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Improving Spatial Visualization Abilities Using 3D Printed Blocks

Mrs. Vanessa LeBow, University of Arkansas

Vanessa LeBow is an undergraduate civil engineering student at the University of Arkansas. Her area of focus is geotechnical engineering. As a part of her undergraduate honors thesis, she is investigating the use of 3D printed aids to improve spatial visual retention. She plans to pursue a M.S. in civil engineering at the University of Arkansas in Fall 2018.

Dr. Michelle L. Bernhardt-Barry, University of Arkansas

Dr. Bernhardt-Barry is an Assistant Professor of Civil Engineering at the University of Arkansas. She received her Ph.D, M.S., and B.S. in civil engineering from Texas A&M University. Her research interests include geotechnical engineering, and the use of 3d printed models to aid learning in K-12 and college classrooms.

Dr. Jyotishka Datta, University of Arkansas

Jyotishka Datta is an Assistant Professor of Statistics at the University of Arkansas at Fayetteville since August 2016. He was an NSF postdoctoral fellow at Duke University and Statistical and Applied Mathematical Sciences Institute (SAMSI) working with Dr. David B. Dunson (Statistical Science) and Dr. Sandeep S. Dave (School of Medicine). He received my Ph.D. in Statistics from Purdue University in 2014 under the guidance of Prof. Jayanta K. Ghosh. Dr. Datta's research interest spans Bayesian methodology and theory for structured high-dimensional or infinite-dimensional objects. He has contributed to the area of large-scale simultaneous testing, shrinkage prior, sparse signal recovery, nonparametric Bayes, computational aspects of big data analysis, bioinformatics, applied probability, and default Bayes. Recent applications include next-gen sequencing studies, auditory neuroscience, and crime forecasting.

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Abstract

Spatial visualization abilities have been shown to be a key predictor of success in science, technology, engineering, and math fields. Past research has revealed that women and underrepresented minorities tend to lag behind in spatial visual abilities, however, research has also shown that these skills can be improved with guided practice. This study seeks to examine whether 3D printed aids help spatial visual retention in 6^{th} graders. A modified Purdue spatial visualization test was used as the assessment standard. Students' mental rotation abilities were assessed before and after the 3D printed aids were administered. Data was collected from five different schools in Northwest Arkansas to measure the effectiveness of the 3D aids and to examine the performance of students across various gender, ethnic, and socioeconomic backgrounds. A prospective power calculation was performed to ensure that the sample size for each group was sufficient enough for significant differences to be detected. A P-value of $8.2x10^{-16}$ was obtained for significant difference between the pre and post assessments. This indicates that the post scores were significantly higher than the pre scores, while adjusting for the other factors. The results suggest that the blocks are effective in improving scores on the Modified Purdue Visualization of Rotation test regardless of a student's gender, socioeconomic background, or language.

Introduction

Spatial visualization is the ability to mentally rotate, manipulate, and flip visual objects. [1] It has also been described as the ability to represent and transform symbolic or non-linguistic information in space. [2] Strong visual skills have been shown to be important in science, mathematics, engineering, and technology classes, and they have been shown to be key indicators of success in these fields. [3],[4] Unfortunately, past research has also shown that females tend to lag behind males when it comes to visual spatial abilities, [5],[6],[7] especially when there are time constraints [8] or increased problem complexity. [9] Heil and Jansen-Osmann [9] attributed this lag to differences in the mental approach that males and females take. Their findings suggested that females tend to use an analytical, or piecemeal, approach while males tend to use a more holistic approach, which could explain why women tend to struggle more than males on visual spatial activities that have time limits and an increased level of difficulty. Other researchers have pointed to the possibility that physiological differences such as a recessive characteristic on the X-chromosome or a male sex hormone could be the source of the gap in visual spatial abilities. [10], [11] As stated by Sorby, [12] it is likely that the interaction of many factors contributes to the differences in abilities. Based on research by Titze, Jansen, and Heil [13], the gap in abilities first develops around age 10. It is believed that above this age, males continue to build their visual spatial abilities, while females do not. While a number of studies have shown this gap exists, additional research is needed to determine the most effective methods for minimizing or closing it.

In addition to the gender gap, it has also been shown that students of lower socioeconomic status tend to not do as well in visual spatial activities as students of higher socioeconomic status. [5] Levels of socioeconomic status are determined based on a family's income, occupation, and education. [14] Some of these differences in visual spatial abilities are believed to be due to children's' exposure to activities such as playing with construction toys, sketching or drawing, playing video or computer games, participating in sports and participating in shop, mechanics, or drafting classes. [15], [16], [17], [18] These gender and socioeconomic differences mean that many students that enter STEM fields may begin their careers at a disadvantage. It could also be a source of discouragement for these students, leading to a lack of diversity in engineering and other STEM fields. While this is an alarming problem, past data has shown that doing exercises and activities that require using visual spatial skills can develop and enhance these skills. [19]

The most effective tools and methods for promoting visual spatial retention and measuring the improvements have been a topic of concern. Martin-Dorta et al. [20] created a game called "Virtual Blocks" for mobile devices to test its effectiveness in improving these skills and bridging the gap between genders. The game consisted of two activities where a participant creates a 3D object on a blank grid or creates a 3D object based on three orthogonal views. The effectiveness of the game was assessed using the Mental Rotation Test. [21] The Mental Rotation Test consists of questions where a participant is shown an original chain of blocks in a specific shape, then they are shown four more chains of blocks. Two of the four block chains are the same as the original, but the orientation is different. The participant is asked to identify the two block chains that match the original chain. This virtual approach was inspired by the findings of Terlecki, Newcombe, and Little where the video game Tetris was used as a tool to improve students' scores on the Mental Rotation Test. [22]

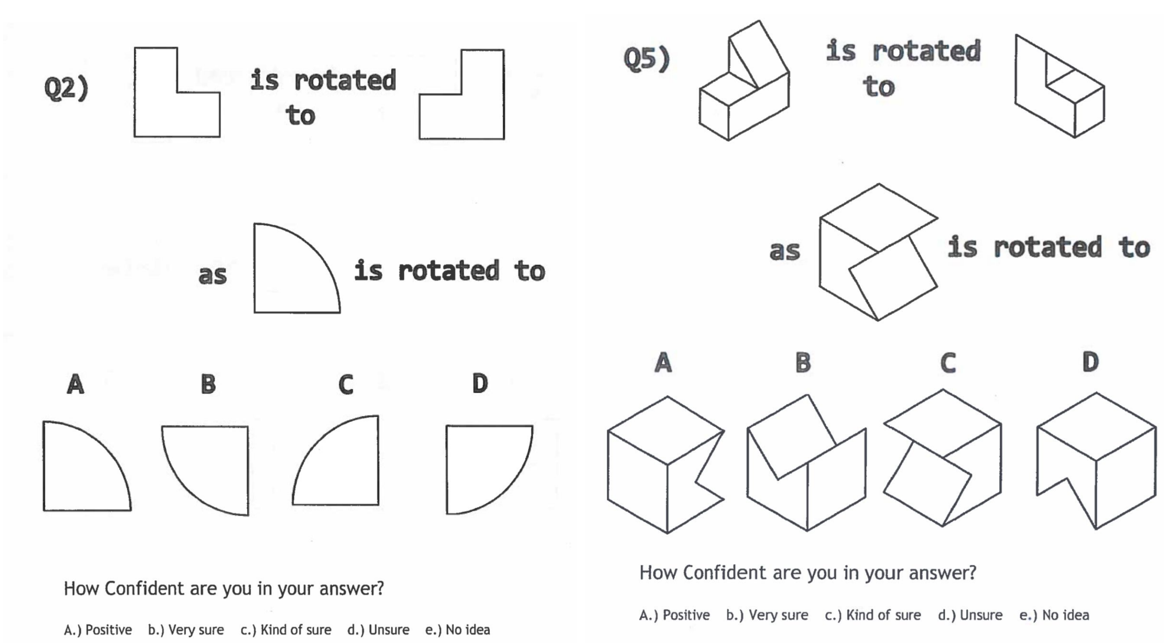
Another study led by Ben-Chaim, Lappan, and Houang, focused on improvement through instruction. Around 1000 students from 3 different schools underwent a three week Middle Grade Mathematics Project Visual Spatial Unit. The students were asked to do several visual activities that involved creating and drawing buildings made out of cubes and using 2D views to understand 3D structures. Following the unit, the students were given the Middle Grade Mathematics Project Visual Spatial Test that consisted of a total of 32 questions broken up into 10 question types. Five of the question types were similar in nature to the exercises that the students completed during the 3 week unit. The other five, however, were quite different from what the students had seen. [5] A similar study was done later with civil engineering students to test the effect of instructions on the visual spatial abilities of college students. They were given activities where they were asked to manipulate and sketch objects. [23] From both of these studies, evidence showed that instruction can improve visual spatial ability in students of all ages.

Despite the importance of spatial visualization and the potential for improvement, it is not currently emphasized in most curriculums. Just like any other skill learned in school, time must be devoted to visual spatial abilities in order for the students to truly improve them. Matthewson [24] stated, that similar to the way a rich verbal environment improves language skills, a rich visual environment will help enhance visual-spatial skills. Without proper practice of these skills, students do not have a way to improve them, and in some cases, may not even realize that they need improvement. This presents the perfect opportunity for effective tools and curriculum to be developed.

This paper presents a study in which 3D printed blocks are used to enhance the visual spatial abilities of 6th grade students. Following this introduction, the methods used, including the pre- and post-assessment strategies, are discussed. Five different schools participated in the study so that students could be examined over a wide range of rural and urban and low and high socioeconomic backgrounds. The effectiveness of the blocks and differences in visual spatial skills for gender, ethnicity, and socioeconomic groups were examined using a robust statistical analysis, which ensured significance of the findings. The conclusions and the applications of the findings in a broader context are then summarized.

Methodology

For the study presented herein, two versions of a modified Purdue Visualization of Rotation Test (mROT) were used to test the effectiveness of 3D printed blocks in improving the visual spatial abilities of 6th grade students. The first version of the mROT was used as a pre-test to assess the current abilities of the students and the second version was used to assess any improvements in visual spatial skills, particularly mental rotation, after they had practiced using the 3D printed blocks. Similar to the Purdue Visualization of Rotation Test (ROT) [25], students are asked to determine the rotations needed to make object (A) look like object (B). The students then take the same rotations and apply them to a third object (C) and choose the resulting orientation out of the four choices given. Figure 1 provides an example problem from the mROT test.



(a) (b)

Figure 1: An item from the mROT that displays a 2D rotation problem (a) and a 3D problem (b) with a confidence survey.

There are two main differences between the mROT developed for this study and the ROT. The first difference is the question content. The mROT includes 2D and 3D rotations. The 2D questions were implemented to determine whether differences in 2D and 3D abilities were distinguishable for the younger age group targeted. There are four 2D questions followed by six 3D questions. There was some concern that a full set of 3D questions may be too difficult for this age group. The combination of 2D and 3D rotation questions allowed the research team to assess the appropriateness of the difficulty level throughout the study. The students ranged from 11-12 years of age, which is slightly older than the age identified by Titze et al. [13] where the gap in visual spatial abilities begins to form. The second main difference is that a confidence survey is given following each question. The participant specifies how sure they are in their answer (Figure 1). This was added to help prevent correct guesses from skewing the data and it was also used to assess whether the 3D printed blocks helped improve student confidence.

The key focus of this study was the method of visual spatial improvement. This research utilized specially printed 3D visual aids to try to improve mental rotation. With a growing popularity in 3D printing and the ability to capture students' attention with the new technology, it seemed appropriate to investigate its use in visual spatial applications. For this study, eight blocks were printed (Figure 2). These blocks were created to match the 3D shapes and the 2D shapes in Version 1 of the mROT. Following the pre-test students were then able to use the blocks to help them think through the rotations in each question. The students were allowed to work with a partner and the project team was also there to teach and work through the problems. The hypothesis was that the students would be able to perform the rotations with the physical 3D printed blocks and through practice they would enhance their mental rotation abilities.

Figure 2: 3D printed visual aids.

The overall process followed at each school was the same. During the first session, students were given Version 1 of the mROT and were asked to complete all 10 questions, along with the confidence surveys, to assess their current visual spatial abilities. They were allotted 13 minutes for this session. They were then given a new blank Version 1 mROT along with the 3D printed blocks and asked to rework all 10 questions in groups using the blocks. This session did not have a time constraint and consisted of additional instruction and help for the students from the project team. During the third and final session, which occurred after a time elapse of approximately 7 days, the students were given Version 2 of the mROT and asked to complete all 10 questions along with the confidence survey. A time constraint of 13 minutes was implemented. These three sessions will now be referred to throughout as "Pre", "With Blocks", and "Post", respectively.

In an effort to successfully represent a wide variety of 6th grade students, five different schools ranging from rural to urban, and high to low socioeconomic backgrounds were tested. One of the American Psychological Association's recommendations for gauging socioeconomic status is income. [26] Therefore, relative socioeconomic levels were assessed using each of the schools percentages of students who receive free and reduced lunches which is based off the family's income. The school number was assigned in order of increasing free and reduced lunches. A higher percentage of students that qualify for free and reduced lunches typically indicate a lower level of socioeconomic status. Table 1 provides details of the schools and the number of students that participated. Ethnicity was not available for these students at the time of the study, however, the language spoken at home (i.e. representing bilingual students) was used as an analogue.

Table 1. Details of schools, percent free and reduced lunches [27], and number of students.

School No.	Public/Private Rural/Urban	% Free and reduced lunches	No. of students in study	No. of bilingual students
1	Private/Urban	<1%	48	1
2	Public/Urban	20.1%	29	3
3	Public/Rural	32.8%	30	1
4	Public/Rural	59.7%	34	8
5	Public/Urban	86.8%	35	25

To ensure a sufficient sample size for the groups analyzed, the prospective or a-priori power was calculated based on 1000 Monte Carlo simulations using R package 'simr'. Session, gender, and language spoken at home were fixed effects with effect size set to 0.5, equivalent to multiplying the odds by exp(0.5) = 1.648. The power to reject the null hypothesis of no difference between different levels of session, gender, and language are respectively 100%, 100%, and 90%, given for this model, which suggests that the current sample size per group is sufficient to detect the significant differences.

Results

The average scores were calculated for each school for the three different sessions. Table 2 shows that the Post scores were higher than the Pre scores by 11%, 7%, 12%, 10%, and 16% for School 1, School 2, School 3, School 4, and School 5, respectively. The highest percent improvement in Post scores was observed for School 5 which had the highest percentage of free and reduced lunches. There is also an even larger increase in scores from Pre to With Block sessions, which makes sense due to the fact that the students were working in groups and that the project team was also instructing students during this session. Overall, the results suggest that the blocks improve the scores on the mROT regardless of socioeconomic background. Additionally, the data show that there were fewer responses in the Post session confidence survey where students claimed that they were "unsure" or had "no idea" when compared to the Pre session. This suggests that the blocks may also increase a student's confidence in their mental rotation and overall visual spatial abilities.

Table 2. Average Pre, With Blocks, and Post test scores for each school.

Session	**School 1**	**School 2**	**School 3**	**School 4**	**School 5**
Pre	66%	65%	62%	51%	49%
With Blocks	78%	80%	69%	78%	71%
Post	77%	72%	74%	61%	65%
Percent Improvement	17%	11%	19%	20%	33%

Table 2 shows that the schools' Pre and Post scores tend to increase as socioeconomic status increases. To investigate the association between scores and socioeconomic status, a comparison of the mean success rate, number of students that scored 7/10 or above, number of students that scored 3/10 or below, and percent of students that receive either free or reduced lunches was carried out (Figure 3). These metrics were chosen for the visual comparison because the score distributions are asymmetric, hence comparing the percentage of high scores or low scores lead to more discernible differences between the schools, as opposed to their mean scores. This is true for any distribution that tends to be skewed towards the left or right, rather than symmetric. The average number of questions correctly answered increased with increasing socioeconomic status. Only School 1 showed a strong ability to achieve "high" scores (7 or above correct), and it appears that even though the use of the blocks improved the scores overall, there was no effect on the ability to achieve high scores for Schools 2-5. The data suggest; however, that the number of students obtaining "low" scores (3 or less correct) increased with an increase in the number of students of lower socioeconomic status at a school.

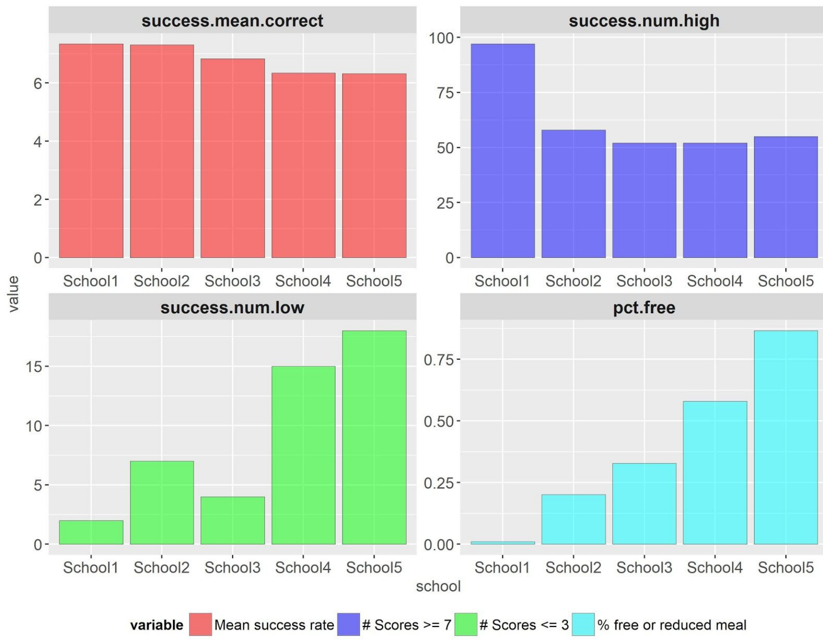


Figure 3: Graphical representations divided by school of the mean success rate, number of students that scored 7/10 or above, number of students that scored 3/10 or below, and percent of students that receive either free or reduced lunches.

Table 3 shows several notable associations. The male scores tended to be 7.4% higher overall than the female scores. One exception was observed at School 3, where the female students scored 10% higher on the 2D questions and 1% higher on the 3D questions to give an overall average of approximately 5% higher on the post-assessment. At School 3, the males improved by 10% while the females improved by 15% after the practice session with the blocks. Additional discussions with the teacher at School 3 explored this finding further to try and understand why female students at this particular school might perform higher than males. One speculation is that it could be related to the type or style of instruction used at this school. This school focuses on encouraging a growth mindset in their students and the teachers spend a notable amount of time explaining these concepts to their students. This type of mindset has been shown to be particularly beneficial to females,[28] which could explain why the females at school 3 outperformed their male classmates. It is noted that this conclusion is speculation only and that there are no additional data to support this theory at this time. This observation will be investigated further as a part of a larger study in the future to better understand these differences.

Overall, the students typically scored higher on the 2D rotation problems than they did on the 3D rotation problems. This is likely due to the lower level of difficulty associated with the 2D rotation problems. The 2D problems considered rotations in only one plane, while the 3D problems had rotations in one plane, and problems with rotations in two different planes. The data also suggest that students from School 5 showed the greatest improvement in skills and that the gap in visual spatial abilities was greatly reduced. It is anticipated that additional practice could improve these skills even more and further reduce the remaining gap. Additionally, in every case, the Post scores tended to be higher than the Pre scores regardless of gender. Table 3 shows that students of both genders in the schools of lower socioeconomic status tended to have larger percent improvements overall than the schools of higher socioeconomic status. This suggests that implementation of these types of activities and curriculum could greatly benefit students of lower socioeconomic status.

Table 3. Average Pre, With Blocks, and Post scores for 2D and 3D questions for male and female students

School	Gender	2D or 3D	Pre	With Blocks	Post	Percent Improvement
1	Male	2D	72%	85%	81%	12.5%
		3D	69%	78%	77%	11.6%
	Female	2D	69%	79%	78%	13.0%
		3D	52%	70%	58%	11.5%
2	Male	2D	82%	91%	89%	8.5%
		3D	74%	85%	79%	6.8%
	Female	2D	60%	78%	80%	33.3%
		3D	49%	70%	58%	18.4%
3	Male	2D	71%	80%	70%	-1.4%
		3D	56%	59%	74%	32.1%
	Female	2D	72%	87%	80%	11.1%
		3D	55%	56%	75%	36.4%
4	Male	2D	59%	94%	80%	35.6%
		3D	47%	86%	68%	44.7%
	Female	2D	58%	85%	54%	-6.9%
		3D	44%	57%	54%	22.7%
5	Male	2D	60%	93%	85%	41.7%
		3D	45%	63%	60%	33.3%
	Female	2D	50%	81%	65%	30.0%
		3D	47%	65%	63%	34.0%

Table 4 provides a break down of the students scores based on language. The bilingual students scored 10%, 3% and 8% lower on the Pre, With Blocks, and Post sessions respectively, suggesting that students that have a non-English primary language may lag behind in visual spatial abilities. One issue that could be a factor, but that is not addressed in this study, is the fact that the school with the highest number of bilingual students is also the school with the lowest socioeconomic standing. There is likely an interaction among these two variables, but more data is needed to explore this interaction fully. Although the bilingual students scored lower overall, the data show that both English and Bilingual students improved their scores in the Post test by over 10%, with the Bilingual students showing a percent improvement of over 27%. This suggests that the 3D printed visual aids can improve scores on the mROT regardless of language and that the gap in abilities can be closed through targeted practice.

Table 4. Average scores of students that speak English and students that are bilingual.

Session	**English**	**Bilingual**
Pre	61%	51%
With Blocks	76%	73%
Post	73%	65%
Percent Improvement	19.7%	27.5%

The significance of gender, session, and language spoken at home were tested using a mixed effects logistic regression. Parameter estimates and P-values for the effect of session, gender, and language spoken at home are displayed in Table 5. A P-value is defined as the probability, under the null hypothesis of no difference, of observing an outcome as extreme or more extreme than the observed outcome, and is used to gauge the significance of a set of results. The lower the P-value, the more significant the results.[29] For this study, a P-value of less than 0.05 is considered significant.

Table 5**.** Parameter estimates β and their exponentiated values, and P-values for the effect of session, gender, and language spoken at home.

Effects	**Estimate**	**Exp.Estimate**	**P.value**	**Significance**
(Intercept)	0.45	1.61	3.2×10^{-3}	Yes
Gender	0.48	1.6	0.16×10^{-3}	Yes
Session Pre	−0.61	0.54	0.81×10^{-5}	Yes
Session WB	0.26	1.3	0.97×10^{-3}	Yes
Language	0.41	1.5	6.4×10^{-3}	Yes

Table 5 shows the parameter estimates and their exponentiated values, which reflects the factor by which the odds for correct response should change. For example, the ratio of the odds that a male student giving a correct answer to the odds that a female student giving a correct answer is exp(0.48) = 1.61. This indicates that a male student is 1.61 times more likely to answer a question correctly than a female student, which agrees with the trend observed in Table 3. Note that the P-values for all four effects are below the significance threshold $\alpha =$ 0.05 indicating that there is strong significance for all effects displayed.

The 95% confidence intervals are plotted for the $e^{\hat{\beta}}$ values in Figure 4. A confidence interval indicates both the accuracy and variability of the estimates by calculating the margin of error due to chance variation in the randomized data generating process. The associated confidence level (95%) gives the probability that the calculated intervals will contain the true parameter value in the long run, if the process is repeated many times. Since the $e^{\hat{\beta}}$ values reflect the odds-ratios between categories, the vertical line at 1 indicates 'no effect'. The effect of all the 4 factors on the odds of a correct response can be seen from Figure 4. The intervals to the right side of the dotted vertical lines lead to higher score and the intervals to the left lead to a lower score, when compared to their respective baseline categories. [29]

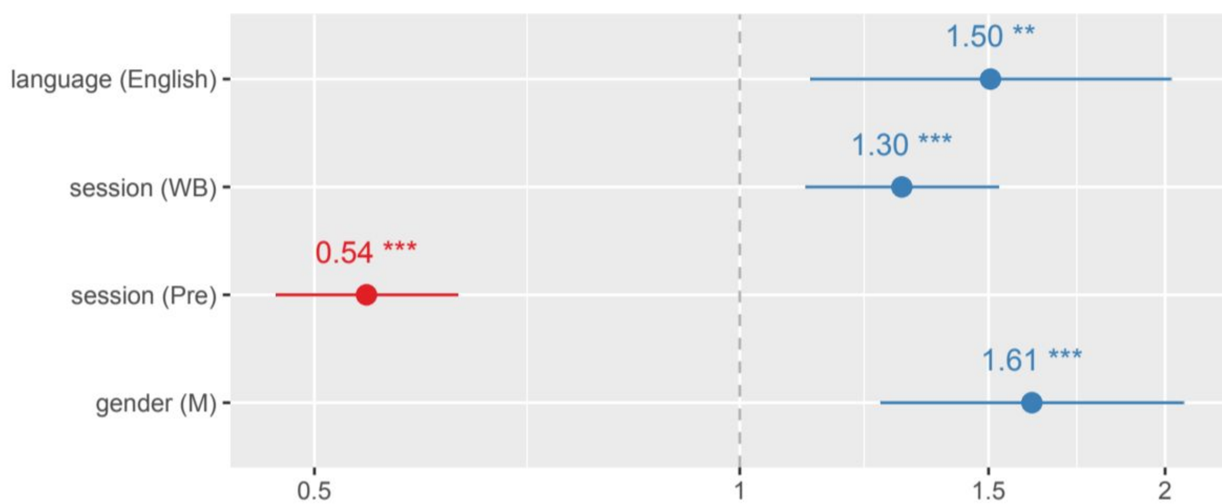


Figure 4: Confidence intervals for the fixed effects for language, session, and gender with asterisks denoting significance at $\alpha = 0.05$.

It should be noted that the Post session was set as the baseline category and then the With Blocks (WB) session and the Pre session were compared to it. Figure 4 indicates that males are 1.61 times more likely to succeed on the mROT than females and English speaking students are 1.50 times more likely to succeed on the mROT than bilingual students. Table 5 and Figure 4 suggest that the students have a higher probability of scoring correctly on the post exam compared to the pre exam with the odds of success increasing by a factor of 1/0.544 = 1.836 with a very small P-value of 8.2×10^{-16}. This suggests that practicing with the 3D printed visual aids can improve a student's mental rotation abilities regardless of gender, ethnicity, or socioeconomic status.

Conclusion

The results support past research findings that suggest that females and students from low socioeconomic background tend to lag behind males and students from higher socioeconomic background in visual spatial abilities. However, the results show that the use of the 3D printed blocks within a guided practice session is an effective method for improving students' scores on the mROT. The data show that the improvement is significant regardless of gender, socioeconomic background, or primary language spoken.

This research also agrees with previous studies that suggest that physical aids do improve visual spatial retention in students. Not only is 3D printing a new and exciting technology that can be used to improve student awareness of STEM fields and career opportunities, it has proven to be impactful in visual spatial applications. With the use of 3D printing becoming more popular in K-12 education, the ability to widely implement these blocks is a very real possibility. All five schools in this study had 3D printers available for education-focused activities. In each case, the teachers and administrators were eager to develop activities and curriculum using these or similar types of blocks or 3D printed aids. This opens the door to develop K-12 curriculum centered around 3D printed aids to help students improve visual spatial skills, but also improve other math and science based skills.

There is additional potential for the blocks or other 3D printed aids to be used at the collegiate level for students that are struggling with aspects of mental rotation. While only 6^{th} grade students were examined in this study, it is likely that similar improvements in abilities would be seen at all age groups. As shown in the study, the 3D printed blocks improve visual-spatial skills, but they also increase student confidence which is also a very important component of increasing diversity in STEM fields.

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