Developing spatial visualization skills with Virtual Reality and hand tracking

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Abstract. Spatial visualization skills are the cognitive skills required to mentally comprehend and manipulate 2D and 3D shapes. Spatial visualization skills are recognized as a crucial part of STEM education. Moreover, these skills have been linked to both students' capacity for self-monitored learning and GPA in STEM programs. Also, many STEM fields have reported correlation between spatial visualization skills and level of academic success of students. Unfortunately, many students have significantly underdeveloped spatial visualization skills. Students traditionally learn spatial visualization skills via the manipulation of 3D objects and drawings. Because Virtual Reality (VR) facilitates the manipulation of 3D virtual objects, it is an effective medium to teach spatial visualization skills. In addition, it has been found that students are more motivated to learn and perform better when taught in an immersive VR environment. Several studies have presented promising results on leveraging VR to teach spatial visualization skills. However, in most of these studies the users are not able to naturally interact with the 3D virtual objects. Additionally, many of the current VR applications fail to implement spatial presence for the user, which would lead to more effective instruction. The level of immersivity a VR application offers can have a direct impact on the users' "first-person" experience and engagement. In light of this, a VR application integrated with hand tracking technology designed to develop spatial visualization skills of STEM students is presented. The inclusion of a user's hand in the virtual environment could increase the users' sense of spatial presence and first-person experience. In addition, this could act as an intuitive input method for beginners. The objective of this work is to introduce this VR application as well as future work on how to leverage Reinforcement Learning to automatically generate new 3D virtual objects [github.com/lopezbec/VR_SpatialVisualizationApp].

Keywords: Virtual Reality, Spatial skills, Immersion.

1 Introduction

Spatial skills are the cognitive skills required to mentally comprehend and manipulate three dimensional shapes [1]. These spatial skills primarily include the rotating and the cutting of the three-dimensional shapes. Spatial skills are recognized as a crucial part of STEM education and are directly connected to both an individual's capacity for self-monitored learning and their GPA in STEM programs [2], [3]. Some of the STEM fields that have recorded relations between spatial skills and level of academic success include Chemical Engineering, Civil Engineering and Computer Science [1], [3], [4]. Unfortunately, many STEM students significantly lack spatial skills when they begin their studies [5].

Whether it is through repetitions of the rotation test or through utilizing building blocks as a toy during their youth, individuals traditionally learn spatial skills via the manipulation of 3D objects [5]. Considering both how virtual reality (VR) facilitates the manipulation of 3D virtual objects, and VR's growing presence as a learning tool, it is an effective medium to teach spatial skills through. In addition, it has been found that students are more motivated to learn and perform better when taught in an immersive VR environment [6], [7]. These benefits would be valuable when used to teach spatial skills. In addition, these benefits are greater the more immersive the VR system is [7]. Currently there are a multitude of examples of VR being used to teach and assess spatial skills, which include the Purdue Spatial Visualization Test (PSVT) [8] - rotation test, the Paper Folding Test, the Mental Cutting Test, the Metal Rotation Test and Spatial Navigation Test [8]. Within these examples, several limitations negatively impact the technology regarding immersion. The primary limitation is that the display method used is only responsible for a fraction of a student's immersion in a virtual environment. The perceived spatial presence of a user, which is based on the controls used to interact with the virtual environment, plays a much larger factor in the immersion of the user [9]. Many of the current VR applications for spatial skills development fail to implement spatial presence for the user, which would lead to more effective instruction [10]. In order to address this requirement for immersion, this project will implement hand tracking, which enables naturalistic movement to interact with the environment. These naturalistic movements will increase a user's immersion [9].

Another limitation to using VR to tach spatial skills is the novelty effect. The novelty effect is the positive motivational effect that accompany an individual trying a new device or technology. When the impact of the novelty effect significantly alters a user's mindset toward a task, it would lead to the positive effects of the new device or technology dwindling once the individual becomes accustomed to it [11]. The lack of new content within VR programs can contribute to the significance of the novelty effect [11]. Novelty effect can be mitigated by creating applications with more content and variety. Unfortunately, the cost of creating content in immersive VR has not significant decreased since it originated [7]. A potential way to avoid this issue is to use procedurally generated content, which this project plans to facilitate using a machine learning agent.

2 Literary Review

2.1 Development of Spatial Skills

An individual's spatial skills are initially developed through the physical manipulation of 3D objects in one's youth [5], [12]. However, it is also known that spatial skills can be taught to individuals beyond this initial learning as a child [8]. The repetitions of spatial tasks such as the Mental Rotation Test (MRT) [8] and stacking blocks can lead to the development of spatial skills in a student [13]. In addition, STEM professionals and teachers all have significantly greater spatial skills than the general population, which further supports the ideas that spatial skills can be learned through the repetition of spatial tasks, such as those in STEM fields [14]. The knowledge that spatial skills can be taught via the manipulation of 3D shapes has led to VR becoming an effective tool for educators to use to teach spatial skills.

2.2 VR in Education

Just as with the onset of the internet, as VR technologies became more widespread, they became more integrated into the education system [15]. During this initial integration, from 2000 to 2016, nearly half of all studies regarding VR as a teaching tool were related to engineering[16]. In these studies, VR as an education tool is usually divided in to immersive and non-immersive VR platforms, however a standardized use of the term immersive had not yet been established [15] In a modern context, immersive VR first requires the use of a head-mounted display (HMD) and secondly requires the user to be able to interact with the virtual environment they are in [7], [16]. Immersion is valuable in the context of VR as means of learning because many of its benefits correlate to how immersed a user is in the virtual environment. Specifically, how enjoyable a learning experience is, how intrinsically motivated a user is, and a user's long term behavior retention of material learn are all proportionally correlated to how immersive their learning experience was [7]. All this considered, there are limits to the benefits of VR as a tool for education such as the novelty effect and the cost of generating immersive VR experience for students. Although the hardware cost of immersive VR platforms has steadily been decreasing, the cost of generating content for those platforms has not significantly changed [17]. With these two flaws in mind, the use of PGC would circumnavigate the cost of generating new content while also generating enough new content to avoid the novelty effect.

2.3 VR for Spatial skills

VR as a medium for teaching spatial skills has been significantly researched in the past, and there are many studies that detailed its effects [16]. From these studies there is a consistent result, which is that VR is an effective medium for teaching spatial skills [8], [18]. In fact, there are many advantages to using VR to teach spatial skills. When compared to other technologies like lecture-based learning, and desktop VR, Immersive VR leads to students more effectively learning and retaining spatial skills [8]. Immersive VR has also shown to increase how much a student can improve their spatial skills from a pre-learning benchmark, when compared to a control using a traditional method of teaching spatial skills [18]. In addition, users have a greater spatial perception in immersive VR when compared to a conventional workstation.

Some studies have already focus on exploring the value of VR for developing spatial visualizations skills [8], [13]. One of these papers [8], was a study of if immersive VR is a better tool for teaching compared to non-immersive VR. He study found that immersive VR was the superior educational tool via the MRT and the PSVT. The application proposed in this study also take inspirations from the MRT and focuses on using PGC to supply shapes to be used in the assessments of students' skills. This generation of shapes could circumnavigate the novelty effect when compared to the previous study. Another study that utilized immersive VR to teach spatial skills by enabling a user to stack blocks in a virtual environment was presented in [13]. The MRT is used in this study as it is a test that can yield quantitative data about a user's spatial skills, which cannot be gathered from a task like stacking blocks. This study also improves on how a user interacts with the virtual environment by implementing hand tracking as the means of user interface, which is more intuitive and easier to use compared to the controller-based user interface in the comparable study.

3 VR Application for Spatial Skills

The application introduced in this work has two versions: (i) one designed for a conventional desktop, mouse, and keyboard, and (ii) the other is designed for a VR headset with hand tracking (e.g. Oculus Quest). These two versions will be utilized to further study the effects of VR as a medium for teaching spatial skills. The data collected from the students using VR will be compared to those of the students using the desktop version. Analyzing such data could enable us to draw a conclusion about the effectiveness of the VR to help developed students' spatial skills. Readers that are interested in the application, videos of it, or following up in its development, can find more information in the GitHub repo: github.com/lopezbec/VR_SpatialVisualizationApp

Fig. 1. Image of the start menu of the application

When the application is started, a user menu, as show in Figure 1, appears and prompts the user to select one of the two available modules. The two modules *Object Viewer* and *Orthographic Viewer* focus on teaching and testing different representations of 3D virtual objects. Within the *Object Viewer* a user will seeing different 3D virtual shapes and will be rotating them in accordance to the scene in use. Whereas in *Orthographic Viewer*, a user will be interacting with a 3D virtual shape and its orthographic representation. Once a module is selected, the user will see a pop-up introduction window that explains the concepts of either perfective or orthopractic views. The user is then within the a "free mode" scene of the module they selected to help them get familiarize with the interface of the module. In the desktop version of the application, they can use their mouse or keyboard to rotate the 3D virtual object in any of the three axes (as shown in Fig 3). In the VR version of the application, they can use their hand directly to rotate the 3D virtual object, as shown in Figure 2.

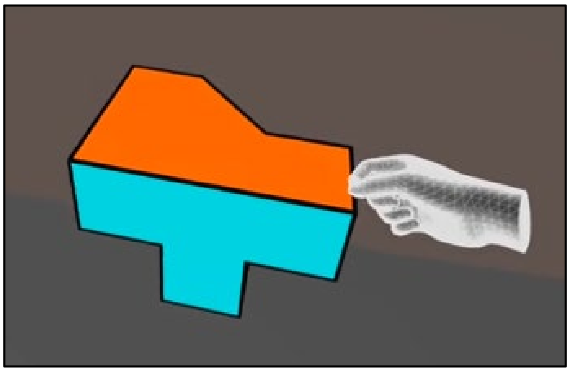


Fig. 2. User in VR uses hand tracking to interact with the 3D virtual shape

Subsequently, they are taken through a series of scenes that presents them with different tasks designed to help them develop and evaluate their spatial skills. These scenes increase in complexity as they advance through the module. The user can also manually select a unique scene they would like to go directly using the scene selection menu on the right side of their screen (see Fig. 3). The content of the application was developed with the help of an engineering faculty that have years of experience teaching students a graphics course designed to help developed their spatial visualization skills. The focus on perspective and orthographic viewing, as well as the tasks introduced in the difference scene were selected based on the areas of spatial skills that are usually more underdeveloped in the students, according to the engineering faculty.

If the user is in the *Object Viewer* module, then they will be able to freely rotate a shape and watch as its hidden line representation, on the top left of screen, changes with the rotation, as shown in the left image of Figure 3. If instead they are in the Orthographic Viewer module then they will be able to freely rotate a shape and watch as its orthographic representation, on the top left of screen, changes with the rotation, as shown in the right image of Figure 3. The *Orthographic Viewer* modules has a series of cameras to give students points of reference from where the different orthographic views (i.e., top, left, right) are taken from.

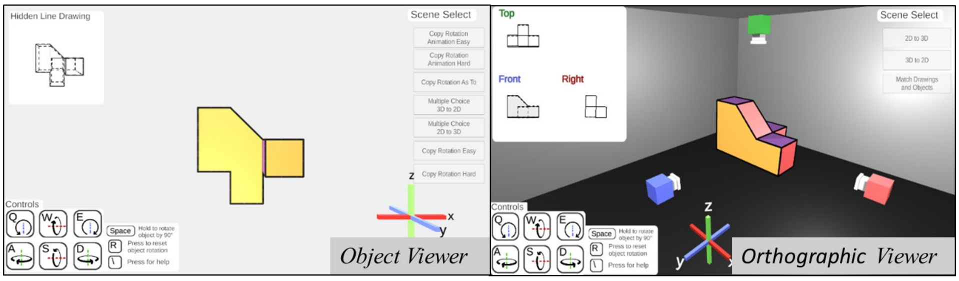


Fig. 3. Free mode of the Perspective and Orthographic Viewer

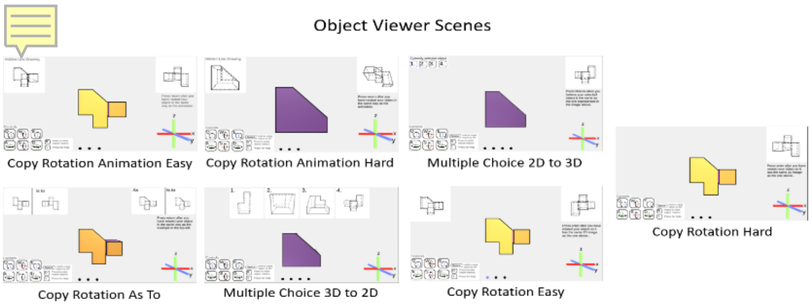


Fig. 4. All seven scenes in the Object Viewer Module

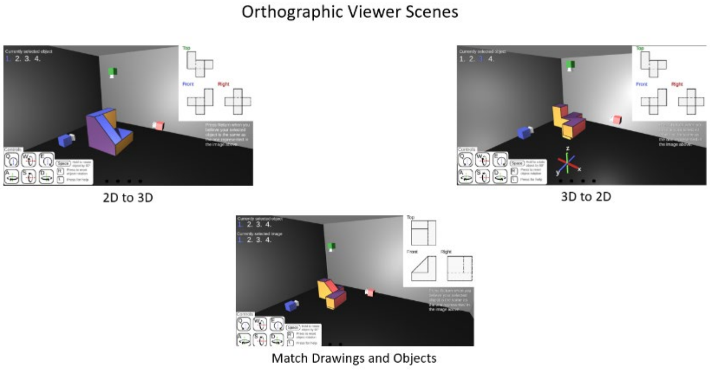
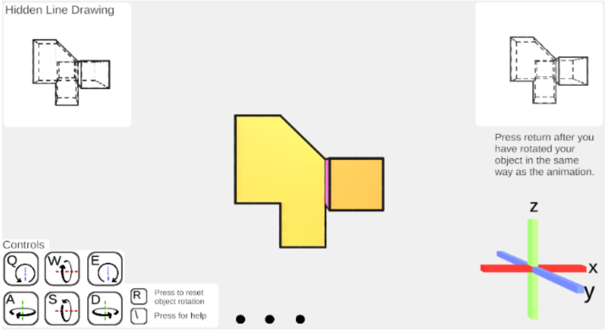


Fig. 5. All three scenes in the Orthographic Viewer Module

Within the *Object Viewer* and *Orthographic Viewer* modules, the scenes, shown in Figure 4 and Figure 5, are designed to teach and assess different elements of the user's spatial skills. The first two scenes in the *Object Viewer* module are designed around the concept of a user mimicking the rotations of an additional shape in the display. The following module *"Copy rotation As To"*, reveals the stating orientation and the ending orientation of a shape, and tasks the user with transforming their shape in the same manner as the one rotated by the computer. The third type of scene the user is shown a 3D or 2D shape that must be paired with their corresponding 2D or 3D shape, as shown in Figure 7. As shown in Figure 8, the *Orthographic Viewer* is similar to the multiple choice section of the other module, however rather than being given shapes to compare, the user is comparing an orthographic view of the object and matching it to the corresponding 3D object. These scenes and modules will help enable individuals to developed spatial skills.



Press return after you have rotated your object in the same way as the animation.

Fig. 6. Rotation mimicry task

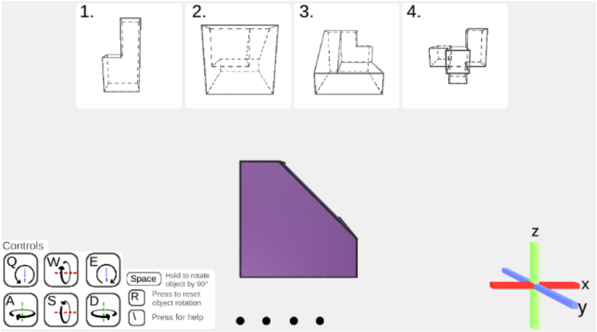
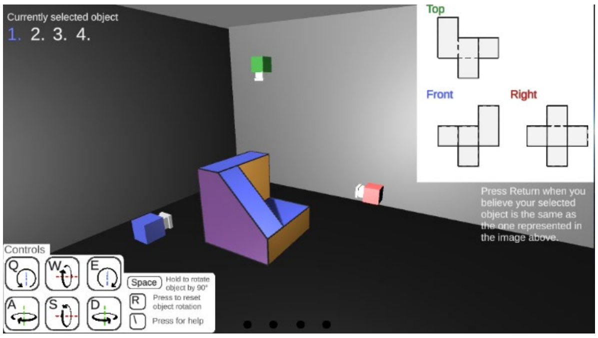


Fig. 7. *Object Viewer* multiple choice question example



Press Return when you believe your selected object is the same as the one represented in the image above.

Hold to rotate object by 90°

Press to reset object rotation

Press for help

Fig. 8. *Orthographic Viewer* multiple choice question example

4 Conclusion

With both versions, both modules, and many scenes, this program could not only enable use to determine how large a factor VR is for teaching spatial skills, but also be used to as a learning tool for those learning spatial skills. In the future, we hope to expand on this project by using Procedural Content Generation to create a wide range of 3D virtual shapes for this program to use, as well as to integrate more modules and scene to help users developed their spatial skills.

References

[1] S. A. Sorby, G. Duffy, N. Loney, and L. Perez, “Spatial skills and their correlation with engineering problem-solving.”

[2] S. Sorby, N. Veurink, and S. Streiner, “Does spatial skills instruction improve STEM outcomes? The answer is ‘yes,’” *Learning and Individual Differences*, vol. 67, pp. 209–222, Oct. 2018, doi: 10.1016/j.lindif.2018.09.001.

[3] C. Roca-González, J. Martin-Gutierrez, M. García-Dominguez, and M. del C. M. Carrodeguas, “Virtual technologies to develop visual-spatial ability in engineering students,” *Eurasia Journal of Mathematics, Science and Technology Education*, vol. 13, no. 2, pp. 441–468, 2017, doi: 10.12973/eurasia.2017.00625a.

[4] J. Parkinson and Q. Cutts, “Investigating the relationship between spatial skills and computer science,” in *ICER 2018 - Proceedings of the 2018 ACM Conference on International Computing Education Research*, Aug. 2018, pp. 106–114, doi: 10.1145/3230977.3230990.

[5] I. Spatial Skills and T. Development, “I. SPATIAL SKILLS, THEIR DEVELOPMENT, AND THEIR LINKS TO MATHEMATICS,” doi: 10.1111/mono.

[6] G. Makransky and L. Lilleholt, “A structural equation modeling investigation of the emotional value of immersive virtual reality in education,” *Educational Technology Research and Development*, vol. 66, no. 5, pp. 1141–1164, Oct. 2018, doi: 10.1007/s11423-018-9581-2.

[7] G. Makransky, S. Borre-Gude, and R. E. Mayer, “Motivational and cognitive benefits of training in immersive virtual reality based on multiple assessments,” *Journal of Computer Assisted Learning*, vol. 35, no. 6, pp. 691–707, Dec. 2019, doi: 10.1111/jcal.12375.

[8] T. Guzsvinecz, É. Orbán-Mihálykó, E. Perge, and C. Sik-Lányi, “Analyzing the Spatial Skills of University Students with a Virtual Reality Application using a Desktop Display and the Gear VR.”

[9] J. Seibert and D. M. Shafer, “Control mapping in virtual reality: effects on spatial presence and controller naturalness,” *Virtual Reality*, vol. 22, no. 1, pp. 79–88, Mar. 2018, doi: 10.1007/s10055-017-0316-1.

[10] M. Coxon, N. Kelly, and S. Page, “Individual differences in virtual reality: Are spatial presence and spatial ability linked?,” *Virtual Reality*, vol. 20, no. 4, pp. 203–212, Nov. 2016, doi: 10.1007/s10055-016-0292-x.

[11] W. Huang, R. Roscoe, M. Johnson, and S. Craig, “Investigating the Novelty Effect in Virtual Reality on STEM Learning,” 2020.

[12] Z. S. Gold, J. Elicker, A. M. Kellerman, S. Christ, A. A. Mishra, and N. Howe, “Engineering Play, Mathematics, and Spatial Skills in Children with and without Disabilities,” *Early Education and Development*, vol. 32, no. 1, pp. 49–65, 2021, doi: 10.1080/10409289.2019.1709382.

[13] M. J. W. Lee, Institute of Electrical and Electronics Engineers. New South Wales Section, IEEE Education Society, University of Wollongong, Charles Sturt University, and Institute of Electrical and Electronics Engineers, *Proceedings of 2018 IEEE International Conference on Teaching, Assessment, and Learning for Engineering (TALE) : date and venue, 4-7 December 2018, Novotel Wollongong Northbeach Hotel, Wollongong, NSW, Australia.*.

[14] K. Atit, D. I. Miller, N. S. Newcombe, and D. H. Uttal, “Teachers’ spatial skills across disciplines and education levels: Exploring nationally representative data.,” *Archives of Scientific Psychology*, vol. 6, no. 1, pp. 130–137, Nov. 2018, doi: 10.1037/arc0000041.

[15] J. Radianti, T. A. Majchrzak, J. Fromm, and I. Wohlgenannt, “A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda,” *Computers and Education*, vol. 147, Apr. 2020, doi: 10.1016/j.compedu.2019.103778.

[16] D. Vergara, M. P. Rubio, and M. Lorenzo, “On the design of virtual reality learning environments in engineering,” *Multimodal Technologies and Interaction*, vol. 1, no. 2, Jun. 2017, doi: 10.3390/mti1020011.

[17] V. Román-Ibáñez, F. A. Pujol-López, H. Mora-Mora, M. L. Pertegal-Felices, and A. Jimeno-Morenilla, “A low-cost immersive virtual reality system for

teaching robotic manipulators programming," *Sustainability (Switzerland)*, vol. 10, no. 4, Apr. 2018, doi: 10.3390/su10041102.

[18] R. Molina-Carmona, M. L. Pertegal-Felices, A. Jimeno-Morenilla, and H. Mora-Mora, "Virtual Reality learning activities for multimedia students to enhance spatial ability," *Sustainability (Switzerland)*, vol. 10, no. 4, Apr. 2018, doi: 10.3390/su10041074.