

# Evaluation of Static and Dynamic Visualization Training Approaches for Users with Different Spatial Abilities

Maria-Elena Froese, Melanie Tory, Guy-Warwick Evans, and Kedar Shrikhande

**Abstract**—Conflicting results are reported in the literature on whether dynamic visualizations are more effective than static visualizations for learning and mastering 3-D tasks, and only a few investigations have considered the influence of the spatial abilities of the learners. In a study with 117 participants, we compared the benefit of static vs. dynamic visualization training tools on learners with different spatial abilities performing a typical 3-D task (specifically, creating orthographic projections of a 3-D object). We measured the spatial abilities of the participants using the Mental Rotation Test (MRT) and classified participants into two groups (high and low abilities) to examine how the participants' abilities predicted change in performance after training with static versus dynamic training tools. Our results indicate that: 1) visualization training programs can help learners to improve 3-D task performance, 2) dynamic visualizations provide no advantages over static visualizations that show intermediate steps, 3) training programs are more beneficial for individuals with low spatial abilities than for individuals with high spatial abilities, and 4) training individuals with high spatial abilities using dynamic visualizations provides little benefit.

**Index Terms**—Spatial ability, 3D visualization, training, evaluation, orthographic projection, CAD

## 1 INTRODUCTION

The use of Computer-Aided Design (CAD) tools has become increasingly popular and important for professionals in many fields. Proficiency with these tools requires that users be adept at operations involving spatial cognition, and research has found that spatial abilities are a particularly important factor for success in professions like mechanics, engineering, architecture, and surgery [4, 47, 31, 12]. However, learning and mastering 3-D visualization tools can be challenging for some users [20, 36]. Researchers have explored different strategies to help students improve their performance on 3-D visualization tasks and tools, and while there is no consensus as to whether spatial abilities can be improved and whether such improvement would be permanent and transferable to other tasks [11], findings suggest that the performance at specific spatial tasks can be improved by proper training [11, 47, 20, 36, 42, 34].

A representative 3-D task within the CAD domain is the Orthographic Projection Task (OPT), which consists of visualizing and drawing 2-D orthographic projections of a 3-D object: typically the top, side and front views (see Figure 1). Learning to draw and relate orthographic projections is a fundamental skill taught in CAD education that can be quite challenging for many students to acquire [47, 34]. Even though virtually all modern CAD systems can automatically generate orthographic views, operators of the software must be able to understand, relate, and work with a combination of orthographic projections and 3D views. Mentally relating different views of a 3D scene is known to be challenging [42], particularly when the relationships involve mental rotation, as is true with orthographic projections.

Our goal in this research is to explore which visualization training approaches most improve OPT performance for users with different spatial abilities. To this end, we have deployed three visualization approaches to illustrate the 2-D projection of the 3-D objects. The first approach animates the transition from 3-D to 2-D, the second displays

the transition as a series of static intermediate steps, and the third displays only the initial 3-D object and the final 2-D views. The third approach serves as a control and resembles typical examples in CAD textbooks. We report how participants' spatial ability affects their performance following training with each tool and we discuss how these results can be used to develop training approaches and software to support education for CAD and other 3-D applications.

Although we focus on orthographic projection CAD training in this research, understanding and relating 2-D and 3-D views is a very common task in many other 3-D visualization domains [47, 11]. For example, medical students must learn how to relate 2-D sagittal, transverse, and coronal medical images to a 3-D structure of the human body. Therefore, our results have relevance to training tasks for a wide variety of 3-D visualizations.

## 2 RELATED WORK

### 2.1 Spatial abilities

Spatial abilities are well known predictors of performance in accomplishing 3-D tasks such as the OPT: individuals with higher spatial abilities are known to perform better at these tasks [20, 47]. Evidence suggests that individuals with higher spatial abilities have a wider range of strategies to solve spatial tasks [9, 33, 35, 20]. Research has shown that people with a predominance of right-brain skills have greater spatial abilities [30]. It has also been shown that spatial abilities improve in childhood as the child gets older [33], but decrease with age in adults [35]. Males tend to have higher spatial abilities than females [31, 26, 48, 1, 20], in particular when the tasks involve mental rotation [19].

### 2.2 Comparing 2-D versus 3-D visualizations

Research has investigated which situations benefit more from 2-D versus 3-D representations of 3-D objects. Findings suggest that 3-D representations are better to gain an overall understanding of the object and to perform tasks that require approximate estimation and navigation [43, 17]. On the other hand, 2-D representations are better for tasks that require attention to detail, precise navigation, and measuring distance [40, 17]. Findings by Tory et al. [43] suggest that combining 2-D and 3-D representations are better for tasks that depend on precise orientation and positioning, rather than using only 2-D or 3-D representations. Users of combined visualizations felt more confident, found the navigation more natural, were faster than using 2-D alone, and were more accurate than using 3-D alone. Probably for these reasons, most modern CAD tools and other 3D visualization software

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(e.g. medical image viewers) present a combination of 3-D and 2-D views.

### 2.3 Comparing static versus dynamic visualizations

The benefit of static versus dynamic representations of 3-D objects is more controversial. It is fairly clear that dynamic rotation is helpful for understanding the shape of 3-D objects. For example, Sando et al. [38] found that animation supported better performance at shape understanding tasks compared to a combination of static 2-D and 3-D views. In a meta-analysis of 26 studies comparing visualizations, Höffler & Leutner [14] found that dynamic visualizations were more effective for learning than static visualizations. Lepper and Malone [22] argue that animations are often more engaging for learners and may lead to better performance. On the other hand, in studies conducted by Lewalter [23], Mayer et al. [27], and Swezey [41], and on a literature review by Tversky, Morrison and Betrancourt [45], it was found that animation provides no advantages for learning.

Few studies have explored how individuals' spatial ability correlates with the effectiveness of static versus dynamic representations, and their results are conflicting. From our literature review, we found two possibilities: 1) dynamic visualizations help low spatial ability people more by acting as a prosthetic (the "ability-as-compensator" effect [28]), and 2) spatial ability is a prerequisite to effective use of dynamic visualizations (the "ability-as-enhancer hypothesis" [28]).

The "ability-as-compensator" effect suggests that individuals with low spatial abilities benefit from dynamic representations because the visualizations provide an external resource that helps to create a mental model of a process [28]. Hays [10] found evidence that those individuals with lower spatial abilities benefit more from dynamic representations. Lee [21] found evidence supporting the ability-as compensator effect but found that dynamic representations make no difference for individuals with high spatial abilities. Furthermore, on a meta-analysis of 19 studies from 1994 to 2009 on such effects, Höffler [13] found that individuals with lower spatial abilities benefit significantly from dynamic representations.

On the other hand, the "ability-as-enhancer" theory suggests that individuals with high spatial abilities benefit from dynamic representations because they already have effective mental models to process 3-D information, whereas individuals with lower spatial abilities do not benefit from such visualizations because they lack these effective mental models [12]. Cohen [3] found that the use of animation is correlated with higher performance and also with higher spatial ability. He explains that it is probably not the level of spatial ability itself that predicts performance, but the fact that individuals with high spatial ability are more likely to use animation effectively and individuals with low spatial ability are more likely to get disoriented with the animation. Huk [16] found similar results: individuals with higher spatial abilities performed better overall with dynamic than static visualization, but individuals with low spatial abilities performed better with static visualizations. Garg [32] conducted a study on learning anatomy and found a disadvantage for people with low spatial ability using animation; these individuals performed better with static views. Lowe [25] showed that interactive control over the animation also affected performance. In his investigations, he found that individuals that effectively manipulated the object performed better, whereas individuals that could not manipulate the object effectively often performed worse. The individuals' spatial abilities were the determining factor of whether individuals could effectively manipulate the object or not.

There are two studies closely related to ours that have explored the effectiveness of a training program. The first study by Lajoie [20] tested a computerized OPT training program which included both static and dynamic representations. Although no comparison between those representations was conducted, she found that individuals with lower spatial skills benefited more from a training program than those participants with higher spatial abilities. Surprisingly, she found that participants with high spatial abilities actually decreased performance after receiving training. However, the size of the sample was small and the high and low spatial ability groups were uneven in size and so her

results should be further explored. Thus, we would like to investigate the change in task performance and find out if a training program is only beneficial for individuals with lower spatial abilities as Lajoie's findings suggest. Our work builds directly upon the second study by Pillay [36]. She compared training on OPT using static representations with and without intermediate steps. She found that participants who received training with intermediate steps outperformed all other participants. Pillay did not take into consideration the individual differences people have in spatial ability and she only investigated static training. We extend this work by considering the spatial ability of learners as a factor, and by considering whether animated transitions between 2-D and 3-D views are as helpful as static transitions for learning OPT. This is important to study because, as discussed above, there is no consensus yet in the research community whether individual spatial ability correlates to the efficacy of static or dynamic visualizations.

## 3 USER STUDY

Our aim in this study was to compare static and dynamic visualization techniques for training people to complete OPT tasks, and to explore whether spatial ability influences the best choice of technique.

### 3.1 Participants

We ran the study as individual sessions with 117 undergrad students. These students were compensated for their participation, and many had to participate in a research study as part of their course requirements. As depicted in Table 1 most of our participants did not have any previous experience with spatial tools and only few had experience with spatial tools such as SolidWorks, SolidEdge, Matlab, Lego Designer, Google Sketchup, or Autocad. Not surprisingly, the participants categorized as having high spatial abilities (HA) had a higher number of individuals with previous experience than the low spatial abilities (LA) group. 80% of our participants came from Arts, Humanities, or Science programs and none from engineering programs. Interestingly, the HA group had more than double the participation of individuals from Science programs than the LA group. As expected from the literature review, there was a higher incidence of females than males categorized as having low spatial abilities. Most of our participants were in the range of 18 to 25 years old. We randomly assigned the participants to one of our training tools (defined below). The Animation group had 39 participants; the Static Steps group had 38 participants, and the Control group had 40 participants.

Table 1. Characteristics of our participants. LA is the group of participants categorized as having low spatial abilities. HA is the group of participants categorized as having high spatial abilities. ALL refers to all participants in the study.

Feature	LA	HA	ALL
With previous experience	4%	18%	11%
Without previous experience	96%	83%	89%
Arts and Humanities programs	60%	45%	52%
Science programs	16%	39%	28%
No program selected yet	24%	16%	20%
Female participants	84%	61%	72%
Male participants	16%	39%	28%
Less than 18 years old	4%	6%	5%
18 to 25 years old	87%	90%	89%
25 to 35 years old	9%	3%	6%

### 3.2 Training and testing environment

We used three training tools: Static Steps, Animation, and Control. The Static Steps tool displayed the transition as static intermediate steps between 3-D and 2-D, the Animation tool displayed the transition as a dynamic animation from 3-D to 2-D, and the Control tool

displayed 2-D views from a 3-D object without intermediate steps (See Figures 1, 2, and 3). The Animation tool initially showed four isometric views of the same object and required the user to press the “S” key to rotate one of the views into the Side view, “T” to rotate another into the Top view, “F” to rotate to the Front view, and “R” to reset the rotations (in Figure 2 the key “T” has been pressed). The Animation displayed the rotation at about 18 degrees per second. Each training tool displayed 5 geometric objects, one at a time, and the user could see the previous or the next object as many times as needed.

Before and after using the training tools, we used a computerized visualization tool to help measure OPT performance. This tool displayed a 3-D representation of an object, and the participant had to draw its three orthographic projections on paper. The visualization tool offered five objects in total and did not allow the user to go back to a previous object after advancing (See Figure 4). The tool did not give any indication of how to do the transitions or how the end views should look, but it provided the user with an example of the orthographic views before the actual tests began. Additionally, we briefly explained to the participants what we meant by top, side, and front orthographic projections.

From a pilot study we noticed that it was more difficult to draw the OPT for some objects than others (See Figure 5 for examples of easy and difficult objects). We split objects into four groups of five objects each, and to match the groups on difficulty we distributed the objects so that the average score from the pilot study for each group was similar. The two groups used for the pre- and post-training tests were randomly determined for each participant.

We implemented the training and the testing tools in C++ and ran the study on MacOS computers with a 27” screen size and a resolution of 2560x1440.

### 3.3 Measures and experimental design

The participants’ ability to perform mental rotation was measured by the Vandenberg and Kuse Mental Rotation Test (MRT) [46]. Hegarty et al. [11] have shown that the MRT has a strong correlation with performance in mental rotation tasks. Our version of the MRT displayed the same problems and figures as the traditional pen and paper version, but was a computer-based application. Each problem presented a 3D object and four similar images. The participant had to identify the two images in the set that represented rotations of the original object. We used this test as a predictor of OPT performance; this measurement was our independent variable. We also measured the participants’ spatial visualization ability using a computerized version of

the Paper Folding Test (PFT) [7]. The PFT includes figures of folded pieces of paper with punched holes. The participant had to identify the one unfolded option that corresponds to the original folded piece of paper. Some researchers have found a correlation between the PFT and spatial visualization performance [15]. However, the results of the PFT did not correlate with performance on our task, so we decided to discard them and use only the MRT results as a predictor.

We measured the participants’ ability to perform OPT using the tool described in Section 3.2. We gave participants five objects and asked them to draw three orthographic projections of each. We assigned one point for each correctly drawn projection for a total of 15 points. We manually marked the tests, comparing the participants’ responses with

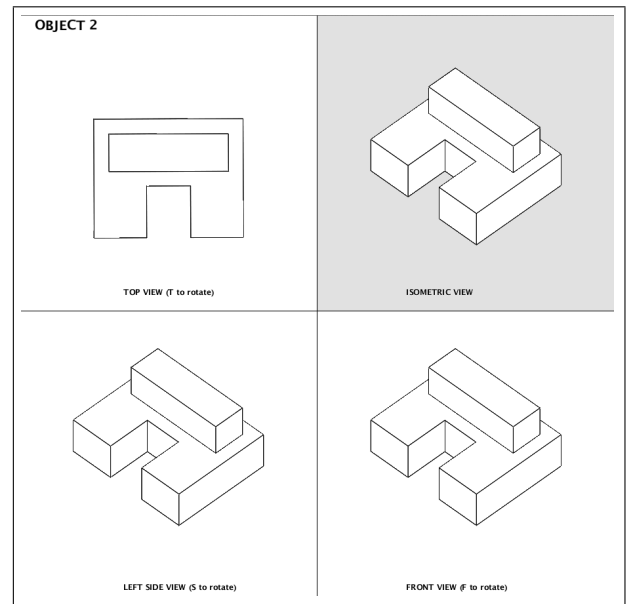


Fig. 2. Animation training tool. Top, Left, and Front views could be separately animated, showing a rotation from the isometric view to the appropriate orthographic projection.

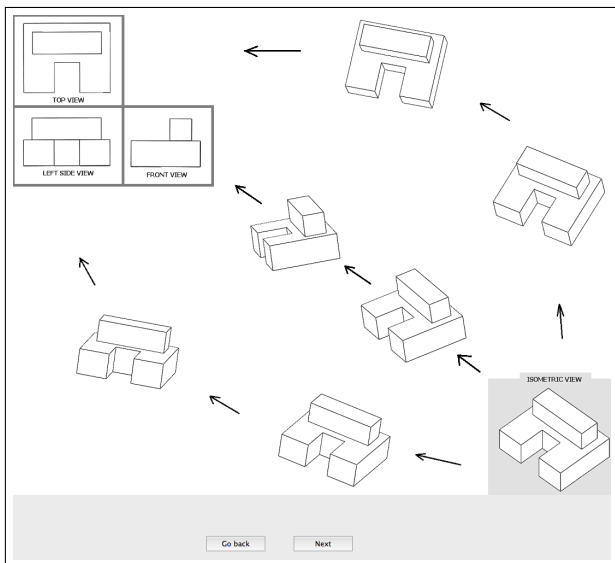


Fig. 1. Transition from a 3-D object into three orthographic views in the Static Steps training tool.

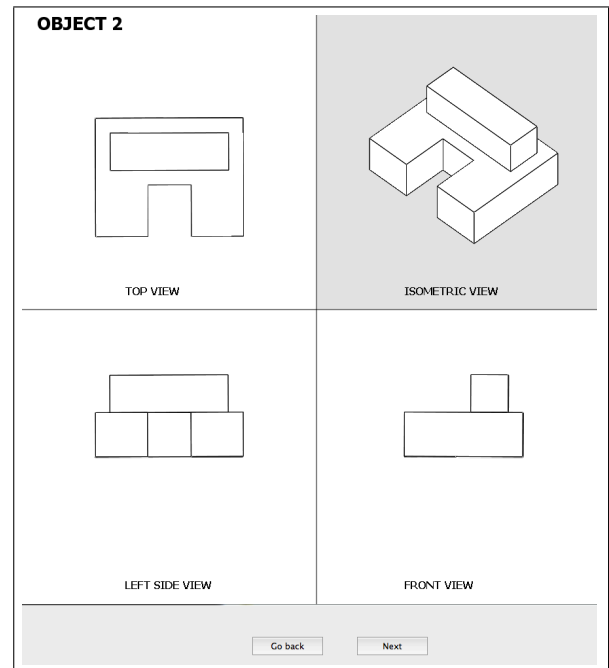


Fig. 3. Control training tool showing the Isometric view and the Top, Side, and Front view of a 3-D object.

the correct projections. To minimize subjectivity in marking of the OPT, two researchers marked the tests independently and then compared their results. Differences in scores were discussed and consensus reached for all the scores. The difference between the scores before training and after training was defined as our main dependent variable,  $P(x)$ . Other dependent variables were the relative number of incorrect responses  $Pr(x)$  and the performance before training  $PRE(x)$  and performance after training  $POST(x)$ .

Our experiment used a fully between-subjects design with 2 factors: training tool (Static Steps, Animation, or Control) and Spatial Ability (High and Low). Spatial ability was measured on a continuous scale, and prior to analysis the participants were divided into high (HA) and low (LA) spatial ability groups as explained in the results section.

Our hypotheses for the study were:

- H1: The LA group will show greater improvement in performance after training than the HA group.
- H2: For the LA group, Animation and Static Steps will lead to greater performance improvement than Control (because the former two techniques will encourage these users towards an effective strategy, mental rotation).
- H3: For the HA group, there will be no significant difference in performance improvements among the three tools (because these users can likely develop an effective strategy without assistance).
- H4: Dynamic visualizations will provide no advantages over static visualizations with intermediate steps (because regardless

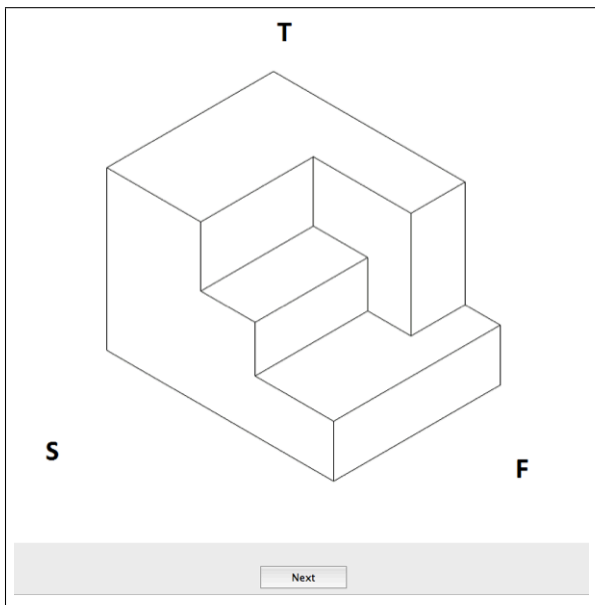


Fig. 4. Testing tool to measure OPT performance displaying only the isometric view of an object.

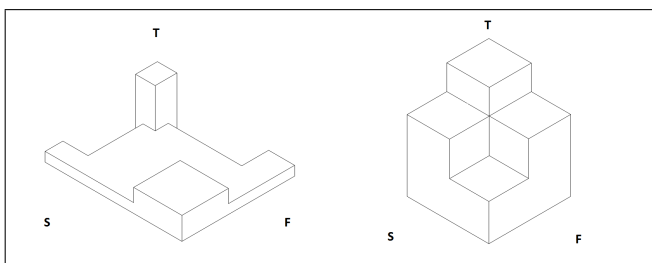


Fig. 5. An easy object for OPT (left) and a difficult object for OPT (right) according to an early pilot study.

of their attractive appearance, dynamic visualizations are cognitively more demanding)

### 3.4 Procedure

The study was conducted in individual sessions with each participant. On average, the study sessions lasted 1.5 hours. At the beginning of each session, participants were asked to complete a basic demographics questionnaire. Following this questionnaire, participants were asked to undertake the MRT and PFT tests. The MRT consisted of 24 problems with no time restrictions for completion. The PFT had 20 problems to solve, and each set of 10 problems had to be solved in three minutes. The participants were not allowed to progress to the next set of PFT problems until the three minutes were over.

After completing the spatial ability tests, participants were asked to complete three sets of OPTs: before, during, and after using our training tools. In each set, participants were presented with a computer-based visualization of five 3-D objects. We intentionally did not give participants any hints or instructions on how to mentally visualize the orthographic projections. We anticipated that the Animation and Static Steps conditions would encourage people towards using a mental rotation strategy, whereas the Control tool would not have such a bias. The participants had to draw 2-D projections for the top, side, and front views of each object on paper. The first and third sets of OPTs were completed by the participants using the tool in Figure 4, whereas the second set was integrated into the training tools. The second set of OPT was called the training session and was done with help from our training tool (either Static Steps, Automatic or Control). There were no time restrictions to finish the first and the third set of OPT, but the participants were required to spend at least 10 minutes in the training session. To finalize the study, we interviewed participants about their experience with the training tool.

## 4 RESULTS

To analyze the data we classified participants in each of our groups (39 in the Animation group, 38 in the Static Steps group, and 40 in the Control group) into two categories: participants with higher spatial abilities (HA) and participants with lower spatial abilities (LA). We took the median of the MRT test scores (79%) as the metric to decide the partition between the two categories; participants above or equal to the median were classified as HA and those below the median were classified as LA. This resulted in six groups as described below (the data collected from these groups showed a normal distribution in a Q-Q plot):

- HA-A: 21 participants with HA that used the Animation training.
- LA-A: 18 participants with LA that used the Animation training.
- HA-S: 25 participants with HA that used the Static Steps training.
- LA-S: 13 participants with LA that used the Static Steps training.
- HA-C: 16 participants with HA that used the Control training.
- LA-C: 24 participants with LA that used the Control training.

To test the efficacy of each of the tools, a two-tailed paired sample t-test on the six groups of participants was used to compare performance before and after training (see Table 2). The t-test revealed that all tools benefited the LA participants (Static Steps, Animation, and Control in order of helpfulness) but only the Static Steps benefited the HA participants. See Figure 6 for a graphical representation of scores before and after training for participants grouped by skills and by tools.

Our analysis reveals that the Animation training program provided little benefit for individuals with HA. The HA group had almost the same improvement when using the Static Steps and the Control tool with  $P(HA-S)=5\%$  and  $P(HA-C)=6\%$  as shown in Table 2, but the higher variability in the Control tool as depicted in Figure 7 suggests that the Static Steps tool is a better choice. We also noticed that a training program might be detrimental more frequently for HA than for LA

Table 2. T-test and change in performance for the six groups of participants ( $*p < .05$ ). PRE(x) is the average performance before training, POST(x) is the average performance after training, P(x) is the change in average performance defined as  $(POST(x) - PRE(x)) / (100\% - PRE(x))$ , and Pr(x) is the reduction of incorrect responses defined as  $(POST(x) - PRE(x)) / (100\% - PRE(x))$ . "Better", "Worse" and "Same" are proportions of the groups that became better, worse or that stayed the same after treatment.

Group	Size	PRE(x)	POST(x)	P(x)	Pr(x)	t-value	p-value	Better	Worse	Same
HA-A	21	88%	89%	1%	8%	.257	.8	38%	29%	33%
LA-A	18	64%	81%	17%	47%	3.402	*.003	61%	6%	33%
HA-S	25	86%	91%	5%	36%	2.671	*.013	52%	12%	36%
LA-S	13	56%	74%	18%	41%	3.317	*.006	77%	15%	8%
HA-C	16	87%	93%	6%	46%	1.209	.24	63%	31%	6%
LA-C	24	70%	80%	10%	33%	2.769	*.011	67%	21%	13%

individuals. For example, we found that 29% of HA-A participants performed worse after training whereas only 6% of LA-A performed worse after training (see Table 2). Similarly, 31% of HA-C participants performed worse after training while 21% of LA-C performed worse after training. Note, however, that these potentially detrimental effects were not statistically significant.

On the other hand, for individuals with LA we found that the Animation and Static Steps training provided almost the same benefits  $P(LA-A) = 17\%$  and  $P(LA-S) = 18\%$  (see Table 2). For LA individuals, the coefficient of variation for the Animation tool is  $c_v = 1.24$  and for the Static Steps tool  $c_v = 1.09$ , indicating that the Static Steps tool is a slightly better option since it exhibits less variability. The Control training was less helpful for these less skilled participants:  $P(LA-S) > P(LA-A) > P(LA-C)$ . The results are illustrated in the box plot in Figure 7.

A two-way analysis of variance (ANOVA) tested changes in performance P(x) for individuals with high and low spatial abilities for the Animation, Static Steps and Control tools. The ANOVA revealed that the spatial abilities of the participants had a significant effect ( $F = 13.819, p = .05, \eta^2 = .111$ ); the individuals with LA had on average a better improvement in performance after training than the individuals with HA, confirming our findings from the t-tests. Differences in the amount of improvement with different training tools were not significant, and there was no significant interaction between training type and spatial ability on the change in performance. We conducted

an ANCOVA analysis, with MRT as the covariate, but found that this did not shed any additional light on our results.

**Post-study interview** In the post-study interview, participants were asked about their experience in the training session (see Table 3). When we asked them about the amount of time for the training, 62% of the participants thought the training time was adequate and 29% of participants thought the training time was long. More LA than HA individuals said that the time was adequate whereas more HA than LA individuals said that the training time was long. We asked participants if they felt there was a change in the way they were solving the OPT tasks after receiving the training, and as expected, more LA than HA individuals indicated that they changed their strategy after training. Additionally, more participants who used the Animation training thought that they changed their strategy than the participants who used the Static Steps and Control tools. We asked users how they would rate the difficulty of the tasks on a scale of 1 (too easy) to 10 (too difficult). On average the participants rated the difficulty of the tasks as 6.06 with standard deviation of 1.95 and a mode of 7.

We asked 2 open-ended questions aiming at finding out what improvements could be done to the training tools or to the tasks. Also, we asked 2 open-ended questions to see if users changed their strategy after the training. We coded the responses and analyzed them to discover trends and patterns. For improvements that could be made to the training tool, the most frequent requests were: 1) to allow the user to freely rotate/manipulate the object from different perspectives;

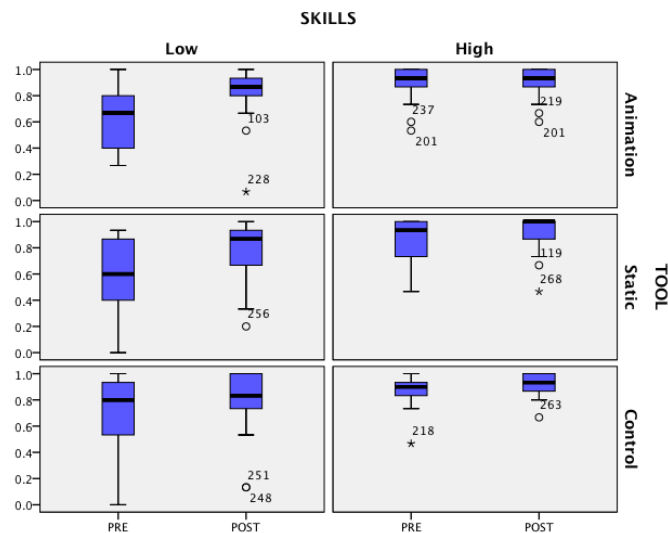


Fig. 6. OPT scores before (PRE) and after (POST) training. Columns show results for individuals with low and high spatial abilities. Rows show results for the three types of training tools.

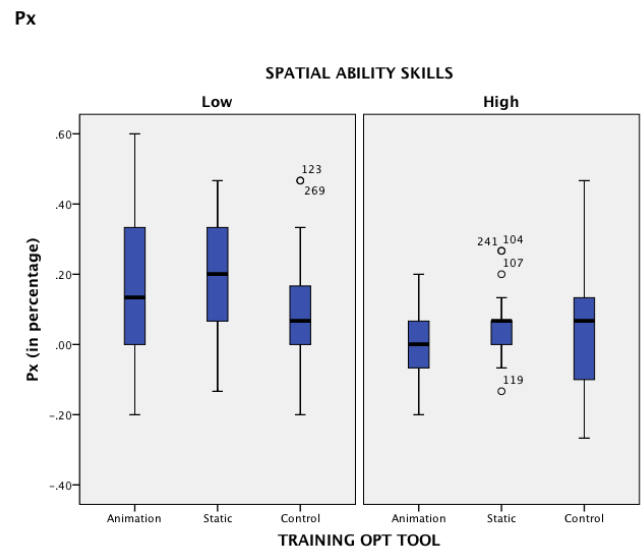


Fig. 7. Changes in OPT performance after training as compared to before training, i.e. P(x).

Table 3. Feedback from users about the training session. LA is the group of participants categorized as having low spatial abilities. HA is the group of participants categorized as having high spatial abilities. ALL refers to all participants in the study. A stands for Animation, S for Static Steps, and C for Control tool.

Feedback	HA-A	LA-A	HA-S	LA-S	HA-C	LA-C	ALL
Training time was adequate	57%	61%	60%	77%	56%	63%	62%
Training time was long	33%	28%	36%	8%	38%	25%	29%
Training time was short	5%	6%	0%	8%	0%	4%	3%
Changed strategy after training	23%	33%	8%	23%	6%	33%	21%
Did not change strategy after training	57%	33%	76%	54%	69%	46%	56%
Did not know if they changed strategy	19%	33%	16%	23%	25%	21%	22%

2) to add more detail to the different perspectives by using colours or shades; and 3) to add labels to distinguish top, front and side views. The main request of both LA and HA individuals was for user-led interaction. HA individuals also requested colour, and shades or labels to facilitate solving the task. Interaction and colour were requested frequently for the Animation tool whereas labels were requested for the Static Steps tool.

When asked what improvements could be made to the drawing tasks, the most frequent suggestions were: 1) to include more challenging objects, 2) to have fewer tasks/objects, 3) to add colour to the objects to make them more engaging, and 4) to provide tips on the steps needed to solve the task. The most frequent request for more challenging tasks came from LA individuals who used the Static tool followed by HA individuals who used the Control tool. Both LA and HA individuals who used the Control tool asked for fewer tasks. Adding tips was a request only from individuals who used the Control tool.

Then we asked users what mental procedures they used to solve the OPT before training. The most frequent responses were: 1) to mentally rotate/picture the objects, 2) to focus on key components of the object, 3) to mentally move themselves in relation to the objects to see them from different perspectives, 4) intuition, and 5) decomposing the objects into simple shapes. LA and HA individuals expressed with similar frequency that they used mental rotation as their first strategy. HA individuals would focus more often on key components while LA individuals seldom reported looking at key components. LA individuals who used the Control tool reported the intuition strategy more frequently.

When asked what mental procedures they used after the training most users said that they basically used the same procedure as before but they said that they paid more attention and were able to better visualize the projections, they mentioned that it was easier, faster or they felt more confident, one user said: "I don't know how to explain it but the sides (F, T, and S) were significantly clearer after the training". Most of the HA individuals reported that they used the same strategy. As expected, more LA individuals changed their strategy into mental rotation than the HA individuals. Changes in strategy occurred more frequently when users were training with the Animation or with the Static Steps than with the Control condition.

**Other observations** While running the study, we observed that there were two types of participants: 1) those who rushed through the process in order to satisfy their course requirement and 2) those who were really interested in doing the tasks, asked for clarification, and were neat and careful in their drawings. It is possible that there may be a correlation between interest in the task and performance, or that apparent interest could be related to some other cognitive ability such as perceptual speed. However, we did not collect the necessary data to investigate this issue. We frequently noticed that the participants' non-verbal signals indicated that they found the tasks difficult and that they became tired by the mental effort required in the study. We suggested participants take a break when they were getting tired or frustrated, but very few accepted the offer.

## 5 DISCUSSION

### 5.1 Discussion of the hypotheses

Our study has shown that the performance at Orthographic Projection Tasks can be improved by providing the user with a training program.

**Benefits of a training program** We noticed that individuals with LA benefit more from a training program than individuals with HA, partially confirming hypothesis H1 (The LA group will show greater improvement in performance after training than the HA group). Clearly, there should be more benefit for the LA participants from a training program since they have more room for improvement than the HA participants. However, looking at the ratio of improvement we can see that the difference is not always as dramatic as we expected (see  $Pr(x)$  in Table 2). The finding that a training program benefits LA participants more than HA participants is a similar result to the study by Lajoie [20], but our methodology was more robust. Our study had 117 participants receiving computerized training while Lajoie's had only 10. We had a more balanced distribution of participants with 62 HA and 55 LA individuals, whereas she had only seven HA and three LA individuals. Similarly to Lajoie, we used dynamic and static visualizations in our training program, but we extended Lajoie's investigations by performing a comparison between those two types of visualizations and their correlation to individual spatial abilities (which we discuss at the end of this section).

**Benefits for individuals with low spatial abilities** We found evidence to support H2 (For the LA group, Animation and Static Steps tools will lead to greater performance improvement than the Control tool). In particular, we found that individuals with LA can benefit from any kind of training, and the Control training was less helpful for these individuals than Static Steps or Animation. This implies that encouraging LA individuals during training to use a specific strategy (mental rotation) is more effective than simply allowing free practice. From our findings, the "ability-as-compensator effect" [28] should explain that training with dynamic visualizations or with static visualizations with intermediate steps helps the LA user to create a mental model of a process.

**Benefits for individuals with high spatial abilities** For individuals with HA, our findings suggest that there is a small benefit from using a training program. We found that they received little benefit from the Animation training (similar results were found by [21]), whereas they received more benefit from the Static Steps training (similar results were found by Höffler [13]) and from the Control training. This contradicts H3, which predicted that there would be no differences between the three conditions for HA individuals (see  $P(x)$  and  $Pr(x)$  in Table 2).

Comments from an earlier pilot study provided a potential explanation for the lack of performance improvement with Animation training. Some HA participants in the pilot commented that the animation training encouraged them to switch to a mental rotation strategy, instead of the strategy that was most natural to them (e.g., feature matching). For high spatial ability individuals, as Cronbach and Snow [5]

suggest, it is possible that their default strategy is already quite effective, and encouraging the use of an alternate strategy could be detrimental. Despite their decrease in performance, the post-study questionnaire indicated that the HA participants still felt confident about their answers to the OPT. Some of these participants expressed that the study took too long. It is possible that they became tired and rushed the drawings and therefore scored lower. It is also possible that some HA participants scored lower because they were trying to scan the 3D object quickly and may have missed important details.

**Benefits of static visualizations with intermediate steps** In general, our findings suggest that dynamic visualizations provide no advantage over static visualizations with intermediate steps in supporting the learning process, which confirms H4. This result echoes previous results found by [23, 27, 41, 45]. Höffler and Leutner [15] argue that animation could be less useful for learning due to the cognitive overload it imposes on the user. They explain that animation requires users to hold numerous pieces of visual information in short term memory while new representations are emerging, changing, or disappearing. Our static steps representation eliminates the need to hold this information in memory, while still providing an indication of how the object should rotate.

We predict that the debate on how spatial ability correlates with the effectiveness of static versus dynamic representations will continue for a while. There are several potential reasons for the conflicting results obtained from current studies, such as the different backgrounds of the people tested, the use of different tasks in different domains, and the lack of consensus on how to categorize individuals into HA and LA groups. To define the HA and LA groups, approaches have included using standardized tests such as the MRT and PFT, previous experience, or gender. For studies that use standardized tests such as MRT or PFT, the partitioning into high and low categories is based on each study's sample population. Usually the median or mean of the spatial measurements is chosen as the partition point. It is highly probable that some HA individuals in one study would have been classified as LA in another. The lack of a standardized metric makes it particularly difficult to perform a fair comparison of results across multiple studies investigating the same research question.

## 5.2 Discussion on the request for interaction

In our study, participants could not directly manipulate the objects and they frequently requested a more user-controlled interaction in the post-study interview. We wonder how a user-controlled interaction would affect OPT performance. Sando et al. [38] showed no significant difference between passive and user-controlled animation (whether or not users could rotate the object and alter the orientation and speed of the animation) for performance at spatial positioning tasks. Hegarty and Waller [12] showed that people with LA had a harder time with 3-D objects because they could not understand how to manipulate the visualization to get a good view. Cohen [3] suggests that individuals with LA get disoriented as they rotate 3-D objects. Thus, even though people seem to want user-controlled animation, these studies suggest that providing this capability could be detrimental for people with LA. Allowing user control for the Static Steps condition would be interesting to investigate as well. To the best of our knowledge there are no investigations that explore a user-controlled static visualization. In such a visualization, the user could decide how many intermediate steps to display and could control when to advance to the next step. However, here again, we suspect that allowing a more user-controlled interaction might increase the cognitive load on the user and could be detrimental to individuals with LA. For individuals with HA, a more user-controlled interaction would definitely be more engaging but perhaps would still not benefit performance.

## 6 LIMITATIONS AND FUTURE WORK

Our study focused on the OPT as a representative CAD task. This is an important limitation since CAD users are required to perform a variety of tasks beyond OPT. For example, user may be asked to judge the relative location, size and shape of 3-D objects or to construct a 3-D object from the three 2-D orthographic views. While we are fairly sure

there is some overlap in the skills required, we acknowledge that the spatial skills required for those tasks may be different than the mental rotation required to perform OPT. Thus, further studies are needed to explore a broad range of CAD or other visualization centric tasks to determine how individual abilities predict change in performance after training with static versus dynamic visualizations.

For future studies, we would like to target a slightly different population. We received positive verbal feedback from five of the participants who had written the Dentistry Aptitude Test (DAT) who found our study very interesting. We wonder how different the results would have been with students who already knew they needed good spatial abilities to succeed in their professions. We suspect that the same study with a higher participation of students from disciplines such as dentistry and engineering may have shown different results. These students might also be more motivated to receive training in a representative CAD task and be more motivated to perform well in the study because of the applicability to their field.

A more sophisticated OPT training tool than what we described here could adapt its content based on individual spatial ability. The tool could offer a test to measure the user's level of spatial ability. The results of the test could be used to provide direct recommendations about strategies a user could employ to improve OPT performance. Individuals with LA could be encouraged to use a mental rotation strategy to solve the problems, and training tasks could be illustrated using static visualizations with intermediate steps. Individuals with HA could be encouraged to practice solving more complex OPT problems with and without the intermediate steps shown, and to continue using their current strategies. We would also like to explore whether adding more intermediate steps in the transitions from 3-D to 2-D would have any impact on the efficiency of the training program, and whether adding more steps near to one end of the transition would have any impact on user performance.

On the other hand, it would be interesting to explore how our results might differ for other types of 3-D visualizations where the 2-D views are axis-aligned slices through the object rather than projections (such as in medical imaging). We know that spatial ability plays a major role in learning tasks involving medial images [18, 11], and although our results cannot be directly applied to this type of spatial data, people with LA will probably benefit significantly from a training program, and static strategies with intermediate steps may be more promising to explore than dynamic strategies for reaching a broad range of spatial abilities.

## 7 CONCLUSION

Our study suggests that an OPT training program focusing on static steps is most likely to be effective for people with a wide range of spatial abilities. However, our results also suggest that OPT training using animation does not lead to substantial performance gains for individuals with high spatial abilities, at least for the duration of training in our short-term study. Thus, for non-critical applications it may be permissible for individuals with high spatial abilities to skip the training entirely since we observed that they already had effective strategies for solving these problems. Dynamic visualizations provide no advantage over static visualizations with intermediate steps for people with low spatial abilities, and are less effective than static steps for individuals with high spatial abilities (sometimes even decreasing performance). There are many open questions regarding the features of a training program that would provide the most benefit to learners with high versus low spatial abilities. Further research is needed to answer these questions and to improve the design of a static training program, including research into how many intermediate steps should be included and whether the frequency of intermediate steps should be higher closer to the 2-D or the 3-D representation.

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