CAAD, COGNITION & SPATIAL THINKING TRAINING

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Abstract. The current study explored different spatial training methods and investigated the sequence of processed-based mental simulation that was facilitated by various structures of external spatial representations, including 3D technology in Computer Aided-Architectural Design (CAAD), spatial cues, and/or technical languages. The goal was to better understand how these components fostered planning experiences and affected spatial ability acquisition framed as the formation of spatial mental models, for further developing spatial training environments fundamental to Science, Technology, Engineering, and Mathematics (STEM) education, specifically for architecture education and cognition. Two experiments were conducted using a between-subjects design to examine the effects of spatial training methods on spatial ability performance. Across both studies learners improved in their spatial skills, specifically the learners in the 3D-augmented virtual environments over the 3D-direct physical manipulation conditions. This study is built upon the work in the fields of computer-user interface, visuospatial thinking and human learning.

Keywords. spatial thinking training; cognitive processes; CAAD.

1. Introduction

Spatial thinking skills are important for architectural education and profession, even though not everyone processes spatial skills on the same level. However, there has been a consistent support in spatial thinking literature illustrating that spatial skills are malleable and acquirable (Baenninger and Newcombe, 1989). People improve their spatial skills performance by experiencing spatial training from practicing a specific task to drawing, or to playing a video game (Uttal et. al, 2013). The effects of spatial training are found to be durable, transferable, and generalizable to other types of spatial
skills (Wright et al, 2008). Particularly, if the training involves cognitively process-based tasks, the effects of spatial skills can have a longer duration (Wright et al, 2008). The question is what these specific processes are.

The current study explored different spatial training methods and investigated the sequence of process-based mental simulation that was facilitated by various structures of external spatial representations, including CAAD technology, everyday life artifacts, spatial cues, and/or technical language. The goal was to better pinpoint what specific cognitive processes were engaged and reinforced mental experiences that affected spatial ability acquisition. Importantly, the goal was to further develop and recommend spatial thinking training environments suited for learners with low spatial ability profiles but have interest in pursuing STEM education like architecture and engineering.

2. Theoretical Framework

2.1. INDIVIDUAL DIFFERENCES

Individual differences 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). Although research in human cognition and artificial intelligence do not clearly explain the source of individual differences in spatial cognitive processing (Lohman, 1988), the individualistic differences could be explained through various influences, such as prior experiences, external representations, mental models and imagery, and working memory and visual attention. As Miyake and colleagues (2001) and Just and Carpenter (1985) found, there is a limited capacity in working memory (WM), storage, and attention used during mental processes of imagery formation depending upon individuals’ prior experiences. This study focused on reinforcing our attention and WM expansion.

2.1. SPATIAL COGNITIVE PROCESSES

Because spatial cognition has not been stemmed out of a certain theoretical basis, spatial skills are diverse in their functions and definitions. Therefore, each individual possesses these skills differently, both kinds and levels. However, the more common identification of spatial ability is via spatial visualization in mental rotation as found in architectural profession from the view of cognitive processes established by Carroll (1993). Carroll defined spatial skills (e.g., spatial visualization) as the ability to understand, mentally encode, and then manipulate 3D spatial forms and objects. This spatial visu-
alization skill captures the essence of mental rotation (Hegarty and Waller, 2005), as well as perspective taking proposed by Piaget and Inhelder (1967).

Prior experiences help develop spatial understanding (Tversky, 2009; Wilson, 2002), which affect human cognitive processing and mental formation (Barsalou, 2008; Rohrer, 2007; Lakoff and Johnson, 1987; Shepard and Metzler, 1971) through mental models and imagery. Kosslyn (1994) demonstrates that mental images also preserve perception properties. This internalization process is a collection of experiences that individuals use to reinforce spatial ability attainment and form better mental models.

There have been various spatial training studies indicating spatial mechanisms that facilitate success in spatial performance improvement, such as a task- and process-specific training, an efficient transformational process, and adaptive strategy (Uttal et al, 2013). The most important mechanism should account for mental process-based changes in thinking (Wright et al, 2008). These processes require high cognitive attention from encoding a visual stimulus to constructing a visual image in WM, transforming an image, and comparing a visual stimulus to an image in WM for a confirmed outcome.

2.3. COMPUTER AIDED-ARCHITECTURAL DESIGN INTERFACE

Humans use external representations, such as 3D models, to assist in developing spatial thinking, as survival and communicative tools to offload WM and executive functions (Goldin-Meadow, 2005). Spatial cues and technical language (e.g., left/right, up/down, 90° turn) help engage in structuring our understanding of spaces (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) and deconstructed for comprehension, when being properly instructed or situated.

Specifically, human-computer 2D/3D technology has been developed as an external representation to assist the simulation of spatial thinking using computer graphics (Card et al, 1999), which facilitate architectural professionals in solving spatial problems (Mitchell and McCullough, 1995). It assists stimulation of spatial thinking in a computer graphics form focusing on human computer interaction (Card et al, 1999), as well as direct manipulation. In fact, this CAAD environment was originated and revolutionized from an early development of Sketchpad in 1963 by Ivan Sutherland at MIT (Mitchell & McCullough, 1995), surprisingly related to the sketchpad conception in WM by Baddeley and Hitch (1974). Abrahamson and colleagues (2010) utilized a handheld device to explore abstract concepts of ratio and proportionality, another example of the use of 3D virtual technology. They
found that this process informed the development of a heuristic design principle to foster similar experiences in learning. It enhances mental simulation of the discovery. Even recently, video game environment research presents a possibility to connect the learner with content and context of his/her mental constructions.

In summary, the processes in manipulation objects in CAAD environments elicit our cognitive experiences and incorporate technical cues into visualizing objects (Kornkasem and Black, 2014). Individual differences in spatial abilities could be shaped by these various factors. The present study investigated the potential spatial skill training components that help learners improve their spatial ability. Specifically, the training addressed how formation of spatial mental models can be systematically facilitated by CAAD representations. The training identified how the facilitation activated planning experiences affecting spatial ability attainment. The goal was to anticipate the formation of spatial mental models that was reactivated through experiences and everyday objects.

3. Methods

3.1. PARTICIPANTS

A total of 72 Columbia University’s graduate students (70% females) were recruited through advertisement over two experiments. All participants were given an IRB approved consent form to participate in the study (Mean age = 26.9 years, SD = 4.1). Qualified participants were defined as ones who were having limited STEM educational experiences and possessing low spatial ability profiles.

3.2. RESEARCH DESIGN

The research design was a between-subject, experimental content analysis. The dependent variable was the test of spatial ability tasks. The independent variables were the external spatial representations, as a learning environment with two levels (Virtual 3D vs. Physical 3D), and the training materials, with two levels (simple geometry materials vs. architectural artifacts).

3.3. PROCEDURE

Participants were randomly assigned to one of the four conditions to learn about building blocks of geometry and/or architectural elements in two 50-minute sessions with 4 activities in two separate days. Pretest, posttest, demographic questionnaires, and brief interviews were conducted with debrief.
3.4. MATERIALS

Based on objects found in everyday contexts, simple geometric forms (i.e., wooden blocks), and architectural elements (i.e., as a pen, table) were used. The virtual 3D level consisted of the preprogrammed *SketchUp* running on a Macbook Pro (Experiment 1) and 11.6"-Inspiron Touch-Screen Dell, (Experiment 2). The physical 3D group used wooden and scaled_MODELED objects in various sizes (Figure 1 and Figure 2).

![Figure 1. Example of virtual 3D and physical 3D environments](image)

![Figure 2. Example of all stimuli for intervention conditions](image)

3.5. OPERATIONAL ACTIVITIES

The activities were designed to parallel the cognitive processes used in spatial visualization tasks, i.e., the ability to understand, mentally encode, and then manipulate 3D spatial forms and objects [6]. In the present study, the specific operational activities were the rotating, viewing, and moving manipulation of the objects to solve specific problems in each activity.

For example, Activity 1 *Familiar with Learning Environment (10 minutes)*, aims for participants to get familiar with the learning environment they are assigned to. Participants in all groups learned about their assigned external representation of the 2D to 3D environments and learned to operate...
and manipulate with the objects. Activity 2 Draw and Move Objects (15 minutes), aims for participants to first draw or build an object within the assigned environment. Activity 3, Rotate Objects (15 minutes), the aim of this activity is for participants to rotate an object with different direction such as in a horizontal plane (left and right) and a vertical place (up and down) to match the given stimulus. The rotation angles are also limited to 90 and 180 degrees. Lastly, Activity 4, Rotation Objects to Solve Puzzle (15 minutes), aims for participants to integrate seven pieces of objects into one object. The participants are expected to put all pieces together by rotating each piece of object and carefully locate them properly. If the participants finish this task before the session ends, the participants will be given the same set and redo the puzzle again.

3.6. INDEPENDENT VARIABLES

There were two types of independent variables of spatial training. One used different external representations of learning environments (Virtual 3D & Physical 3D) and the other used different training material types of geometry or architecture (nonsense geometric & everyday objects).

3.7. DEPENDENT VARIABLES

Five assessments of spatial skills/tasks were used for Pretest, Posttest and Transfer, namely Guay’s Visualization of Viewpoints and Purdue Spatial Visualization Test with a score from 0-16 each, and Mental Rotations Test, and Surface Development Test for experiment 2. For Near Transfer, an estimation of the building dimensions was used (a score from 0-10).

3.8. MANIPULATION CHECK & QUESTIONNAIRES

To assess whether participants were aligned with the conditions randomly assigned to, the Likert Scale from one to five was used, one indicating the most unfamiliar, implicit (abstract), and five indicating the most relatable, explicit (concrete). Demographic questionnaires asked participants about their general background, prior experiences in science and mathematics learning, and hobbies. A brief exit interview was conducted to verify participants’ attitude and motivation.

4. Results

4.1. SPATIAL TASKS

Overall, participants in both the control and experimental conditions improved in their posttest spatial measurement. For the mean pretest of all par-
participants (M=22.14, SD=7.85), there was no significant difference, F(1, 45)=.022, p=NS. This indicates that in general all participants had a relatively equal level of spatial skills prior to the experiment. After the intervention, however, there was significant differences, t=1.15, df=45, p<0.05, between the mean posttest for the control group (M=30.2, SD=7.6) and the experimental group (M=34.6, SD=5.9). There was also significant differences, t=2.351, df=45, p<.05, between the mean gain score for the control group (M= 7.8, SD= 4.7), and for the experimental group (M=12.6, SD=5.8). This result suggested the participants with the virtual 3D tool improved significantly (Figure 3).

4.2. TRAINING MATERIALS

The effects of training materials used between simple geometry blocks and architectural elements were hypothesized for its content explicitness for the imagination. The results indicated that the participants from the geometry group made slightly more efforts in imagination when being exposed to the content: the mean gain score for the geometry group was M=10.62, SD=5.68 and for the architectural element group M=10.2, SD=5.06. However, the difference was non-significant, t=.199, df=45, p=NS.

4.3. GROUP LEVEL

ANOVA was further conducted on performance for all four groups and covariates with their pretest scores to answer two questions. First was whether the improvement in scores was greater for the group with the virtual 3D learning environment than the one using physical 3D artifacts. Second was whether improvement in scores was greater for the group with the simple geometry content than the one using architectural elements. The gained
scores were then computed from the difference between the pretest and posttest for each participant. The results (Table 1) showed the main effect for the type of learning environment were statistically significantly different, $F(1, 45)=6.19, p<.05 (\eta^2=.143)$ in favor of the virtual 3D. For the main effect of the type of content used, the result showed no significant difference $F(1,45)=.12, p=.731 (\eta^2=.003)$ with no interaction between the two main effects. These findings showed that the learning outcome in the virtual 3D environment was better. The type of training material showed only marginal significant difference, which implied that participants who encountered less familiar objects might have used imagination.

Table 1. Analysis of variance for gain scores of four groups with pre-tests as covariate.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>Sig.</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment</td>
<td>1</td>
<td>224.16</td>
<td>6.19</td>
<td>0.017*</td>
<td>0.143</td>
</tr>
<tr>
<td>Material</td>
<td>1</td>
<td>4.34</td>
<td>0.12</td>
<td>0.731</td>
<td>0.003</td>
</tr>
<tr>
<td>Environment * Material</td>
<td>1</td>
<td>35.44</td>
<td>0.98</td>
<td>0.329</td>
<td>0.026</td>
</tr>
<tr>
<td>Error</td>
<td>44</td>
<td>44.01</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

*p < .05

4.4. TRANSFER TASK AND STEM CORRELATION

There was no difference in estimating building heights and dimensions among participants for all groups. This could be due to the transfer tasks not being relevant to the spatial skills training. A more specific transfer task should be further investigated. In terms of correlation between previous experiences in math and science to the gained score improvement, the result showed correlation $r(45) = .22, p<.05$, which is in line with previous research from Wai and colleagues (2009). For manipulation check validating whether participants were aligned with the randomly assigned conditions, using the Likert Scale from one to seven (most abstract to most relatable), the results showed that the mean score in the abstract condition was 1.96 (SD=0.42), and the more relatable condition was 5.13 (SD=1.23).

4.5. RESULTS OF EXPERIMENT 2

There was no difference in estimating building heights and dimensions among participants for all groups. This could be due to the transfer tasks not being relevant to the spatial skill training. A more specific transfer task should be further investigated. In terms of correlation between previous experiences in math and science to the gained score improvement, the result showed correlation $r(45) = .22, p<.05$. For manipulation check validating whether participants were aligned with the randomly assigned conditions,
using the Likert Scale from one to seven (most abstract to most relatable), the results showed that the mean score in the abstract condition was 1.96 (SD=0.42), and the more relatable condition was 5.13 (SD=1.23) (Table 2).

Table 2. Means scores and standard deviations on spatial ability test for Experiment 2.

<table>
<thead>
<tr>
<th>Spatial Ability Test</th>
<th>Pretest (40)</th>
<th>Posttest (40)</th>
<th>SD Transfer (30)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>virtual</td>
<td>12</td>
<td>18.9</td>
<td>3.4</td>
</tr>
<tr>
<td>physical</td>
<td>12</td>
<td>17.8</td>
<td>2.4</td>
</tr>
</tbody>
</table>

5. Summary

The present study pinpointed the potential steps during cognitive processes and their components of the spatial training environments that fostered learners better spatial mental simulations to improve their spatial abilities. Specifically, the study explored the effects of the trainings that integrated certain spatial cues of mental representation guided by direct manipulation processes found in CAAD technology. Overall, this study built upon the work in the fields of visuospatial cognition, computer user interface, and human learning. To help learners with lower spatial ability profiles, it is important to consider trainings or tasks that incorporate spatial cues and situated environments during cognitive processes. This allowed individuals to engage in activities that increase their spatial mental abilities, which ultimately would help learners more initially comfortable when facing with mental rotation tasks in STEM area as in architecture and engineering education.

5.1 LIMITATIONS AND FUTURE RESEARCH

Two main issues were found; the number of comparison intervention conditions, and the different tasks during the intervention. Future studies should address this concern by having more equivalent conditions between physical and virtual conditions, as well as the conditions with the situated instruction and without. The variety of tasks should be limited to the rotation task only to make sure that there is no confound with extra cognitive processes.

References


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