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SHORT REPORT

Formation of spatial thinking skills through different training methods

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Abstract Spatial training can be durable and transferable if the training involves cognitive process-based tasks. The current study explored different spatial training methods and investigated the sequences of process-based mental simulation that was facilitated by various structures of external spatial representation, *3D technology, spatial cues, and/or technical languages*. A total of 115 Columbia University's students were conducted through three experiments using a between-subjects design to examine the effects of spatial training methods on spatial ability performance. The conditions for training environments included 3D-virtual and 3D-physical interactions with abstract (*nonsense-geometric*) and concrete (*everyday-object*) contents. Overall, learners in the treatment conditions improved in their spatial skills significantly more than those in the control conditions. Particularly, 3D-direct-manipulation conditions in the third experiment added promising results about the specific sequences during spatial thinking formation processes.

Keywords Spatial thinking training · 3D environments · Cognitive processes

Introduction

Spatial thinking skills are important for science, technology, engineering, and mathematics (STEM) disciplines, including architectural profession. Individuals improve their spatial skills performance by experiencing spatial training from practicing a specific task, taking a drawing class, or playing a video game (Uttal et al. 2013). The effects of spatial training can be durable, transferable, and generalizable to other types of spatial skills, if the training involves cognitively process-based tasks (Wright et al. 2008). These processes require cognitive attention from encoding a visual stimulus to constructing a visual image in working memory (WM), transforming an image, and comparing a visual stimulus to an image in WM for a confirmed outcome. *Our research questions remain: What are these specific processes? Can we use them in different trainings, physically and virtually?*

The present study explored different spatial training methods through a series of experiments using both three-dimensional (3D) virtual (computer-assisted) and 3D-physical (direct-manipulation) tools. We investigated a specific process-based mental simulation that was facilitated by the structures of these 3D external spatial representations, including contents used, spatial cues, and technical language. The objective was to understand how the external spatial representations fostered and affected spatial ability acquisition, *the formation of spatial mental models*.

Strategies used by individuals play an important role in developing spatial thinking skills associated with mental processing of tools, objects, and dynamic spatial displays (Hegarty 2010; Newcombe 2010; Hegarty and Waller 2005). There is a limited capacity in working memory (WM), storage, and attention used during mental processes of imagery formation depending upon individuals' prior experiences (Miyake et al. 2001; Just and Carpenter 1985). Individuals also use external representations (3D models) to assist in developing spatial thinking, as survival and communicative tools to off-load WM and to assist executive functions (Goldin-Meadow 2005). Spatial language helps engage in structuring our understanding of spaces

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(Talmy 1983) and help how we view spatial relations among objects in hierarchical manners (McNamara 1986). In other words, the entities of spatial relations can be decomposed (Tversky and Lee 1998), situated (Tversky 2009), and deconstructed for comprehension. Furthermore, human–computer interaction 3D technology offers spatial thinking simulation through computer graphic forms (Card et al. 1999) and facilitates architectural and engineering professionals in solving spatial problems (Mitchell and McCullough 1995). The processes and usages seem to relate to the sketchpad conception in WM by Baddeley and Hitch (1974).

Here, three experiments identified a specific part of cognitive processes affecting spatial ability formation and improved spatial skills. Experiment 1 was to explore the different sequences between manipulation with 3D-virtual (computer-assisted) and 3D-physical (direct-manipulation) tools. Experiment 2 and Experiment 3 were redesigned to eliminate some confound from various activities during Experiment 1 and to confirm the specific training effect. The results confirm the insights of spatial skills formation from both training environments.

Experiment 1

Forty-eight graduate students (70 % females) were recruited through advertisement or course credit (Mean age = 26.9 years, SD = 4.1). Qualified participants were screened as ones who had limited STEM educational experiences and low spatial ability profiles. A between-subject experimental analysis was used. The dependent variables were the test of spatial ability tasks during pretest, posttest, and transfer, modified from Guay's Visualization of Viewpoints and Purdue Spatial Visualization Test. The independent variables were *the external spatial representations*: comparing 3D-virtual, preprogrammed *SketchUp on PC* ($N = 24$), versus 3D-physical, *wooden blocks and objects* ($N = 24$), see Fig. 1. *The training materials* were simple nonsense-geometric shapes versus everyday-life artifacts, seven stimuli for each category, see Fig. 2. Participants attended four activities (an introduction, a drawing, and two rotation tasks) over two 50-min sessions in two separate days.

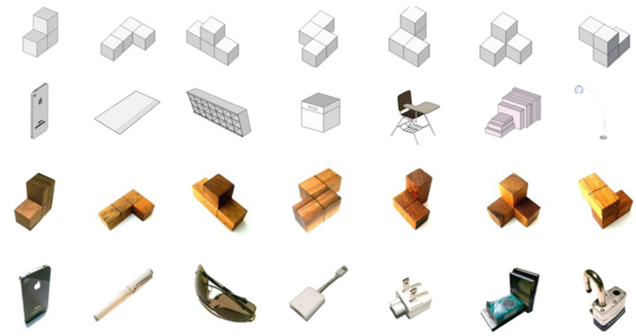

Fig. 2 Stimuli for all intervention categories

Two rotation tasks were designed to map the use of cognitive processes during spatial visualization tasks, such as to understand, mentally encode, and then manipulate 3D spatial forms (Carroll 1993). Activity 1, *Introduction*: *Familiar with Learning Environment*, aims for participants to become familiar with the learning environment they were assigned to. Participants learned to manipulate the objects in their assigned environments. To operate the object rotation tasks, participants in the 3D-virtual condition must select a tool first and then indicate an angle and direction input. For the participants in 3D-physical group, they first directly pick up an object and then rotate by hand. Activity 2, *Drawing Objects*, aims for participants to draw 3D representations of the given seven stimuli.

Activity 3, *Object Rotation I*, aims for participants to rotate an object in different directions such as in a horizontal plane (left and right) and a vertical plane (up and down) to match the given stimulus. The rotation angles are also limited to 90° and 180°. There were two blocks of rotations: single (only either 90° or 180° rotation) and double rotation (first rotation of either 90° or 180°, then another rotation of either 90° or 180°), see Fig. 3. Participants performed a total of 28 trials. Activity 4, *Object Rotation II: Solve Puzzle*, aims for participants to integrate seven pieces of objects into one big cube object. The participants are expected to put all given pieces together by rotating each piece and carefully locating them.

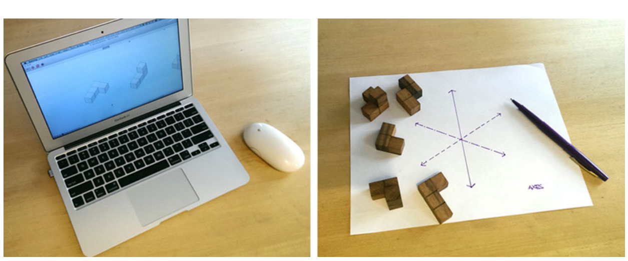

Fig. 1 3D-virtual and 3D-physical environments

Results

Overall, participants in all conditions improved in their posttest spatial measurement. There was no significant difference for the mean pretest of all participants ($M = 22.14$, SD = 7.85), $F(1, 45) = .022$, $p =$ NS. This indicates that participants had a relatively equal level of spatial skills prior to the experiment. However, after the intervention, there were significant differences, $t = 1.15$,

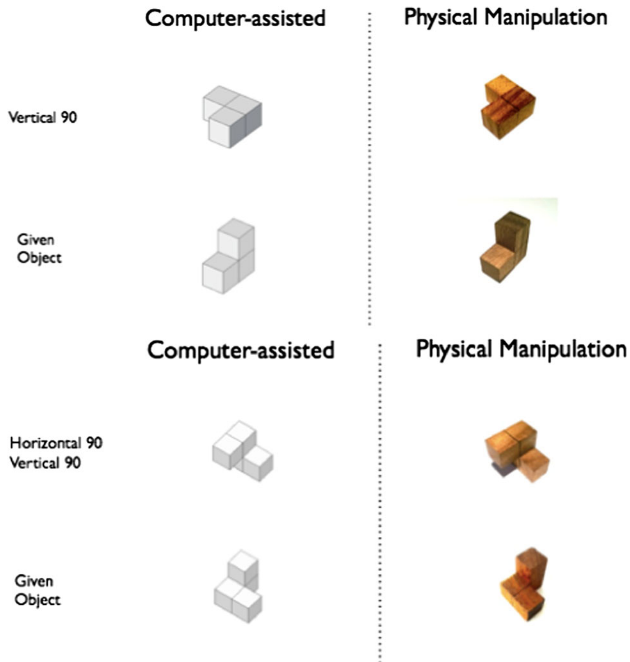

Fig. 3 Example of a single and multiple rotation tasks

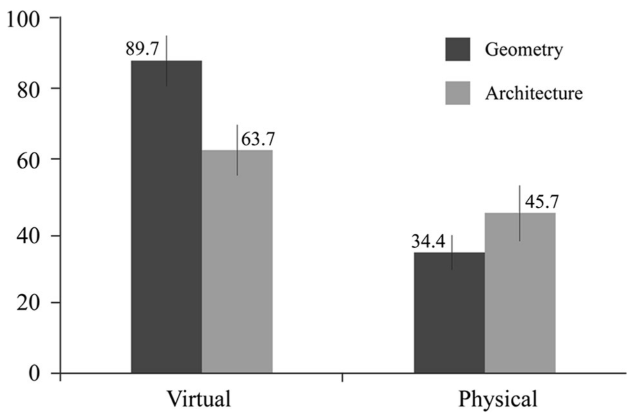

Fig. 4 Means on gain score performance (percentage)

$df = 45$, $p < 0.05$, between the mean posttest for the 3D-physical group ($M = 30.2$, SD = 7.6) and the 3D-virtual group ($M = 34.6$, SD = 5.9). There were also significant differences, $t = 2.351$, $df = 45$, $p < .05$, between the mean gain score for the 3D-physical group ($M = 7.8$, SD = 4.7), and for the 3D-virtual one ($M = 12.6$, SD = 5.8), see Fig. 4. The effects of training materials used between simple geometrical nonsense blocks and everyday-life elements were hypothesized for their content explicitness for the imagination, but the results were not significant, $t = .199$, $df = 45$, p = NS.

Furthermore, the ANOVA was conducted on performance for all groups and covariates with their pretest scores to answer: (1) whether the improvement in scores was greater for the group with the 3D-virtual learning environment than the 3D-physical artifacts, and (2) whether improvement in scores was greater for the group with the simple geometrical content than the one using everyday-life elements. Using gained scores to compute, the learning outcome in the 3D-virtual environment was significantly better than the 3D-physical group but the type of training material showed no significant difference, see Table 1. However, Experiment 1 posed some limitations, such as computer user-interface issues, various activities to indicate the cause of improvement (drawing or rotation), and the modified standardized test used. Experiment 2 was redesigned to address these issues.

Table 1 Analysis of variance for gain scores of four groups

Source	*df*	MS	*F*	Sig.	η^2
Environment	1	224.16	6.19	0.017*	0.143
Material	1	4.34	0.12	0.731	0.003
Environment × material	1	35.44	0.98	0.329	0.026
Error	44	44.01			

* $p < .05$

Experiment 2

Twenty-eight graduate students with similar profiles were recruited. The independent variables were *the external spatial representations*: comparing 3D-virtual, preprogrammed *SketchUp with touch screen* ($N = 14$), versus 3D-physical, *wooden blocks and objects* ($N = 14$). After the introduction phase as similar to Experiment 1, participants performed on rotation activities in two sessions in two separate days. The drawing activity was eliminated from this experiment.

Results

The results of the training effect were replicated from Experiment 1. Overall, participants in both conditions improved in the posttest spatial assessments of the V-K Mental Rotation Test (Shepard and Metzler 1971) and the transfer test of the Surface Development Task. The results confirmed that the 3D-virtual group improved more significantly than the 3D-physical group, see Table 2.

The results from the first two experiments informed some advantage the 3D-virtual group may have gained, but what exactly did the 3D-physical group not have? One prediction was the situated condition may have required by human–computer interaction, such as selection and

Table 2 Means scores and standard deviations

	Spatial ability test-MRT						
	MRT_pretest (40)			MRT_posttest (40)		SDT_transfer (30)	
	n	*M*	SD	*M*	SD	*M*	SD
Virtual	12	18.9	3.4	27.1	3.2	15.4	3.8
Physical	12	17.8	2.4	24.3	2.7	12.6	5.9

information input processes (numbers of angles and directions). *Could these processes have helped learners* (1) *decompose the mental rotation tasks into steps*, (2) *offload their pictorial images of the objects*, and (3) *ultimately complete their imagery understanding?* To answer these questions, we designed the next training experiment to include information input processes in both conditions. Additionally, a spatial measure of physical-based form beyond paper–pencil based such as building a puzzle task was added to offset any advantage or disadvantage.

Experiment 3

Thirty-nine graduate students were recruited. Participants were randomly assigned to one of the two groups of 3D-virtual (N = 19) and 3D-physical ($N = 20$). Within these groups, half of the participants operated the objects either *freely*, without information input, or *integrated*, with information input processes. Participants in the 3D-physical group in the information input process had to write down the number of an angle and direction of the rotation before proceeding to touch the object. Participants in the 3D-virtual group without text input processes directly touched a virtual object and rotated it on the screen (Fig. 5).

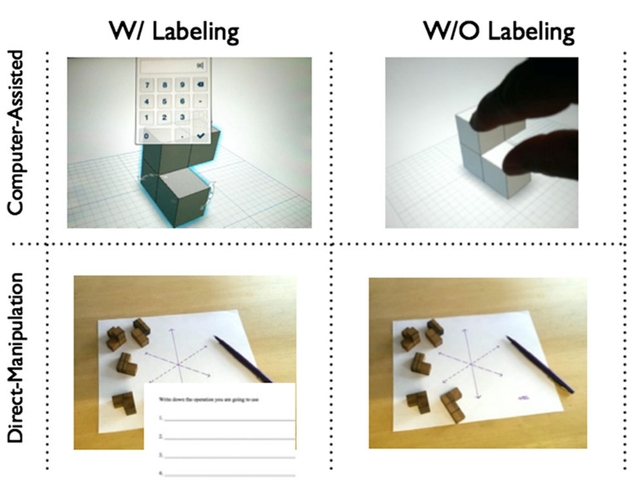

Fig. 5 All four intervention conditions

Results

For the V-K Mental Rotation Test, participants in all conditions improved in their posttest. The analysis of variance of gained score results showed potential significant close to $p < .05$ ($p = .066$) among all four groups. However, in pairwise comparison, the results indicated significance $F = 8.72$, $p < .05$ (.007) for the group that integrated text input processes and nonsignificant results in between 3D-physical and 3D-virtual, $F = .0116$, $p =$ NS (.736). The Building Puzzle Task indicated nonsignificant results for all group comparison, $F = 0.007$, $p =$ NS (.946). Finally, the results for the Surface Development Task showed close to significance in a group comparison (ANOVA), $F = 2.853$, $p = .061$, but more significantly in pairwise t tests of the group that integrated text input processes, $t = 3.004$ ($df = 24$), $p < .05$ (.006), see Fig. 6a, b.

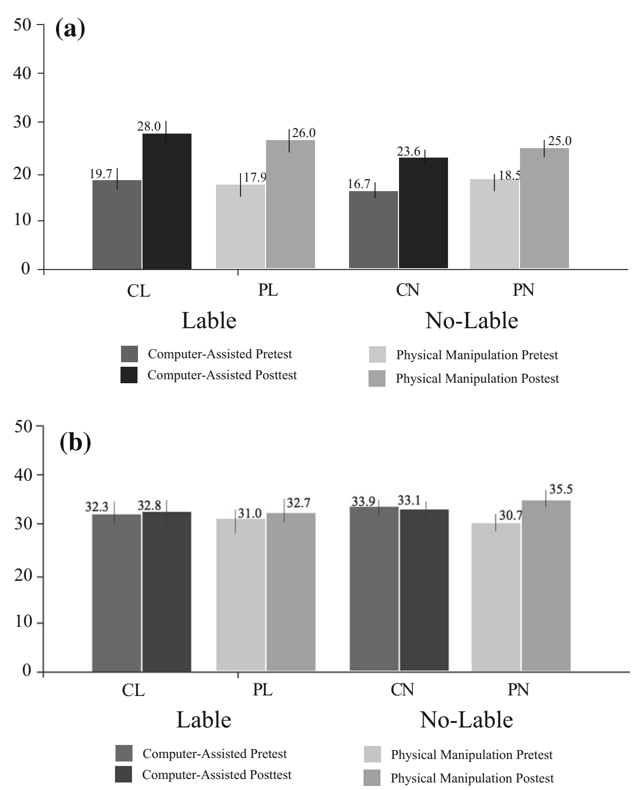

Fig. 6 **a** Mean scores for paper-based V-K Mental Rotation Task. **b** Mean scores for physical-based Building Puzzle Task

Discussion

Taken together, three studies reported positive improvement of the spatial ability trainings of mental rotation. The first two experiments explored different spatial training methods by investigating the potential sequences of process-based mental simulation in spatial thinking. The results initially indicated overall improvement in spatial training, but particularly more significant from the 3D-virtual training condition. However, after the specific processes of the 3D-virtual environment were carefully looked at, the third experiment was designed. As expected, the results showed improvement in spatial skills in both 3D-virtual and 3D-physical conditions with information input processes. This suggests that participants may have formed a complete spatial understanding and imagery (Kosslyn 1994).

It is important to design a training instruction, *for either a physical or virtual environment*, that pays attention to where the crucial cognitive processes are and helps learners formulate better mental representation. Everyday activities may help situate learners with some integration through the use of spatial cues or technical terms into spatial learning. This allows individuals to engage in activities that increase their spatial mental abilities. Ultimately, spatial training may provide learners with strategies when facing mental rotation tasks in STEM fields as in architecture and engineering education.

The next phase following this research is set out to conduct a study with a larger population, including a control group (no spatial training), as well as to report on sex differences, error rates, and response times during the trials.

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