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Use of Mixed Reality Tools in Introductory Materials Science Courses

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Abstract

Spatial visualization skills of rotation and manipulation of three-dimensional objects often present major challenges that students face when learning new concepts in different areas of STEM education. In material science, students must possess a profound and intuitive understanding of its complex, 3D concepts to fully comprehend the fundamental interplay between structure and properties of different materials. Mixed reality technology offers material science educators the possibility to create 3D visualizations, overlay them on a classroom environment and allow students to interact with them in real-time. In this paper, we introduce an innovative and interactive mixed reality application, "Holo-MSE" - designed to help students visualize and fully control holographic models of threshold material science concepts. This paper is an interim report on an on-going study to implement Holo-MSE app in teaching selected threshold concepts of crystal structures and Miller indices with the aim to improve student performance and understand their spatial visualization ability in the mixed reality environment. Our preliminary results on spatial visualization ability indicate the effectiveness of mixed reality tools and highlight their tremendous potential in improving such skills in engineering students.

1. Introduction

Improving academic performance of the students in science, technology, engineering, and mathematics (STEM) fields is a national priority for many countries. STEM educators around the world often rely on abstract theory, but a continuing goal is to provide students more tangible experiences to effectively explain important concepts. Often, new engineering students find science-based subjects especially daunting because they must imagine abstract concepts and depend on their spatial visualization ability. Materials science is no different; it is a highly interdisciplinary subject that borrows topics from physics, chemistry, and engineering.

As a case in point, introductory materials science courses explain the fundamental interplay between structure, properties, and processing of different materials. A student taking a material science course must quickly develop a profound and intuitive understanding of its 3D, abstract, concepts to progress further in this important field. In a typical classroom setting, materials science educators rely heavily on conventional methods of instruction such as sketching, or video animations, etc., to help students visualize such complex structural objects. Some students may have the innate spatial visualization ability or visuospatial ability to rotate and manipulate two- and three-dimensional objects. While other students may need several hours of practicing to comfortably visualize 2D and 3D depictions, causing loss of interest in this important subject because it requires proficiency in skills they cannot master quickly.

Two thresholds introductory materials science concepts that have historically been difficult to grasp and visualize by undergraduate students are crystal structures and crystallographic planes (see Figure 1). Students are introduced to atoms and ions in solids; differing in size, number, and positions. They must visualize the ordered arrangement of atoms, ions or molecules in three dimensions and be able to identify and draw crystallographic directions and planes given their Miller indices. These two concepts; crystal structures and crystallographic planes, are usually presented to students as 2D isometric projections and students are expected to mentally rotate and manipulate them to develop a complete and intuitive appreciation of the 3D objects. These observations from introductory material science teaching raise a significant question, “What role does spatial ability play in student’s success in undergraduate introductory material science courses?”. Other researchers have looked at similar questions in introductory chemistry courses [1][2].

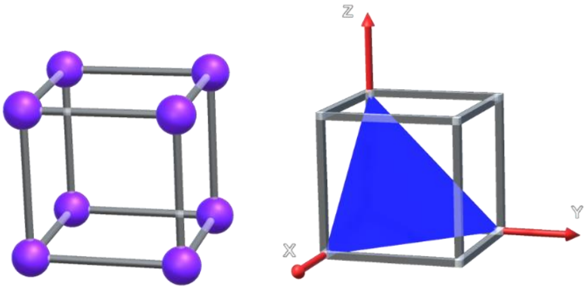

Figure 1. 3D representation of (left) a simple cubic unit cell, (right) (111) crystallographic plane.

Virtual learning (VL) technologies include the use of computer software, the internet or both to deliver instruction and help students create mental models of complex concepts. Today, advances in VL technologies have made 3D visualization accessible, low-cost and user-friendly to implement [3]–[6]. VL technologies provide students a playful and deep learning experience to tackle complex concepts and enhance conceptual understanding of certain topics by promoting active engagement [7]–[9]. For example, in physics courses virtual learning allows students to enact concepts and experience critical ideas through whole-body activities [10]. This has led to significant learning gains for students due to a higher level of engagement, and more positive attitudes towards science [10]. Also, studies have found that VL can reduce mental workload when compared to the traditional teaching methods [11]–[13].

The two well-developed technologies that are increasingly being deployed today to support STEM education are immersive virtual reality (VR) and Augmented Reality (AR) [6]. The first allows users to completely engage in virtual environment and gives them the perception of physically being in a virtual world by shutting them off from their actual environment. The second provides the capabilities to view 3D models as an overlay on surroundings using a camera or glasses. Previous studies in literature have explored to integrate virtual reality, augmented reality and even a mix of both in education as a mean to enhance, motivate and stimulate understanding of certain concepts, especially those for which the traditional notions of instructional learning have proven inefficient or difficult [14]–[19]. These studies have documented that students can learn in a speedy and joyful manner in virtual learning environments which improves their motivation and academic performance.

1.1 Recent implementations of Virtual Reality and Augmented Reality

Researchers have used virtual reality and augmented reality in the context of VL to promote better and intuitive understanding in various science topics. In a typical VR learning scenario, virtual reality can be used to display any 3D models such as crystal structures, as well as complex data such as neutron scattering data sets [20]. One study showed that 3D models representations have shown to engage students and give them a better understanding in the case of carbon nanotubes structures when compared to traditional methods as well as the physical ball-n-stick models [21] . VR tools provide a ‘playful’ environment to help students develop better understanding by exploring strong representations of 3D data [22]. The cognitive load associated with visual processing of simple and complex learning tasks using stereoscopic 3D displays was found to be lower than when processing identical content from 2D videos [11]. Among the three major VR systems (Immersive VR three degrees of freedom, six degrees of freedom and corner cave system) and the traditional teaching approach, it was shown that using any VR system dramatically increases the students’ performance with the highest being the VR system offering six degrees of freedom due to a higher level of immersion [23].

On the other front, a large body of work has focused on applying augmented reality as a mean to enhance the user’s performance and stimulate learning. AR can improve task performance and can relieve mental workload on assembly tasks [12]. In a previous study, users of augmented reality had the shortest time when completing the tasks. Additionally, users had the lowest error rates and the lowest mental workload using the NASA task load index in comparison with other instructional media (printed manual, computer-assisted instruction, and a head mounted display) [12]. In another study, simple AR integration was adapted to evaluate augmented reality, virtual reality and cloud-classroom to teach basic materials science courses. The student would point their iPad or smart phone’s camera towards the 2D crystal structure, and the corresponding 3D crystal structure would appear on their screen. Students can then rotate and view the models and watch related videos. The participants in the experimental teaching outperformed the control group across the three learning dimensions [24]. Therefore, there is some consensus that AR represents a promising and stimulating tool that can be applied to materials science learning. It can be highly effective when used in tandem with traditional methods of instruction [25].

1.2 Mixed Reality and Scope of this work

Mixed Reality (MR) represents a new frontier with tremendous potential for applications in training and education [26]. Unlike virtual reality, MR users are not completely shut off from their environment. Instead, they view their environment normally with an overlay of a digital world. Instead of pointing out their smartphones, users can look around to see the 3D models around them. Users can walk around to examine the 3D models from different sides and angles. The details about MR and some important current applications can be found in reference [26]–[30]. Utilizing MR tools and dedicated applications in introductory materials science courses present educators with an opportunity to enhance and motivate students’ learning process. Exploring visuospatial abilities of mental rotation and working memory in the context of MR is important as it strongly impacts student performance when learning STEM topics [31]. Researchers have shown that virtual technologies can be applied to help improve visuospatial skills in students [32], [33].

At this preliminary stage of our work, we introduce a mixed reality application for introductory materials science courses that allow students to interact, manipulate and fully explore visualizations of crystal structures and crystallographic planes in real-time, shown as an overlay on their original environment. Also, we present our initial results on visuospatial abilities of users in mixed reality environment to understand the effectiveness of MR tools. As previously mentioned, materials science courses are highly dependent on visuospatial abilities, measuring them through standard 2D and 3D tests adopted for mixed reality can allow educators to benchmark, and use them as a measure to gauge the teaching effectiveness of using MR tools.

2. Research Design

2.1 Mixed Reality Application

We have developed an application called, "Holo-MSE" for Microsoft Hololens [34] using Unity® [35] to support teaching two key concepts in introductory materials science courses, i.e. Crystal Structures and Crystallographic Planes. Microsoft Hololens is a self-contained, holographic computer, enabling the user to engage and interact with holograms in the surrounding environment; it brings both the physical and digital world together. In Hololens, the user is shown a cursor on the screen that moves with his head and allows to highlight buttons around him/her, to click a user can simply use gestures with his hands. In our study, we decided that participants must be familiarized with the Hololens gestures through training applications. The first app "learn gesture," designed by Microsoft introduces a participant to all the gestures and controls in Hololens. Also, we developed a second App, "MS-training" to introduce a participant to the Holo-MSE application' buttons, gestures and 3D models. The training session takes approximately 10 to 15 minutes and ensures that the participants are familiarized with Hololens controls and the specific nature of the "Holo-MSE" application. The Holo-MSE App's main menu exposes the user to two main modules: crystal structures and crystallographic planes, they are described in the following section.

Crystal Structures

When a user starts the Crystal Structures module, he/she is prompted to choose a specific class of material and enter the Free-roam stage to learn about common unit-cells in detail. It is important to note that the image shown in Figure 2 is taken from the Hololens engine itself for high- resolution; when the App is used the black background shown in the image is replaced by the user's original environment.

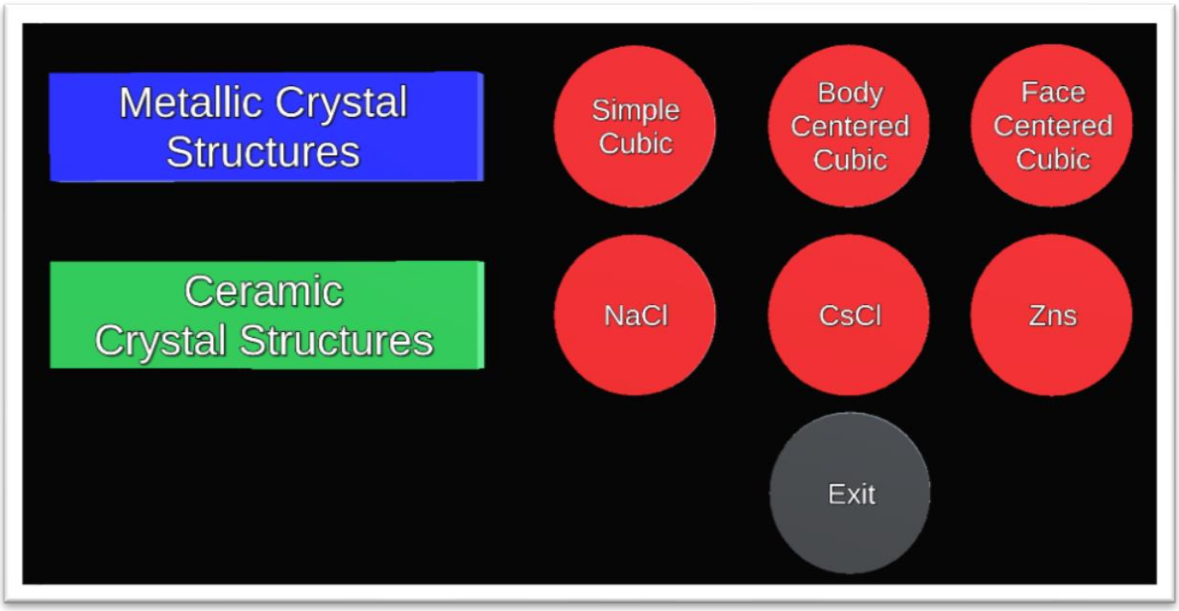

Figure 2. Crystal Structure module of the Holo-MSE App.

The Free-Roam stage contains information about the chosen unit cells based on the hard-sphere model as shown in Figure 3. Once selected, the user can examine the unit-cell from different sides and angles by moving around it. The user is provided with other options to explore the densest plane and scaling to increase and decrease the atomic size and learn about important closed-packed directions. Moreover, the user can rotate the unit-cell in any direction by tapping and moving (usual gestures in Holo-lens environment) his/her hand. Other functionalities are also provided that include showing only the atoms inside a unit cell and showing an aggregate of unit-cells.

The stage guides the user by providing a general explanation of crystal structures. The user gets audio cues, sees information on the screen and near the crystal structure itself. Also, the audio cues ask the user to perform specific actions and interact with the user-interface to obtain more information.

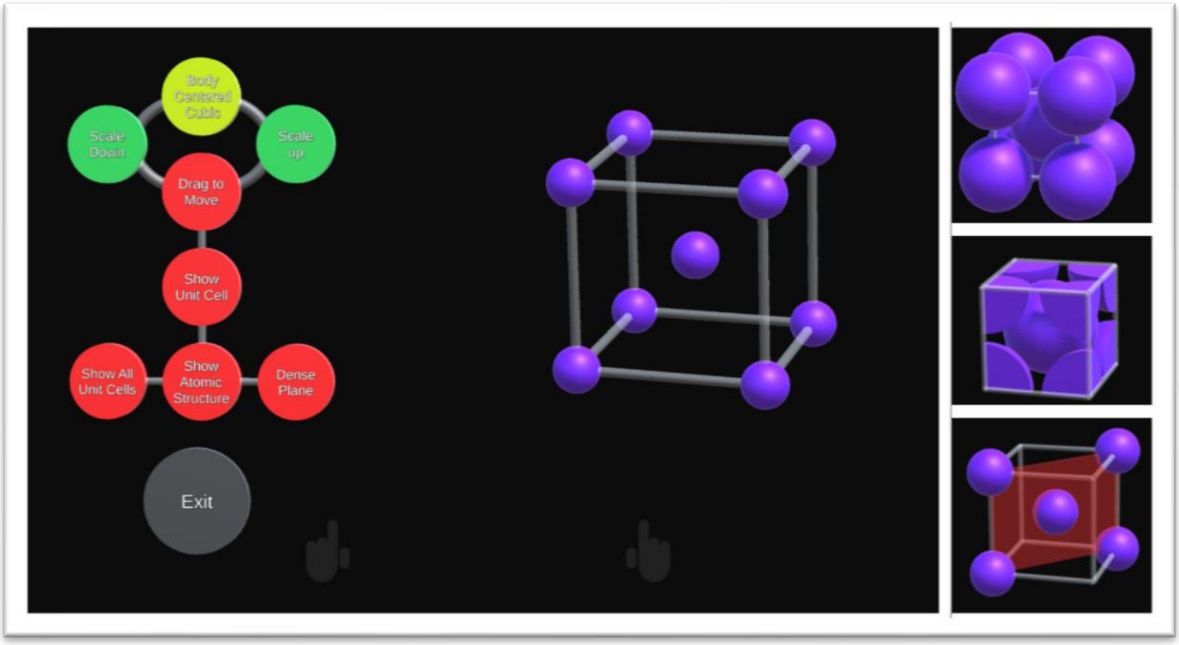

Figure 3. Free-roam stage in the Crystal Structure module of the Holo-MSE App. Images in the in-set show different realizations of the body-centered cubic unit cell as a representative case.

Crystallographic Planes

The second module is designed to help students learn about miller indices by visualizing crystallographic planes. The crystallographic planes module has a similar layout. At the start, the user is provided with detailed information about Miller indices and how to draw a lattice plane in Holo-MSE. The audio cues also help the user to plot different planes and explanations are provided at each step. Next, the user enters the Plane calculator stage which allows him/her to input Miller indices and draw any lattice plane he can think of to test his/her understanding.

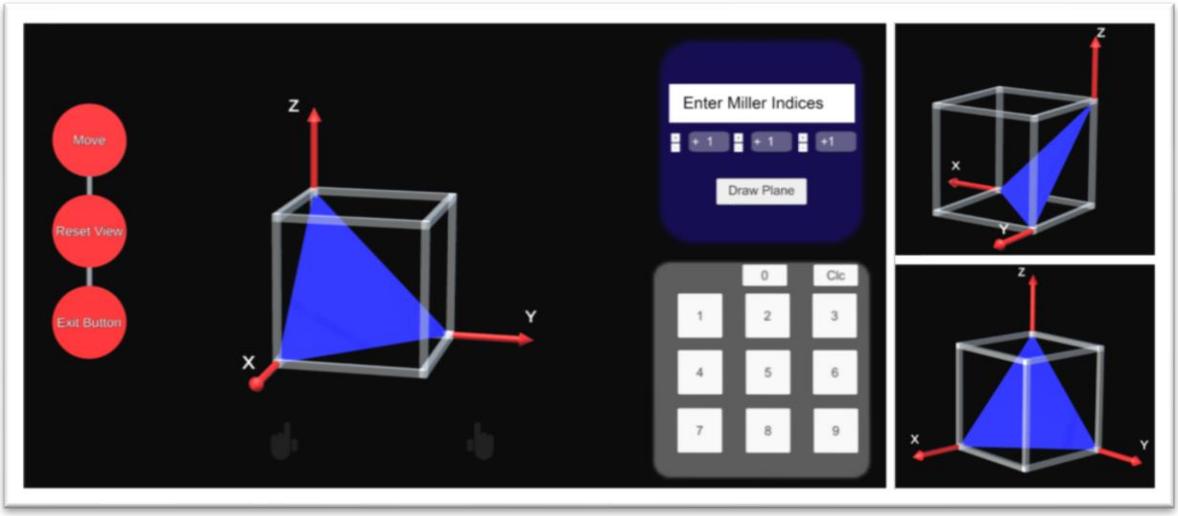

Figure 4. Draw tool in the crystallographic planes stage of the Miller indices module. (left) Rotated (111) planes, provide more spatial information to the user. In-set images show how a user can rotate the plane along any direction to observe it from different viewpoints.

2.2 Visuospatial Skills Tests

As part of our study, we wanted to evaluate how users can apply their innate visuospatial abilities in the MR environment of Hololens as compared to traditional settings and how it may impact their learning. Therefore, we selected five tests that are widely used in literature to assess visuospatial abilities. Traditionally, these tests are administered on paper or by using blocks positioned on a wooden board, but numerous computerized versions have also been developed and widely applied. However, limited work in utilizing these tests in MR environment is available in the literature.

In this study, we developed both 2- and 3D visuospatial ability tests of mental rotation and working-memory for MR environment adopted from Ref. [36] and the Purdue spatial visualization test adopted from Ref. [2]. The four visuospatial skill tests we selected include: (1) 2D Card Rotation test, (2) Corsi Block Tapping test and (3) Colored Bars test, (4) Purdue 3D Spatial Visualization test as shown in Figure 4 and 5. These standard tests are widely accepted to measure skills such as mental rotation and manipulation, spatial ability, the visuospatial short-term working memory and its precision respectively.

1. *The 2D Card Rotation* is a test of mental rotation of two-dimensional shapes. From an array of 4 different shapes, participants must answer which figures are rotated and/or mirror-reversed. The test has five initial shapes that participants are asked to compare and make a choice.
2. *The Corsi Block Tapping* is a test of working memory that measures the spatial component of the visuo-spatial ability. The participants must memorize and replicate a sequence of blocks highlighted in a certain speed. The sequence and the number of blocks increases with each answer with a maximum sequence of 6 blocks but with no limit on the number of blocks.
3. *The Colored Bars* is a test of visuo-spatial memory using arrays of colored bars. The test starts by presenting a memory arrays of colored bars programmed to last 500 ms, then after an interval of 1000 ms, one of the bars chosen randomly changes colors with another

color not already shown in the display. Participants must choose the right bar which changes in color. The number of bars increase as the user's score increases. The colored bars test was modified and made more precise as users need to know which bar changed in color where in [36] they had to know if a bar changed in color or not which may involve luck.

4. *The* 3D Spatial Visualization test for MR is a test adapted from the Purdue Spatial Visualization of Rotations, which is a part of the Purdue Spatial Visualization Test Battery [2][1]. There are several standardized tests available to measure a person's ability in this regard, but the Purdue test has been shown to produce results that are least likely to be complicated by the type of analysis.

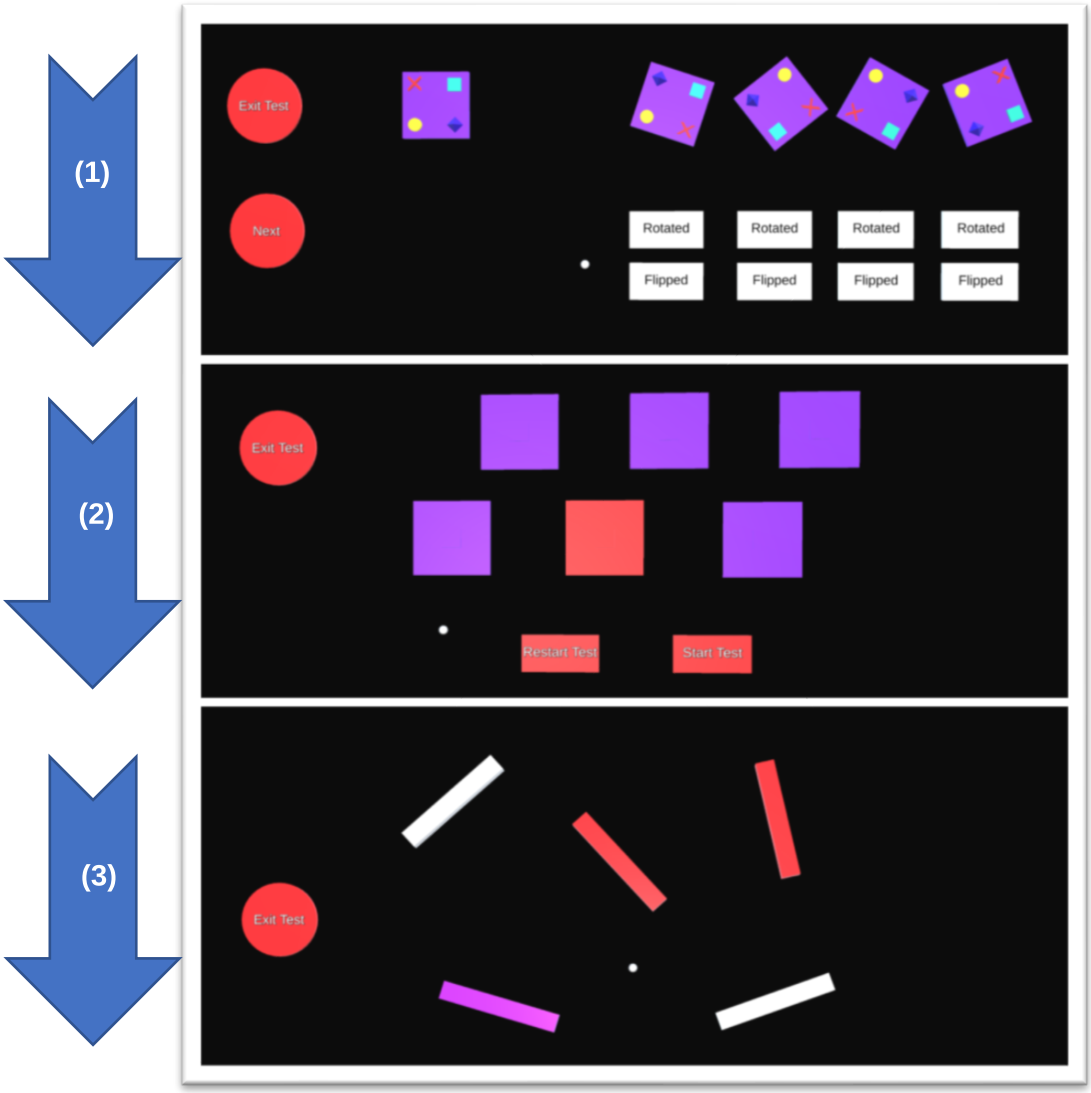

Figure 5. The 2-dimentional visuospatial ability test matrix adopted for this study: (1) Card Rotation Test, (2) Corsi Block Tapping Test, (3) Colored Bars.

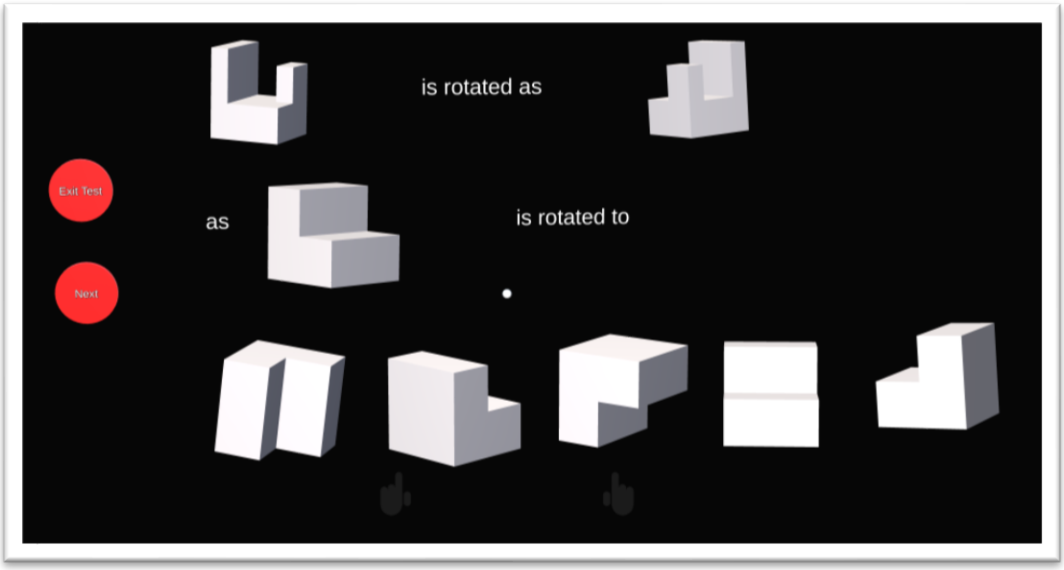

Figure 6. The 3-dimensional visuospatial ability test adopted from the Purdue Spatial Visualization of Rotations [1][2].

Ten participants between the age of 18 and 24 participated in the study and were divided into two groups: Mixed Reality group and control group. The control group took the tests on a computer; this allowed us to set a base score for the students. The students completed the two training applications on Hololens before taking the tests. The study was explained to each participant before taking the tests. As a requirement, each participant signed an individual consent form as required by the guidelines laid out by the appropriate research ethics committee, and the institutional review board.

3. Preliminary results on spatial ability

This section describes the preliminary results obtained by a battery of 2D visuospatial tests. The participants were graded on time needed to complete the first visuospatial abilities test (Card Rotation) and on the score of each of all three tests. The average time and scores results are shown in Figure 7 and 8 respectively.

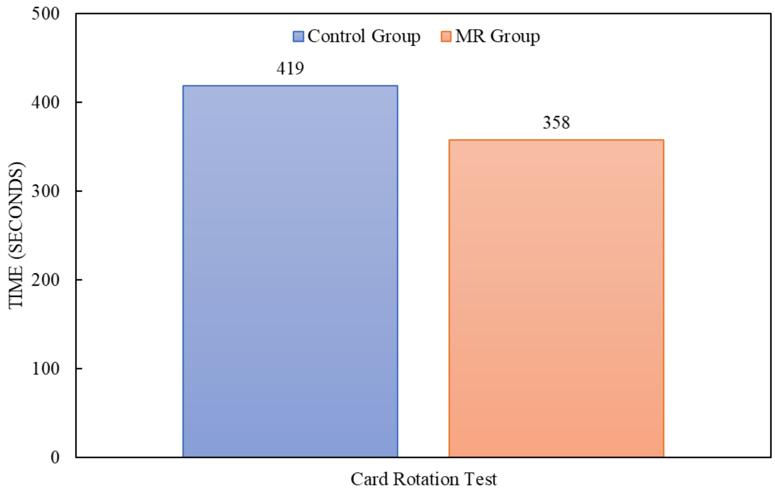

Figure 7. Average total time for each group in the card rotation test

Although MR experience was new to the users and they took minor training on it, on average MR users took less time to complete the card rotation test when compared to the participant in the control group. MR users were able to figure out if the object was rotated or flipped quicker than the control group. The difference was 61 seconds between both groups. Users found it very easy to use their head as a cursor and tap with their hand to select or choose buttons.

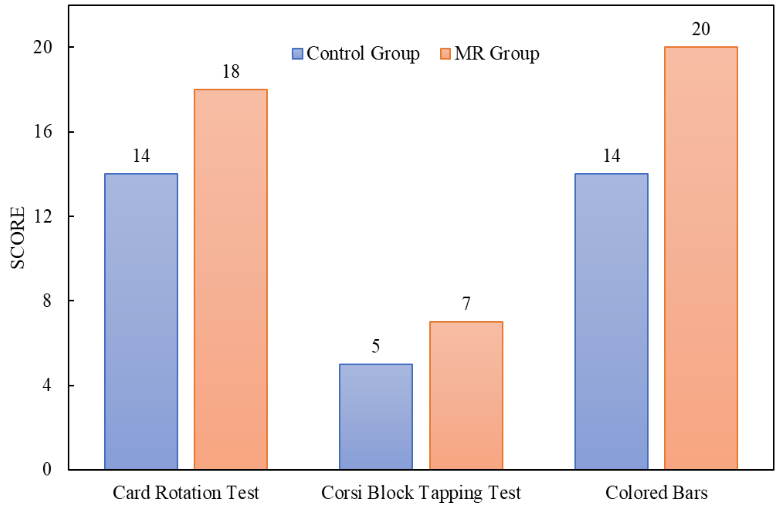

Figure 8. The cumulative score for the 2D visuospatial abilities tests.

Participants in the MR group got a higher average score in the three tests when compared to the control group. The card rotation test had a final score of 20. The MR group scored an average of 18 while the control group scored an average of 14. Participants in the control group complained about having difficulties in the card rotation test as they could not look at the structure from different sides. However, no complaints were given from the MR group as they could move around and check the structure from all sides. The Corsi block-tapping test average scores were close between the control and the MR group, but the MR group scored 2 points higher on average. The ability to memorize the spatial components was slightly higher in MR environment. The final test was the colored bars test where participants in the MR group scored significantly higher than the control group. Users could easily differentiate which bar changed in color in MR. Accordingly, mixed reality had a positive influence on the visuospatial abilities of participants. A study on a higher student population is needed to confirm these results. A full-scale study with a large number of participants including the MR version of Purdue test mentioned earlier is currently under-way to confirm and further substantiate these results.

4. Closing note and future work

Mixed reality presents a fun and interactive way to help students apply their spatial visualization skills and create accurate mental models of complex, three-dimensional material science concepts. Our preliminary results indicate mixed reality tools can improve academic learning and visuospatial abilities of students by reducing the gap between the abstract and real in a classroom's natural setting.

The future work in this on-going study will involve a full-scale spatial visualization ability evaluation of students by using the methodology outlined in this report to identify students who may have weaknesses in spatial visualization skills. This will be done before they start any introductory material science courses to identify the relationship between spatial visualization skills and success in spatially intensive tasks. An effort will also be made to estimate the reliability and validity of the test matrix in evaluating spatial visualization ability of students in mixed reality environment.

The work will them involve the implementation of the Holo-MSE app in introductory material science course to teach the selected concepts. Students will be asked to utilize the app, interact with holograms and take built-in quizzes for each module (Crystal structures and Miller indices). Their performance will be compared with the historical student performance data for the two concepts as well as with a control group where the mode of instruction will be intentionally kept traditional, i.e. reliance on 2D drawings and video animations.

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