid where the performances of the women increase a level of performance similar to men. To examine the possibility of differential effect of training between genders, a two-way ANOVA that has genders and groups as the between-subject variable was conducted. The results indicate a significant difference between women and men, $F(1, 72) = 10.509$, $p < 0.01$, partial $\eta^2 = 0.127$, power = 0.892, but no group effect was observed ($F < 1$). Further post hoc comparisons show that the mean score for women in the experimental group was significantly greater than that of men in the experimental group ($p < 0.01$), although there was no significant difference between women and men's training improvement in the control group (Table 4).

Discussion

Women in the experimental group reported a significantly higher perception of playfulness than those in the control group, whereas there was no significant difference between groups for men. Furthermore, women in the experimental group reported higher perceived playfulness than men. The training approach employed in this study applied two technologies: motion control and

Table 4: Mean (SD) improvement scores by gender across conditions

	Female	*Male*
Experimental group	4.61 (2.004)	2.33 (2.181)
Control group	3.67 (2.508)	2.63 (2.408)

stereovision. The results indicate that men did not find the application of these technologies more interesting than animated film training, whereas women reported a greater level interest in the experimental method. This may be attributable to differences in events, objects and situations that men and women encounter in their daily lives. For example, the 3D images and motion control applied in the training activities in this study are not novel to current male college students; however, the women that participated in this study considered the motion control and stereovision system to be more novel and interesting. This may be explained by the following possibilities: (1) men may have more experience with computer games or sports activities that involve mental rotation; or (2) because the mental rotation ability of women that participated in this study is not as developed as that of the men, the discussed approach may reduce cognitive load and assist in the development of mental rotation skills for women; thus, women find the discussed experimental approach more interesting.

In addition, a significant performance improvement was observed in both groups as one compares the performances between pretest and posttest. Although there was no significant difference in the overall learning performance improvement between groups (collapsing scores of men and women together), however, the detail analysis on individual gender reveals that the magnitude or the amount of improvement for women in the experimental group was significantly greater than that of their male counterparts. On the other hand, no significant difference was evident between genders in the control group.

Several factors could potentially contribute to this finding. First, as we argued, differences in improvement may be attributable to the women reporting greater perceived playfulness than men in the experimental group, thereby producing greater levels of improvement. Additional correlational analysis between the scores of playfulness and improvement supports this argument in revealing a marginal significant positive correlation, $r(74) = 0.20$, $p = 0.085$. Although the correlation result does not imply a causal relationship between the two variables, our positive correlation result is important because it is consistent evidence in illustrating the importance of playfulness in medicating the engaging behavior or learning performance (Barnett, 1990; Martocchio, 1992; Roca & Gagne, 2008).

An alternative explanation for differences in improvement could be the initial difference between men and women or the ceiling performance of men. In other words, because women's pretest average scores were less than those of the men; thus, women had greater room for improvement. On the other hand, because men are performed at ceiling, it caps the room for improvement. These possibilities are examined by first checking the initial pretests scores among women across the experimental and control conditions. No difference was found among women in these two groups and thus ruled out the possibility that by chance women in the experimental group happened to have lower scores and therefore higher magnitude of improvement. Second, specific *t*-test comparing the pretest and posttest of men (collapsed across groups) indicated a significant difference. Thus, it suggests that excess room for improvement is also available even for men. Although these two checks did not completely rule out the possibility that improvement difference is caused by the initial difference in men and women, we believe that magnitude of improvement differed between genders despite the same training method is employed.

In addition to studies that focus on finding methods of enhancing performance or narrowing the gender difference (eg, McWilliams, Hamilton, & Muncer, 1997; Parsons *et al*, 2004; Wiedenbauer & Jansen-Osmann, 2008), our study contributes in illustrating that other factors also influence learning. Playfulness of the tool, for example, affects subsequent performance. Several similarities and differences exist in between our study and those in the mental rotation literature. First, difference in the initial pretest scores of men and women in our study is consistent with the marked gender difference that has been reliably found in mental rotation literature (Linn & Petersen, 1985; Masters & Sanders, 1993; Voyer, 2011; Voyer, Voyer & Bryden, 1995). Second, similar to our study, other training or aid has been found to reduce such a difference (McWilliams, Hamilton, & Muncer, 1997; Parsons *et al*, 2004; Wiedenbauer & Jansen-Osmann, 2008). For example, using realistic wooden figurines as stimuli in mental rotation task, McWilliams, Hamilton, and Muncer (1997) showed that the gender bias can be greatly reduced. Also, training in manually rotating a 2D figure (on one of the comparison objects) during mental rotation task helps to eliminate the gender difference in children (Wiedenbauer & Jansen-Osmann, 2008). Similarly, Parsons *et al* (2004) also found no gender difference when participants were given computerized aid to rotate the object in mental rotation task. Although these studies are similar to our study in illustrating methods for increasing performance, their results are typically measured when participants were given aids to the task and whereas in our study the focus is on retention of learning based on our training program as measured in pretest–posttest design fashion. In other words, learning is emphasized. Although direct comparison between scores of those studies to ours maybe impossible, however, it will be interesting to compare the magnitude of improvement across studies. In addition, besides introducing methods for performance enhancement, our study also focuses on revealing other associated factors in influencing learning. Playfulness in an immersive environment could potentially attribute to performance. Thus, the design of future systems should consider approaches to improving the interest of men and women.

These results indicate that the learning performance of both groups improved significantly. Although there was no significant difference between groups for the degree of improvement, based on observations of the experimental process, learners in the experimental group were more focused. Conversely, learners in the control group occasionally shifted their gaze to the left or right. Based on this observation, we assume that hands-on activities might encourage learners to focus and continue to be engaged by learning activities. Although the aid of a motion control interface may produce greater levels of perceived playfulness, it might not inherently promote greater levels of cognition.

Conclusion

This study proposed an innovative mental rotation training approach that integrated motion control and stereovision. To evaluate the effect of the approach, comparisons were made between the discussed system and the viewing of animated videos as a training method. The experimental results indicate that users perceive motion control and stereovision as appealing approaches to training. Compared with the video training approach, participants showed greater attention when using motion control and stereovision. Women showed a greater degree of improvement in learning performance and expressed significantly higher perceived playfulness than men when using the motion control and stereovision system.

To identify the types of learners that motion control and stereovision systems would have the greatest benefits for, future studies should consider learners with various academic backgrounds, experiences and learning styles. This would allow more effective improvements in mental rotation abilities for learners from various backgrounds. Further research should also consider approaches to associating performance scores from the discussed training system with those obtained using traditional mental rotation paper tests.

References

Barnett, L. A. (1990). Playfulness: definition, design, and measurement. *Play & Culture*, *3*, 4, 319–336.

Bruner, J. S. (1961). The act of discovery. *Harvard Educational Review*, *31*, 21–32.

Chen, C. J. (2006). The design, development and evaluation of a virtual reality based learning environment. *Australasian Journal of Educational Technology*, *22*, 1, 39.

Cooper, L. A. (1976). Demonstration of a mental analog of an external rotation. *Attention, Perception, & Psychophysics*, *19*, 4, 296–302.

Cousineau, D. & Chartier, S. (2010). Outliers detection and treatment: a review. *International Journal of Psychological Research*, *3*, 1, 58–67.

Cruz-Neira, C., Sandin, D. J. & DeFanti, T. A. (1993). *Surround-screen projection-based virtual reality: the design and implementation of the CAVE*. Paper presented at the Proceedings of the 20th annual conference on Computer graphics and interactive techniques.

Dalgarno, B. (2001). Interpretations of constructivism and consequences for computer assisted learning. *British Journal of Educational Technology*, *32*, 2, 183–194.

Davis, F. D., Bagozzi, R. P. & Warshaw, P. R. (1989). User acceptance of computer technology: a comparison of two theoretical models. *Management Science*, *35*, 8, 982–1003.

De Lisi, R. & Wolford, J. L. (2002). Improving children's mental rotation accuracy with computer game playing. *The Journal of Genetic Psychology*, *163*, 3, 272–282.

Linn, M. C. & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: a meta-analysis. *Child Development*, *56*, 6, 1479–1498.

Martocchio, J. J. (1992). Microcomputer usage as an opportunity: the influence of context in employee training. *Personnel Psychology*, *45*, 3, 529–552.

Masters, M. S. & Sanders, B. (1993). Is the gender difference in mental rotation disappearing? *Behavior Genetics*, *23*, 4, 337–341.

McWilliams, W., Hamilton, C. J. & Muncer, S. J. (1997). On mental rotation in three dimensions. *Perceptual and Motor Skills*, *85*, 297–298.

Moe, A. & Pazzaglia, F. (2006). Following the instructions!: effects of gender beliefs in mental rotation. *Learning and Individual Differences*, *16*, 4, 369–377.

Moon, J. W. & Kim, Y. G. (2001). Extending the TAM for a world-wide-web context. *Information & Management*, *38*, 4, 217–230.

Parsons, T. D., Larson, P., Kratz, K., Thiebaux, M., Bluestein, B., Buckwalter, J. G. *et al* (2004). Sex differences in mental rotation and spatial rotation in a virtual environment. *Neuropsychologia*, *42*, 4, 555–562.

Rafi, A. & Samsudin, K. (2009). Practising mental rotation using interactive Desktop Mental Rotation Trainer (iDeMRT). *British Journal of Educational Technology*, *40*, 5, 889–900.

Rafi, A., Samsudin, K. A. & Ismail, A. (2006). On improving spatial ability through computer-mediated engineering drawing instruction. *Educational Technology & Society*, *9*, 3, 149–159.

Roca, J. C. & Gagne, M. (2008). Understanding e-learning continuance intention in the workplace: a self-determination theory perspective. *Computers in Human Behavior*, *24*, 4, 1585–1604.

Roussos, M., Johnson, A. E., Leigh, J., Vasilakis, C. A., Barnes, C. R. & Moher, T. G. (1997). NICE: combining constructionism, narrative and collaboration in a virtual learning environment. *Computer Graphics-New York-Association for Computing Machinery*, *31*, 62–63.

Shepard, R. N. & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, *171*, 701–703.

Vandenberg, S. & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills*, *47*, 2, 599–604.

Vanselst, M. & Jolicoeur, P. (1994). A solution to the effect of sample-size on outlier elimination. *Quarterly Journal of Experimental Psychology Section A-Human Experimental Psychology*, *47*, 3, 631–650.

Voyer, D. (2011). Time limits and gender differences on paper-and-pencil tests of mental rotation: a meta-analysis. *Psychonomic Bulletin & Review*, *18*, 2, 267–277.

Voyer, D., Voyer, S. & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: a meta-analysis and consideration of critical variables. *Psychological Bulletin*, *117*, 2, 250.

Wiedenbauer, G. & Jansen-Osmann, P. (2008). Manual training of mental rotation in children. *Learning and Instruction*, *18*, 1, 30–41.

Woszczynski, A. B., Roth, P. L. & Segars, A. H. (2002). Exploring the theoretical foundations of playfulness in computer interactions. *Computers in Human Behavior*, *18*, 4, 369–388.