Virtual and Augmented Reality as Spatial Ability Training Tools

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ABSTRACT

Virtual reality (VR) and augmented reality (AR – overlaying virtual objects onto the real world) offer interesting and wide spread possibilities to study different components of human behaviour and cognitive processes. One aspect of human cognition that has been frequently studied using VR technology is spatial ability. Research ranges from training studies that investigate whether and/or how spatial ability can be improved by using these new technologies to studies that focus on specific aspects of spatial ability for which VR is an efficient investigational tool. In this paper we first review studies that used VR technologies to study different aspects of spatial ability. Then results and findings will be presented from one of the first large-scale studies (215 students) that investigated the potential of an AR application to train spatial ability.

Author Keywords

Virtual reality, augmented reality, spatial ability, training.

ACM Classification Keywords

H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

Spatial ability is one of the main components of human intelligence [48] and is especially important for several occupations or educational programs and training [10]. Eliot [10] even argues that spatial ability is pervasive, which means that we need it for almost each activity in everyday live. Spatial ability refers to being able to mentally represent and manipulate visual-spatial information. This ability can be subdivided into several sub domains [33]. “Visualization” includes most complex, multi-step tasks, “Spatial Relations” includes more simple tasks such as speeded mental rotation of rather simple stimuli, and “Orientation” includes tasks where one has to imagine change of perspective. This means that skills in orientation (large-scale aspects) and skills in mentally manipulating visual stimuli (small-scale aspects) are grouped under the same skill. Although on the one side it seems likely that for both, large-scale aspects and small-scale aspects of spatial ability, similar processes are involved [37], on the other side it seems advisable to look separately at each of them [e.g. 9, p. 9]. There has been a lot of research regarding gender differences in spatial ability [18, 20, 40, 51, 50]. Although gender differences in spatial ability has seemed to diminish [50], this is still a very interesting field of research especially in the context of using VR-technologies to train or investigate spatial skills.

In the next section, studies using VR to investigate large-scale aspects of spatial ability will be discussed. In these studies participants normally have to solve navigation and / or orientation tasks in virtual environments. Afterwards studies examining small-scale aspects of spatial ability will be addressed and findings from our own research on the trainability of spatial ability using an augmented reality based geometry education tool presented and discussed.

NAVIGATION AND ORIENTATION IN VIRTUAL ENVIRONMENTS

Most of the previous research regarding VR or AR and spatial ability dealt with studying large-scale aspects of spatial ability. Investment in technical development might seem relatively high on first sight but will mostly be justified by the benefit of using VEs. With VR-technology it is possible to minimise or even overcome some of the problems that occurred when attempting to study spatial ability with other methods [9]. Researchers can create environments in which people can act without being exposed to certain dangers that potentially occur in real environments (e.g. military based research, fire-fighter training). Studies investigating orientation or navigation in large environments can be conducted in smaller labs and do not have to be set up on the real location which often could be hard or even impossible to achieve. Using VR enables researchers to create exact the same stimulus conditions for all participants or to vary certain environment variables in real-time and thus gives researchers more control over experimental settings. Changes on virtual objects can be undone very easily which often is not possible when using real objects: "The real power of VR technology is that it allows people to expand their perception of the real-world in ways that were previously impossible" [36, S. 154]. An additional advantage of using computer generated environments lies in the possibilities of automatically logging certain variables of interest like reactive and non-reactive user data. Compared to other methods of analyzing user data (taking notes, video analysis, etc.) this can be a very efficient alternative.

Durlach et al. [9] mention that most studies only focus on quite special aspects of spatial ability and "...little attention has been given to the use of VEs for training spatial behavior in general, i.e., improving a subject's general spatial abilities and skills." (p. 5). It is not completely clear which aspects of spatial ability can actually be trained but Durlach et al. argue that with well designed training programs, basic spatial abilities can be improved. Ideally this kind of research should be interdisciplinary, as researchers with different backgrounds (psychology, engineering, computer sciences, education) can bring in their specific skills and knowledge.

Fitting und Glück [12, 13] compared spatial knowledge gained after navigation through a virtual environment by people who self-rated their sense of orientation as high or low. The VE was projected on a big screen and 64 participants (32 male and 32 female) navigated using cursor keys. Results showed that participants who rated their sense of orientation as high could build up significantly more survey knowledge. They used holistic strategies more often (e. g. trying to imagine a map of the environment), whereas participants who rated their sense of orientation as low, more often reported not using any strategies. Females who rated their sense of orientation as high, performed better in way finding than those who rated it low. In men no such differences could be observed.

Astur et al. [1] investigated gender differences of people navigating through a virtual Morris-water-maze, an experimental setup that is normally used to test spatial memory in rodents. The task was to find a hidden platform to get out of the water. Men found the platform faster than women ($F(1, 51) = 8.74$, $p < 0.01$), and showed a tendency to swim shorter distances but did not swim faster than women. Men more often used a direct strategy whereas women more often used strategies that where rated as less spatial (swimming in a circle, zigzag).

Cutmore et al. [5] conducted several studies to investigate cognitive and gender specific factors that influence orientation performance. They found that even simple VEs, like 2D projection of rooms, can aid in building up spatial knowledge. However, performance was better in dynamic environments. Building up spatial knowledge could be achieved by active and passive exploration. Using EEG measures the authors found that for verbal-sequential subjects, navigation in VEs requires more cognitive effort.

Waller, Hunt und Knapp [52] investigated orientation ability and the concept of fidelity (extent to which a VE and interaction in a VE cannot be distinguished from a real environment). They compared participants who navigated through different real and virtual setups of a maze and completed various tasks. Completion time, number of touching barriers and the path subjects took were analyzed. The experiment showed that short VR training was not more efficient than learning from maps, and that immersive VR conditions (using head mounted displays) are not more efficient than desktop VR conditions. Participants did not gain better survey knowledge after immersive VR training. The authors argue that navigational aids like survey maps would be needed for improving survey knowledge. No gender differences could be found after exploration of the real room, but men outperformed women in the VR conditions.

Diaz and Sims [7] investigated navigation in VEs and transfer to real environments. They argued that it is important to take individual differences into consideration when studying training in VEs. The authors refer to results from Koh et al. [26] who found that variability in performance caused by inter-subject differences was greater than the differences caused by the independent variables. They also found this in their own experiment. Spatial ability (measured with an orientation test from Guilford and Zimmerman [19] explained more variance in orientation performance differences than the treatment conditions (how participants learned the VE: route, survey or composite view).

In Lawton and Morrin’s [29] study participants had to navigate through corridors of a VE and afterwards try to point to the place they started. Results showed that pointing accuracy decreased with increasing number of turns. Pointing accuracy of men was better by an average of 10 degrees. This could also be explained by experience, as men reported to have more experience with computer games that also require navigation through corridors.

Foreman et al. [14] report findings from several studies investigating orientation in VEs with disabled children. Handicapped children often experience difficulties finding their way about new environments. After exploring 3-D simulated environments (reconstructions) they could acquire a substantial degree of spatial competence and were able to successfully orient in the real environments. A comparison of 2-D and 3-D training showed that only 3-D experience led to training effects.

Other studies that examined the importance of movement for building up spatial knowledge have been carried out by Wraga et al. [53], Brooks et al. [3] Klatzky et al. [25], or McComas, Pivik und Laflamme [34]. Evaluating an AR-based Computer-Aided-Drawing program, Shin, Dunston and Wang [46] studied differences between rotating a model and moving around the model. Performance in remembering and finding objects was better when moving around the object, regardless of stimulus complexity.

Virtual Reality and *small-scale* aspects of spatial ability

Fewer studies used VR or AR to study small-scale aspects of spatial ability. This is quite surprising because these new technologies offer innovative and unique tools of research in this field. Mohler [36, p. 154] states that VR provides a superb vehicle for testing, and improving not only orientation but also visualization skills. However more research would be needed to quantify and qualify the impact of its use. VR allows the experimenter to control the stimulus material and virtual objects can be created and adapted very easily which often can be difficult when using real objects. Two of the main advantages of using VR-technologies, however, are the spatial visualization and 3-dimensional interaction capabilities provided. This should allow creation of very intuitive hands-on training setups that can be very useful for educational purposes. Studies on the trainability of spatial ability have shown the importance of hands-on practice [11].

Small and large-scale aspects of spatial ability often cannot be divided very easily [6, 37] and some of the studies discussed above also included both aspects. Not just considering them as one and the same seems to be advisable "It is not at all obvious that individuals who exhibit a high (low) level of spatial behavior with objects will exhibit a high (low) level of spatial behavior with environments." [9, p. 9]. There also is evidence for a distinction between object vision and spatial vision and Mishkin et al. [35] argued that there exist two distinct cortical pathways.

Oman et al. [37] studied how people learn to rotate simple object-configurations. They compared real and virtual (using HMD) object configurations. They found that people more likely imagine rotating themselves than rotating the objects around them. But the authors assume that performance in this experiment correlates more with cognitive-analytic abilities than with the mental rotation abilities. Oman et al. found that participants using HMDs performed slightly better than the other group. The authors conclude that VR is an excellent tool for spatial trainings.

Schnabel and Kvan [44] compared the perception and understanding of spatial volumes using real 2-D environments, non-immersive VR (Computer screen), and immersive VR (HMD). They found that their participants (twenty four architectural students) who studied the volume using the 2-D condition achieved the highest accuracy in rebuilding the volume. However, students in the immersive VR condition gained a better 3-dimensional understanding of the volume and its components. Also the more complex the volume was, the better it could be perceived using the HMD. The authors conclude that students using 2-D environment more likely just learned the volume configuration instead of gaining a 3-dimensional understanding.

A study that investigated whether mental rotation abilities can be trained using VR was done by Passig and Eden [39]. In their experiment deaf or hard-of-hearing children, for whom mental rotation abilities are essential when interpreting sign language, practiced with a 2-D or VR 3-D version of the computer game Tetris over several training sessions. Results indicate that mental rotation ability can be trained by VR-training with 3-D stimuli.

Tsutsumi et al. [49] evaluated a stereographic 3-D version of the Mental Cutting Test (MCT) (using shutter glasses) by comparing it to a computerised 2-D version. Results from the 70 students who worked on the stereoscopic version did not differ significant from those of the 51 who worked on the 2-D version. Although most participants could identify objects more easily when presented with a 3-D view, participants with low spatial ability seemed to have particular problems with 3-D representation.

The Virtual Reality Spatial Rotation (VRSR) system [42] allows people to solve Shepard & Metzler [45] tasks, which are also used in the Mental Rotation Test (MRT), directly in 3-D. Using a HMD or big rear-projected screen the user sees block configurations which she should superimpose using a sphere shaped interaction device. Studies have shown that performance in the paper-pencil MRT improved after training with the VRSR. Whereas in the paper-pencil MRT males performed better than females, no gender differences could be observed in VRSR performance [28, 38, 43]. Interestingly the authors could not find gender differences in MRT performance when it was administered after practising with the VRSR.

Gender differences

The discussion of these studies did not show a clear picture on gender differences regarding performance in VR. When navigating through virtual environments males seem to perform better than females. In the studies from Waller et al. [52], Astur et al. [1], and Lawton und Morrin [29] males performed better in terms of navigation speed, navigation accuracy, and pointing accuracy. Possible explanations could be differences in strategies used to perform the tasks [1, 16], the finding that women are more prone to cyber sickness [28], or that men have more experience with computer games that require navigation in VEs [e.g. 29].

However, in less immersive VR scenarios, gender differences were not as present. Differences in mental rotation ability disappear when assessed with VR methods [43]. Larson et al. [28] conclude that women can manipulate 3-D objects as efficiently as men, but cannot visualize them as well. Parsons et al. [38] discuss other performance criteria such as transformation between 2-D images and 3-D mental objects, or the tendency to cross-check the solution [32]. Thus less immersive VEs seem to be a promising training-tool for spatial ability especially for women. VR can support people in the process of visualization and cognitive load from transformations between 2-D and 3-D can be minimised.

This overview illustrates that VR and AR technologies offer unique possibilities to display and manipulate three-dimensional objects in space, making them ideal tools to study spatial ability. These technologies allow users to dynamically interact with three-dimensional objects and perceive their spatial properties. Objects can be changed and viewed directly and alterations can be undone easily. This should help people to understand spatial concepts more easily and to practice their spatial skills. Thus there seem to be a lot of advantages in using VR and AR to design training applications for spatial ability. However, until now no large-scale user studies have been conducted to investigate training effects of a training using AR on different aspects of small-scale spatial ability.

STUDY ON TRAINING SPATIAL ABILITY WITH AR

The main research question addressed by the study was whether spatial ability can be trained by an AR application and which aspects of spatial ability can be trained specifically. Additionally we were interested in gender-specific training differences. We investigated the effects of a training using AR-technology on different aspects of spatial ability with a focus on small-scale aspects.

Participants

In this training study data was analyzed from 215 high school students attending 5th grade (technical high school) and 11th grade (high school) in Vienna, Austria. One hundred and four (48.4%) were female, and the average age was 17 years 0 months (minimum 14 years 2 months, maximum 20 years 3 months).

Materials and methods

Construct3D that was used to design and conduct the AR-based trainings [22, 23]. Construct3D is a 3D geometric construction tool that uses a collaborative AR setup with see-through head mounted displays, allowing the user to see the virtual models as well as the real environment and the collaboration partner (see figure 1). The main interaction device is the PIP (Personal Interaction Panel) which consists of a position tracked pen and tablet and allows direct interaction and manipulation of content. The main strengths of Construct3D for spatial ability training can be seen in visualization of spatial problems and dynamic interaction with objects. Students can build models in 3D space, walk around them and modify them in real time.

The study followed a pre-test – training - post-test design. The effects of the training with Construct3D ($n = 47$) was compared to a computer training utilizing a computer aided design program (CAD3D – using traditional computer screens and interaction devices (mouse, keyboard)) ($n = 44$). The two control-groups (one with geometry classes in school ($n = 66$), one without geometry classes ($n = 58$)) did not receive additional training. In both training groups two students and a tutor worked on similar geometry problems and attended six 45 minutes training sessions (once a week). The training covered a range of different geometry tasks. The training sessions were structured in an introduction (getting familiar with the respective systems and interaction techniques), Boolean operations, transformation in space, combination of Boolean operations and transformation in space, and modeling objects.

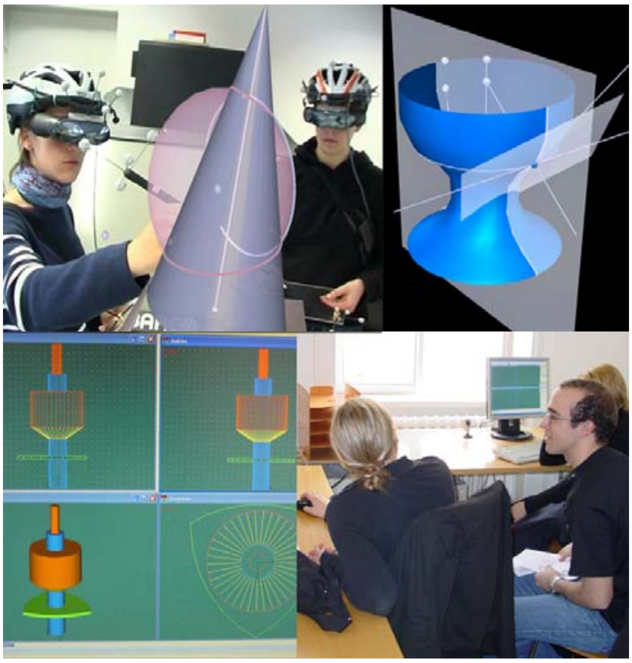

Figure 1 Top (Construct3D): Students working with Construct3D (left) and model (right); Bottom (CAD3D): model (left) and students working with CAD3D (right)

In order to work on these tasks, students in the training groups had to have knowledge in geometry and thus only students with geometry education were eligible for the training. The tutors explained the tasks to the students and supported them if they needed some help. Interaction between students was not analyzed in this study.

In a pre and post-test spatial ability was assessed with four tests that measure different aspects of spatial ability.

- Differential Aptitude Test: Space Relations (DAT:SR) [4] (15 Item short version) – visualization (paper folding).
- Mental Cutting Test (MCT) [2] (15 Item short version) – visualization (object cutting).
- Mental Rotation Test (MRT) [40], German version by [41] - speeded mental rotation.
- Objective Perspective Test (OPT) [21] – orientation (change of perspective).

Results

Training effects for each test were analyzed by a three factorial ANOVA with one repeated measures factor and two between groups factors, or nonparametric tests where prerequisites for an ANOVA were not met. For the non-parametric tests, score differences were used and analysed with mKVA (multiple Rang Kovarianzanalyse [multiple rank covariance analysis]) developed by Kubinger and

Häusler. Theoretical background for this procedure can be found in [27].

The analysis for the DAT:SR did not show significant differences between treatment-groups or gender. Only the within-subjects performance comparison (pre-test - post-test) was significant ($F(1, 205) = 55.73$, $p < .01$, $\eta^2 = .21$), thus all subjects, regardless of treatment group or sex, could solve more items in the post-test. This can be interpreted as a general learning effect.

		mean			**SD**		
group	**sex**	**pre**	**post**	**diff**	**pre**	**post**	**N**
C3D	m	8.50	8.90	0.40	2.84	3.49	20
	f	7.35	7.77	0.42	2.76	3.08	26
	total	7.85	8.26	0.41	2.82	3.28	46
CAD3D	m	9.17	10.39	1.22	3.11	2.78	23
	f	6.52	6.10	-0.43	2.54	2.41	21
	total	7.91	8.34	0.43	3.12	3.37	44
geometry	m	7.33	7.00	-0.33	3.42	3.68	48
	f	5.82	6.35	0.53	2.92	2.45	17
	total	6.94	6.83	-0.11	3.34	3.40	65
no geometry	m	5.95	6.26	0.32	3.34	3.81	19
	f	5.67	6.18	0.51	2.19	2.29	39
	total	7.01	7.28	0.27	3.10	3.33	213

Table 1: Descriptive statistics for the MCT pre and post-test score (mean, difference, standard deviation)

Also in the MCT a general learning effect could be observed ($F(1, 205) = 4.27$, $p = .04$, $\eta^2 = .02$). Furthermore the analysis showed a significant interaction between performance difference, gender, and treatment group ($\chi^2(3, N = 213) = 8.24$, $p = .04$). Post hoc tests (LSD) showed that men in the CAD3D group performed better than women in the same group ($p = .01$) and men in the geometry group ($p > .01$)..

		mean			**SD**		
group	**sex**	**pre**	**post**	**diff**	**pre**	**post**	**N**
C3D	m	12.05	12.62	0.57	5.79	7.90	21
	f	12.15	13.31	1.15	5.02	5.12	26
	total	12.11	13.00	0.89	5.32	6.44	47
CAD3D	m	15.22	18.39	3.17	3.98	3.59	23
	f	10.86	14.62	3.76	4.37	5.37	21
	total	13.14	16.59	3.45	4.67	4.86	44
geometry	m	14.02	16.63	2.60	4.49	4.51	48
	f	10.89	14.89	4.00	4.38	4.81	18
	total	13.17	16.15	2.98	4.64	4.63	66
no geometry	m	12.58	15.58	3.00	4.39	5.28	19
	f	9.21	11.90	2.69	4.99	5.96	39
	total	10.31	13.10	2.79	5.02	5.96	58

Table 2 Descriptive statistics for the MRT pre and post-test score (mean, difference, standard deviation)

Results for the MRT showed a large general improvement in performance ($F(1, 207) = 72.98$, $p < .01$, $\eta^2 = .26$). The interaction between performance difference and treatment group was significant ($F(3, 207) = 3.82$, $p = .01$, $\eta^2 = .05$). But because the prerequisites for the ANOVA were not met (Box's M test and Levene test) nonparametric tests were calculated that did not show a significant result for this interaction ($\chi^2(3, N = 215) = 3.03$, $p = .39$).

The analysis of the OPT scores showed a significant general improvement in performance ($F(1,207) = 5.05$, $p = .03$, $\eta^2 = .02$) and a 3-way interaction between performance difference, gender, and treatment group ($F(3, 207) = 3.45$, $p = .02$, $\eta^2 = .05$). As can also be seen in table 3 those male participants working with Construct3D could improve their score more than those with geometry education (LSD; $p = .02$) and those without geometry education ($p = .03$). With females the Construct3D group showed less gain than the no geometry group ($p = .03$). Women in the CAD3D group also showed relatively high score gain, but results from this group do not differ significantly from the Construct3D group results ($p = .07$).

		mean			**SD**		
group	**sex**	**pre**	**post**	**diff**	**pre**	**post**	**N**
C3D	m	152.50	160.61	7.31	19.39	10.80	21
	f	148.42	147.58	-0.84	23.85	15.83	26
	total	150.24	153.40	3.16	21.83	15.16	47
CAD 3D	m	162.39	162.58	0.19	9.27	10.63	23
	f	147.47	155.72	8.25	18.35	10.31	21
	total	155.27	159.30	4.03	16.04	10.92	44
geometry	m	155.02	153.12	-1.90	19.20	18.78	48
	f	145.25	148.07	2.82	25.66	19.14	18
	total	152.36	151.74	-0.62	21.40	18.87	66
no geometry	m	155.44	152.06	-3.38	20.49	23.60	19
	f	141.14	149.65	8.51	26.79	22.03	39
	total	145.82	150.44	4.62	25.63	22.38	58

Table 3 Descriptive statistics for the OPT pre and post-test score (mean, difference, standard deviation)

Discussion

In this study we could not find clear evidence on the effectiveness of augmented reality as a spatial ability training tool. Almost all participants could improve their scores in the post-test in the different spatial ability tests. Participants worked on the post-test 10 weeks after completing the pre-test, thus familiarity with the stimulus material and learning effects can explain this result. Untrained women and especially those without geometry education showed high score improvement, especially in the OPT. When interpreting these results ceiling-effects should be considered. Women mostly had low pre-test scores and therefore more scope for improvement. Women without geometry education having a low base level in spatial ability tests can partly be explained by findings of other studies that have shown that geometry education has effects on spatial test performance [15, 17, 24].

Results from the MCT showed that men could profit from computer training using traditional computer screens whereas post-test performance of women even slightly decreased compared to pre-test results. Thus for women, training using 2-D computer screens does not seem to be effective in terms of improving visualization of rather complex stimuli. Men on the other hand can improve their performance when working with CAD3D compared to other men, who do not receive additional training.

In the MRT no significant differences could be found. On a descriptive level, the CAD3D group showed higher performance gains than the Construct3D group. This would indicate that 3-dimensional augmented reality training does not affect the ability of speeded mental rotation of simple stimuli. This agrees with the hypothesis that training that offers a high amount of visualization and interactivity should mainly affect the visualization factor which covers a broad range of spatial skills and therefore probably have transfer effects on other, more specialized components [8].

Analysis of the OPT scores show quite interesting gender specific results. In men the group training with Construct3D could improve OPT test-performance. Also women without geometry education could improve their performance, but this again can be explained by their low base level and thus their greater potential for improvement. In men only those who worked with Construct3D could improve their test-scores. In women, on the other hand, performance even slightly drops after the augmented reality training. Why men can profit from Construct3D training, while women do not especially is not completely clear at the moment. One explanation could be that women, who had a lower base level, are overtaxed by this kind of training. Studies have shown that especially people with a high level of spatial ability can profit from holistic, visualization based trainings [24, 31]. Another explanation could be that working with Construct3D involves a lot of manipulation and transformation and such tasks tend to produce performance advantages for males [30]. Stumpf [47] found that the male advantage was relatively small on recognition tasks, but larger on measures of mental manipulation. However this does not explain why men working with Construct3D only showed score gain in the OPT but not in the other spatial ability measures.

In general this study could not find a clear advantage for AR-based geometry training in improving spatial ability. The OPT results show that men can improve test scores after working with Construct3D. Other results indicate that training in a 2-D environment may be more effective to improve test-scores. For solving paper-pencil based spatial ability tests, participants have to transform 2-D images to 3-D mental representations. This is also required when working on computer screens that produce 2-D images. When working with Construct3D users directly see and interact with 3-D objects which do not have to be interpreted or mentally transformed [8]. Thus these tests are probably not suited very well to detect skills that are required or trained in 3-D space.

CONCLUSION

Virtual and augmented reality are very useful tools to investigate for training spatial ability and as the literature review shows these technologies were successfully used in a wide range of studies to examine different aspects of spatial behavior and skills.

Our study was the first large-scale study that focused on using 3-D computer technologies to investigate training aspects of spatial ability. We found some interesting results on the trainability of spatial ability using augmented reality, but more research in this field has to be done. Our findings indicate that augmented reality can be used to develop useful tools for spatial ability training. But traditional spatial ability measures probably do not cover all skills that are used when working in 3-D space. Thus new tools to measure spatial ability directly in 3-D would be desirable.

Future studies should also take individual differences into account, especially gender differences. As we found in this study male and female students showed quite different training results. One goal should be to develop technologies and applications from which all users can profit equally.

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