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A gamified approach to assessing mental rotation in virtual reality

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Abstract

We present a new spatial skills assessment tool, the Virtual Reality Mental Rotation Assessment. Results suggest that the gamified immersive experience enabled increased levels of engagement and motivation and the instrument was likely not biased in favor or people with past virtual reality (VR) experience. Using VR did not appear to introduce additional problems beyond those present in a traditional spatial test, as moving one's body to change perspective did not correlate with improved performance. Our findings have implications for training and assessing spatial skills in engineering.

Keywords: spatial skills, mental rotation, virtual reality (VR), design education, visualisation

1. Introduction

Spatial ability, or the ability to mentally manipulate objects and space, has traditionally been considered an important predictor for success in STEM, and assessment and training of spatial abilities is popular in engineering education research (Sorby et al., 2018). (In this paper, the terms spatial ability and spatial skills will be used interchangeably.) The ability to envision three-dimensional solutions is certainly an important skill in engineering design. Thus, recent studies have investigated the relationship between spatial skills and engineering design creativity skills (Reid and Sorby, 2023). Virtually all spatial skills research relies on standardized spatial tests to measure spatial skills. Thus, ensuring the accuracy of spatial tests is fundamental to our understanding of spatial skills and their relationship to engineering design. Many spatial skills tests still in use today were developed during the 1970s and use visualization technologies that may or may not be relevant to students today. In this paper, we will describe some initial testing of a new instrument designed to measure mental rotation skills in virtual reality (VR), the Virtual Reality Mental Rotation Assessment (VRMRA).

We chose to focus on mental rotation because mental rotation tests are some of the most widely used spatial ability assessments. The Mental Rotation Test (MRT) (Vandenberg and Kuse, 1978) is commonly used in the fields of psychology and social sciences, and the Purdue Spatial Visualization Test of Rotations (PSVT:R) (Guay, 1976) is popular in STEM education research (Maeda and Yoon, 2013). In the MRT, the test-taker must identify which two shapes in a given set are different rotated views of the same shape shown on the far left. The MRT is a 20-question test which is typically administered with a 10-minute time limit. An example question from the MRT is shown in Figure 1.

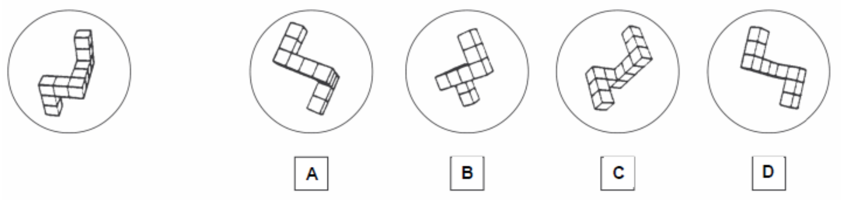


Figure 1. Example problem from the MRT [24], correct answers are B and D

In the PSVT:R, the test-taker must judge the rotation that occurred to transform the reference shape shown in the top left into the position in the top right. The test-taker must then apply the same rotation to the shape in the middle row and identify the correct answer from the five multiple-choice options. The PSVT:R contains 30 questions presented in multiple choice format. An example question from the Revised PSVT:R, a redrawn version of the original PSVT:R, (Yoon, 2011) is shown in Figure 2.

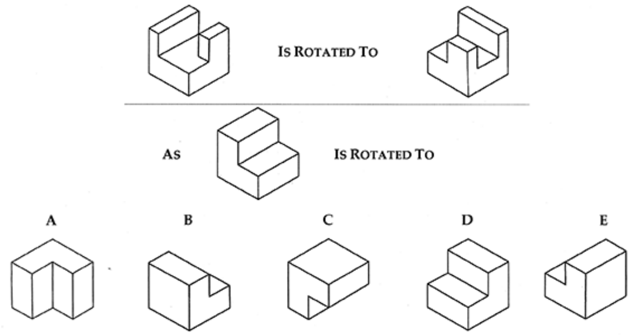


Figure 2. Example problem from the Revised PSVT:R [27], correct answer is D

We decided create a VR version of PSVT:R and MRT because, while these spatial skills assessments have remained popular over the course of many decades, the tests do not necessarily assess mental rotation skill accurately. Depicting 3D shapes in 2D is inherently difficult, and factors related to figure perception have been found to significantly impact the difficulty level of questions on the MRT (Caissie et al., 2009). For example, in many cases viewers are unable to know what the obscured side of a particular shape really looks like (Pizlo, 2008). Furthermore, tests like the MRT and PSVT:R present figures as black and white line drawings, which lack many of the visual cues that people use to interpret 3D shape in the real world. When researchers have depicted shapes in spatial skills test more realistically, scores often improved. Bartlett and Camba (2023a) argued that this trend of improved scores with improved stimuli realism demonstrates that spatial tests like the MRT and the PSVT:R may not be accurate measures of mental rotation, since graphics interpretation impacts performance (Bartlett and Camba, 2023a). They also suggested that the use of more natural representations of the shapes can result in more accurate assessments of mental rotation skill (Bartlett and Camba, 2022). Thus, we hypothesized that using VR to present questions from the MRT and PSVT:R would lead to a stronger relationship between the amount of "mental rotation" needed to solve a question and the difficulty of the question.

Updates to spatial tests have historically focused on correcting errors in previous versions (Yoon, 2011) or completely redrawing the test because the quality of the original copies had degraded over time (Peters et al., 1995). More recently, researchers are leveraging various visualization technologies to improve spatial assessments. For example, while traditional spatial tests use black and white line drawings to depict shapes, the authors of the Santa Barbara Solids Test employed computer rendering to create shaded color figures for the stimulus material (Cohen and Hegarty, 2012). In a later iteration, researchers used video animations instead of static images to present the figures (Sanandaji et al., 2017). Researchers developed a gamified Mental Cutting Test for the Android mobile platform (Tóth et al., 2020) in which users had the option to display the shapes in augmented reality (AR) as a “lifeline” on difficult questions. At present, Tóth and colleagues appear to have not yet published their findings about how gamification impacted test performance. Gamification strategies have been used successfully in multiple spatial training applications. However, to the best of our knowledge, no gamification strategies have yet been applied to mental rotation testing.

While more commonly used for spatial training than testing, VR applications have been investigated for some spatial testing. Guzsvinecz et al. created a VR version of three popular spatial tests (the MRT, PSVT:R and MCT) on the Gear VR device. They found that the performance of women students, left-handed students, and older students improved in the VR version of the test compared to the desktop version. They also found that the PSVT:R style questions were easier in VR (Guzsvinecz et al., 2020). Traditionally, researchers have believed that men have better spatial skills than women, yet some recent research calls this fact into question and argues that spatial testing perpetuates deficit models (Bartlett, 2023; Bartlett and Camba, 2023b; Stieff et al., 2018). The work Guzsvinecz and colleagues suggests that there is a possibility that VR-based spatial tests could be more gender fair.

In addition to fairness issues, motivation may also be a problem with traditional spatial tests. If participants are not motivated to put full effort into a test, the assessment cannot accurately measure their skill level with the subject matter. It has been shown that low motivation may affect performance on traditional spatial tests like the PSVT:R. For example, Wauck and colleagues reported having to remove data from 23.6% of the participants in their study who took the PSVT:R as a benchmark of spatial ability because this group "did not take the test seriously" (Wauck et al., 2020). We have observed similar trends in our own work using the Revised PSVT:R. Many participants appeared to have rushed through the test without making a sincere effort, sometimes spending less than 5 minutes which, as Wauck and colleagues observed, seems to take a minimum of 8 minutes for adequate performance.

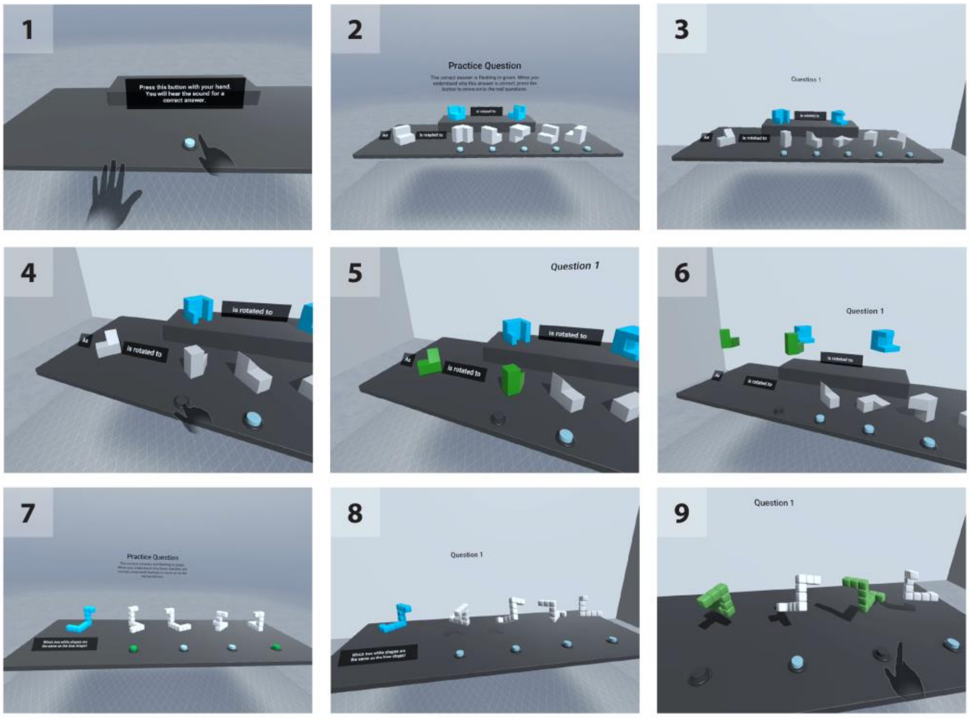
The Virtual Reality Mental Rotation Assessment (VRMRA) is a gamified VR-based mental rotation instrument designed to improve on existing tests by increasing the level of realism of the test figures and the motivation of the test-takers through an immersive experience (Bartlett et al., 2023). The results of the initial validation testing of the instrument suggested that the VRMRA was likely more accurate in assessing mental rotation ability in comparison to traditional instruments which leverage 2D media. The main reason for this was because the pattern of item difficulty in the VRMRA was more related to the complexity of rotation needed to answer the questions in comparison to the difficult patterns observed in the traditional MRT and PSVT:R. However, the results also suggested that the fundamental design of the MRT and PSVT:R may not be ideal for the assessment of mental rotation skill. In the present work, we describe three additional investigations related to the VRMRA: investigation of the possibility that prior VR experience influences performance on the VRMRA, investigation of the possibility that strategy choice influences performance on the VRMRA, and investigation of the effectiveness of using VR and gamification to create an engaging spatial test. We conclude with the implications of our work for engineering design education.

2. Methods

2.1. Application design

The VRMRA was created to provide an intuitive experience for users, including those without prior experience using VR headsets. The system was designed to run on the Meta Quest 2 and leverage the hand-tracking feature in the device. We have observed that users who are new to VR can sometimes struggle with the controllers since they cannot see their hand placement on the controllers while wearing the headset. Therefore, we opted to use the hand-tracking and virtual buttons so that the participants wouldn't have to hold controllers, enabling a more intuitive and less intimidating interaction, especially for non-gamers or people who were new to VR. In this initial prototype of the VRMRA, we focused on two elements of gamification: creating an immersive game-like visual experience and providing real-time feedback to the player about their progress though audio and animations. The VRMRA application was built in Unity version 2020.3.11f1 using C# scripts and Oculus Integration version 0.37.0. We used the standard shader for materials and unidirectional real time light in the virtual environment. For our application, we recreated 12 questions from the PSVT:R and 12 from the MRT using solid models of the same shapes depicted in the same positions as the original tests. We used SolidWorks 2021 to build the 3D models and reformatted in them Blender version 3.0.1 before importing them into Unity.

The VRMRA application is composed of four scenes. Two are designed to train the user before being able to solve the real problems, which compose the two remaining scenes. The order in which the scenes are displayed is training scene 1, problem type 1 (consisting of 12 PSVT:R-style questions), training scene 2, problem type 2 (consisting of 12 MRT-style questions). Screenshots of the flow of the application are shown in Figure 3.



Press this button with your hand. You will hear the sound for a correct answer.

Figure 3. Screenshots from the VRMRA application, fully described in the text

Figure 3 is described as follows: (1) First, the user is shown a training scene in which they can practice pressing the virtual button and become familiar with the sounds for correct and incorrect answers. Pushing the buttons automatically advances the application to the next scene. (2) The player then is shown practice question 1. In the practice question, the button for the correct answer flashes green. Once the player understands why that answer is correct, they press the button to advance to the real questions. (3) The first set of questions is modeled after the PSVT:R. The player must select the one correct answer. (4) The player logs their answer by pressing the button. The button turns black after it is pressed to indicate that it is disabled. (5) The correct answer shape then changes to green, and a sound plays so the player knows if the answer was right or wrong. (6) An animation plays in which all three model shapes and the correct answer shape raise up from the table, and blue and green shapes on the left-hand side rotate simultaneously to reach the final position of the shapes on the right-hand side. This visual feedback demonstrates to the player why that answer was correct. (7) After completing the 12 questions from part 1, the player is shown a practice question for part 2. The two correct answer buttons flash green. Once the player understands why those answers are correct, they press the two buttons to advance to the real questions. (8) The questions in part 2 are modeled after the MRT and each has two correct answers. Players cannot change their answers after pressing a button to log an answer. (9) Once a player presses a button, the button turns black to indicate that the button is disabled. After the player logs two answers, the correct answer shapes turn green, and a sound plays to indicate whether the answer was correct or not. (10) An animation then plays in which the two green correct answer shapes rotate into the same position as the blue shape, to demonstrate why those answers were correct. Though the shapes in the VRMRA appear to be solid shapes resting on the table or hovering above it, players cannot interact with the shapes. This behavior was intentional, because we did not want players to be able to manually manipulate the shapes in place of mentally rotating them. Figure 4 (1) shows that a virtual hand which attempts to “pick up” a shape in the VRMRA will simply pass through the shape as if it is not there. The only interaction the hands are permitted to make is to press the buttons to identify the correct answers. Figure 4 (2) shows a side view of the virtual table. Players were instructed that they could walk to either side of the virtual table if they wanted to view the shapes from another angle. However, they were directed to not walk behind or through the table.

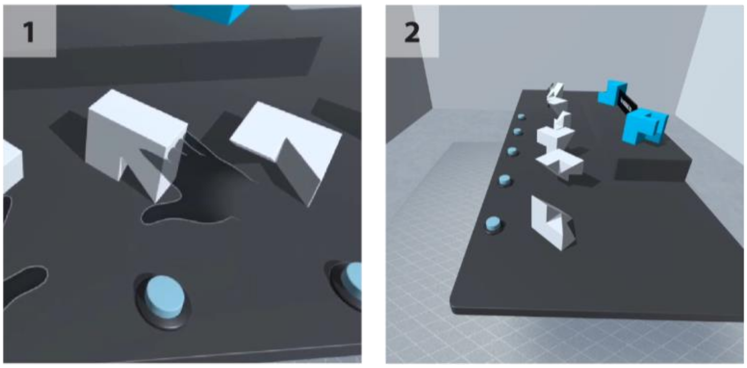


Figure 4. (1) Virtual hand cannot pick up or manipulate blocks. (2) Player can view shapes from the sides of the table

2.2. Testing procedure

In this study, we investigate whether administering a VR version of a mental rotation test leads to a difference in performance between people who had past experience with VR and people who did not. We also investigate whether people adopt new strategies for mental rotation tasks that take place in the virtual environment, which may change the nature of the assessment. For example, some researchers have suggested that in a VR test environment, the participant could simply move their head or body to find the answer in place of "mentally rotating." We questioned whether this strategy would really be used by any participants, and if so, would it be effective? Our specific research questions are as follows:

RQ1: Did people with prior VR experience perform better in the VRMRA than people without prior VR experience?

RQ2: What strategies did people most commonly report using to solve both question types in the VRMRA?

RQ3: Which strategies (if any) were most correlated with test performance in the VRMRA?

RQ4: How does user engagement in the VRMRA compare to the traditional PSVT:R?

Participant demographics are reported in the previous study (Bartlett et al., 2023). Participants were asked to self-report whether they had prior experience using VR. Sixty-eight percent of the participants reported having prior experience. Participants gave informed consent for the study and then viewed a short video tutorial on a computer while the researcher explained the kinds of questions they would see in the VRMRA. The user interactions in the VRMRA application are described in detail in the previous section, but we note that the only actions the users can take during the test are to physically move their own body through space in order to view the shapes from other angles, and to press a button to select an answer. The test-takers cannot manipulate the shapes on the table. Participants were instructed to lift their hands back up after pressing down on a button so that the game could progress, because keeping a button pressed down would prevent the game from advancing. Participants were told that they could move around the room, including walking to either end of the front of the virtual table and walking to the sides of the table, but due to space limitations in the room they were instructed not to walk behind the table. They were also asked not to walk through the table since this could cause an inadvertent push of a button. Participants were instructed to take as much time as they wanted during the tutorial portion and practice questions, but to complete the main game as quickly as possible without making mistakes. Participants then played through the VRMRA and filled out a survey which asked for a description of the strategies they used in each section of the game. The participants provided their answers as typed responses in the post-test survey. Most strategy description responses were a few sentences long. We coded all the responses for themes in an attempt to find common strategies. Since the strategies were described using open-ended responses, not every participant described these strategies in exactly the same way, but we grouped them in a way that captured the same general principle. Participants who described multiple strategies in their typed answers were coded as using multiple strategies.

3. Results

3.1. Role of prior VR experience

We used an independent samples t-test to determine if there was a significant difference in scores between participants with and without prior VR experience. (H0: there will be no difference in scores between people with and without prior VR experience. H1: people with prior VR experience will score higher on the test.) There was no significant difference in scores based on prior VR experience, t(66) = -.938, p = .176, despite the group of 46 people with VR experience (M = 18.7, SD = 3.7) attaining a higher average score than the group of 22 people without prior VR experience (M = 17.9, SD = 3.3).

3.2. Strategy

In part 1, which was based on the PSVT:R, we identified six common strategies that were used by more than one participant. The strategies and an example quote from someone who reported using the strategy are listed in Table 1.

Table 1. Reported Strategies in Part 1 of VRMRA

Strategy	% Who Used Strategy
General mental rotation. “I tried to rotate the object in my head to match the example”	44.1%
Rotation of a single side or face. “I kept track of one face’s rotation, which made it easier to solve”	42.6%
Split rotation into increments. “I broke down the rotation into 90- or 180-degree steps”	25.0%
Rotation of own hand. “I put up my hands as if I was holding the model, and physically made the motion of turning it”	20.6%
Rotation of a single feature or point. “I visualized a key feature on the question shape being rotated”	14.7%
Move head or body to look from different viewpoint. “I tried to see the shapes from all angles by walking to the edges of the table”	8.8%

The strategies people reported using in part 2 of the VRMRA (modeled after the MRT) and the percentage of people who reported using them are shown in Table 2. Example quotes that illustrate the strategies are included as well.

Table 2. Reported Strategies in Part 2 of VRMRA

Strategy	% Who Used Strategy
Tracing direction or orientation of segments “I could move my eyes along the edge and eliminate the shapes that didn’t follow the same path”	50.0%
General mental rotation “I tried to rotate the displayed object in my head”	29.4%
Count length of segments “I counted the number of cubes per ‘section’”	27.9%
Recognizing same shape or not “I paid attention to how the shape looked”	19.1%
Pay attention to one part/feature “Focusing on one component and finding similarities among the possible solutions”	13.2%
Move head or body to look from different viewpoint “The act of moving allowed me to see a slightly altered perspective that usually confirmed my initial thought”	10.3%
Rotation of own hand “I tried to use my hands to model how the model shape rotated”	5.9%

After identifying the common strategies, we wanted to find out which strategies, if any, were correlated with accuracy on the VRMRA. A point-biserial correlation was run to determine the relationship between each strategy type and accuracy on each part of the VRMRA. The results from part 1 are reported in Table 3. None of the correlations were statistically significant.

Table 3. Part 1 strategies vs. accuracy

Strategy	Correlation with accuracy
General mental rotation	-.098, p = .428
Rotation of a single side or face	.073, p = .554
Split rotation into increments	.211, p = .084
Rotation of own hand	.068, p = .584
Rotation of a single feature or point	.084, p = .495
Move head or body to look from different viewpoint	-.098, p = .428

The results of the point-biserial correlations from part 2 are reported in Table 4. None of the correlations were statistically significant.

Table 4. Part 2 strategies vs. accuracy

Strategy	Correlation with accuracy
Tracing direction or orientation of segments	.182, p = .137
General mental rotation	-.061, p = .621
Count length of segments	.067, p = .588
Recognizing same shape or not	.010, p = .939
Pay attention to one part/feature	-.005, p = .969
Move head or body to look from different viewpoint	-.044, p = .721
Rotation of own hand	.023, p = .854

3.3. User engagement

While we did not formally ask participants about their enjoyment playing the VRMRA, many made unprompted comments afterward saying that they thought it was fun and that playing it made them want to play more VR games or use VR more often. The participants' behavior during the game also indicated that many of them were engaged. For example, we observed many participants expressing frustration verbally when they answered a question incorrectly or expressing excitement when they answered correctly, which suggested that they were motivated to perform well in the game. Though the current version of the VRMRA prototype did not display a score, many participants either kept track of how many questions they missed and discussed this afterward with the researcher, or asked the researcher what their score was, which again highlighted the competitive aspect of the gamified experience and suggested that they were motivated to do well.

As a rough proxy for measuring engagement, we compared how long participants spent answering the questions in the VRMRA versus administrations of the traditional PSVT:R. The average response time for questions in part 1 of the VRMRA was 9.29 (SD = 4.22) in the VRMRA, which is 46.4 seconds per question. In previous studies which used the traditional Revised PSVT:R, the average answer time for the PSVT:R was 27.5 seconds per question even after we had excluded the people that spent less than 5 minutes on the test in total. This data suggests that people are spending longer to answer questions in the VRMRA than they typically do on the traditional PSVT:R. The average time to answer the part 2 (MRT style) questions in the VRMRA was 7.44 minutes (SD = 3.51), which is 37.2 seconds per question. Participants reported that part 2 was easier than part 1, so it makes sense that they were able to answer more quickly in part 2.

4. Discussion

While players with previous VR experience did score higher than players without previous experience on the VRMRA, results were not statistically significant. Thus, from these initial results, we can tentatively conclude that the VRMRA is not likely biased in favor of people who have prior VR experience. However, it is possible that the individuals with VR experience were also more likely to be STEM majors who have more experience with mental manipulation of 3D models in general, and who may be more likely to score high on spatial tests. In the future, it would be better to recruit a group of either all STEM majors or all non-STEM majors to make this comparison about prior VR experience.

None of the problem-solving strategies we identified were significantly correlated with accuracy on the VRMRA, which could be partly due to the fact the participants reported their strategies in an open-ended way and reported multiple strategies without any kind of ranking. The open-ended nature of strategy data collection can be viewed as a limitation in this study, and future studies could ask participants to select their main strategies from a list of options. While no previous studies that we know of have discussed strategy use on the traditional PSVT:R, one study found that on the MRT, accuracy was positively correlated with the use of a "global-shape strategy" (Hegarty, 2018). In this global-shape strategy, which is not considered to involve "mental rotation," participants eliminated answers options that were structurally different than the shape in question (Hegarty, 2018). This is the same strategy that we have called "recognizing same shape or not." The fact that our findings differed from Hegarty's suggests that strategies used in traditional paper-based spatial tests might be less effective in VR.

One notable observation is the fact that the strategy which was afforded by the presentation of the media in room-scale VR, "move head or body to look from different viewpoint," was employed by only about 10% of participants. Based on this finding, researchers who create mental rotation tasks in VR do not necessarily need to worry that participants will substitute the movement of their own body for more typical mental rotation problem-solving strategies. Another notable finding was the frequency of people who used their own hands to mimic the rotations of the shapes in part 1 (20.6%). Had we not used hand-tracking and showed the virtual hands in the VR interface, this strategy would not have been possible. Although this was also not seen to be a very effective strategy, it does correspond with what we have observed many test-takers do when taking the traditional PSVT:R. People often use their hands to track the rotations of the shapes. The popularity of this strategy begs the question of whether participants would have used a physical game controller as a manipulable and rotated it in the same way as the blocks had they had the opportunity in the VRMRA. Since we used hand-tracking and no controller in the VRMRA, we did not have to worry about this effect. But the possibility should be kept in mind by others who develop mental rotation tasks in VR.

Based on the participants' reactions and comments while using the VRMRA, we are confident that most people found the gamification aspects and the VR presentation engaging. While the participants spent more time answering the VRMRA than is typical in traditional mental rotation tests, it is difficult to know whether this time difference is due to increased effort or other factors such as increased difficulty or a slower interaction mode in VR compared to the computer-based test format. The questions could have been more time-consuming because there is more visual information to take in in the VRMRA than in traditional PSVT:R. The difference also could have been related to the fact that participants knew they were being observed by the researcher while answering the VRMRA, while most computer-based spatial skills tests are typically administered remotely without the element of observation. Furthermore, unlike in a traditional spatial skills test, participants taking the VRMRA typically could not see the entire question in their field of view at once and needed to move their head or body to consider each answer choice option.

5. Conclusion

Our results in this study suggest that the VRMRA is likely not biased in favor of people with prior VR experience, but more research is needed with homogeneous groups of STEM or non-STEM majors. While participants spent more time answering questions in the VRMRA than they typically do in the traditional PSVT:R, we cannot necessarily conclude that this means they found the test more engaging. However, the reactions and comments from the participants indicated that they found the VR media and gamification elements of the test engaging and motivating.

Our analysis of strategies used by participants suggest that no particular strategies were significantly positively correlated with performance in the VRMRA. Future work could build on our initial strategy investigation by giving the participants a list of strategy options to choose from, based on the strategies identified in this study. Our findings also suggest that when taking a mental rotation test in VR, people are not likely to use the physical movement of their bodies in place of mentally rotating shapes, at least in the case of the VRMRA. Thus, we conclude that administering a mental rotation test in virtual reality does not appear to remove the element of "mental rotation" from the test.

The VRMRA is freely available on GitHub: https://github.com/krisd1024/VRMRA-application. Researchers can use the system to further investigate the critical issues of validity and fairness in spatial testing. As "spatial" technology like VR is leveraged in the study of spatial skills, it is possible that our understanding of spatial skills will change, as interpreting spatial graphics in 2D media versus 3D media may be very different categories of skill. As engineers increasingly use technologies like CAD and VR to design and to communicate, it makes sense that our conception and assessment of spatial skills might need to change to keep up with the current standards in educational and professional practice.

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