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The Impact of College Physical Sciences on Mental Rotation Ability

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Abstract

Men typically outperform women in Mental Rotation (MR) tasks, a skill that is crucial to many STEM (Science, Technology, Engineering, and Math) fields. Research suggests this difference may be a partial cause for the gender gap in the sciences. Previous findings indicate that practicing MR, especially through physical science classes, may increase women's MR performance and, perhaps, increase their involvement in STEM disciplines. However, conflicting results from existing studies make it difficult to determine the exact effect various science experiences have on MR. This study examined the relationship between physical science experience and performance on selected items from the Purdue Visualizations of Rotations Test (PVRT). College student participants with different science backgrounds (physical science, biological science, no science) completed the PVRT and provided data about their personal and childhood experiences with MR-related tasks, their perceptions of their task performance, and their college course experiences. Our results showed no significant sex differences in performance but did show that experience in physical science courses (chemistry and physics) predicted MR, while biological science experience decreased performance on these tasks. A lack of self-handicapping also predicted MR. These findings suggest that practicing these skills in classes may increase MR ability.

Keywords

Mental Rotation Ability, Physical Science Experience, Societal Advancement

1. Introduction

Women continue to be underrepresented in scientific fields, a salient concern during a time in history where scientific advancements are crucial for societal success (Sax et al., 2015). The fields of Science, Technology, Engineering, and

Math (STEM) all require spatial abilities, more specifically Mental Rotation (MR; Sharobeam, 2016). Spatial ability is a general umbrella term for three distinct tasks: spatial orientation, spatial visualization, and MR (Coleman & Gotch, 1998). It is on MR tasks where ability is different between men and women, with men outperforming women (Heil et al., 2018; Maeda & Yoon, 2013; Voyer et al., 1995), a difference that begins in infancy (Enge et al., 2023). An MR deficit may contribute to a lack of interest and motivation for women to pursue STEM fields (Coleman & Gotch, 1998). Several other inter- and intrapersonal variables, such as time pressures (Voyer, 2011), MR anxiety (Lourenco & Liu, 2023), stereotype threat (Doyle & Voyer, 2016; Ortner & Sieverding, 2008), and experience in physical science (Brownlow et al., 2003), also impact women's MR.

MR is the process of visualizing and manipulating three-dimensional objects in space (Heil et al., 2018; Voyer et al., 1995). One of the most frequently used methods to evaluate MR ability is the Purdue Visualizations of Rotations Test (PVRT; Bodner & Guay, 1997), which requires people to identify a complex, multi-step pattern of rotation between a pair of three-dimensional shapes, then apply the same rotations to another shape and select the correct result of the rotation. Many parallels have been drawn between the tasks of the PVRT and the rotation of molecules, a skill requirement in advanced-level chemistry classes (Boone & Hegarty, 2017).

One of the major hypotheses regarding sex differences in both STEM achievement and STEM involvement identifies MR as a potential culprit. Several individual studies (e.g., Bodner & Guay, 1997; Boone & Hegarty, 2017; Brownlow et al., 2003; Heil et al., 2018) have shown that men outperform women on MR, and two meta-analyses (Maeda & Yoon, 2013; Voyer et al., 1995) confirmed that the effect size of this difference was significant and relatively large. The difference is not a function of differential problem-solving strategies (Boone & Hegarty, 2017), but may be influenced by whether time limits for the tasks are imposed. Indeed, two meta-analyses of MR ability focusing on time limits (Maeda & Yoon, 2013; Voyer, 2011) demonstrated time pressure decreased MR performance for women.

Stereotypes about women and their MR abilities may also lead to a stereotype threat, which in turn may further decrease women's performance on MR (Brownlow et al., 2008; Ortner & Sieverding, 2008). However, the mere presence of a stereotype threat in the air alone is not the cause of women's lesser performance in MR. The meta-analysis of Doyle & Voyer (2016) revealed that consideration of intra-experiment variables such as experimenter sex and situation help explain whether women's MR is affected negatively by stereotype threat. They also demonstrated that intra-experiment variables were essential to stereotype "lift" in MR. Researchers have since shifted their focus to understanding ways to combat this stereotype threat, including rewards (Kanoy et al., 2012), training (Uttal et al., 2013), and priming of positive female stereotypes before the task (Ortner & Sieverding, 2008; Wraga et al., 2006).

Can sex differences in MR be reduced or ameliorated? Several studies have determined that practice with spatial tasks and MR can increase performance (Kass et al., 1998; Uttal et al., 2013), in part because the practice may decrease MR anxiety in women (Lourenco & Liu, 2023). The similarities between the skills used in science classes and the skills used for spatial tasks and MR have led some researchers to investigate whether there is a relationship between MR and science experience, which not only calls on the use of MR but also serves as a means of practicing these skills. Coleman and Gotch (1998) evaluated the effects of both chemistry experience and sex on spatial perception, finding that those with the most chemistry experience performed significantly better on the spatial ability questions. Their work aligns with results from other studies showing that science experience may predict MR in both men and women (Bodner & Guay, 1997; Brownlow & Miderski, 2002; Brownlow et al., 2003; Sharobeam, 2016), as well as performance on spatial tasks at the two-dimensional level and three-dimensional level (Sharobeam, 2016). Moreover, evidence detailed in a meta-analysis by Uttal et al. (2013) has pointed to the idea that not only are spatial skills and MR ability malleable, but also that practicing these skills within an educational environment can increase involvement in STEM fields. Therefore, practicing spatial tasks may help to increase women's involvement in the sciences, as well as improving their performances on MR so they stay involved in sciences.

The ever-persistent sex differences in spatial abilities have prompted numerous questions regarding ways to increase women's performance on MR, such as increased time to complete the tasks, rewards, positive priming, and practice. Our study examines how various types of science experiences predict MR ability in both men and women using the PVRT (Bodner & Guay, 1997), based on the assumption that physical science experience increases MR ability (Brownlow et al., 2003). Our specific focus was whether all science courses, or just physical science courses, could predict MR, as well as whether other MR-related abilities from non-science experiences, were essential to MR skill.

2. Method

2.1. Participants

Our study was approved by the Catawba College Institutional Review Board (approvals 2021-28 and 2022-02). We had a total of $N = 82$ participants ($n = 61$ women, $n = 21$ men), which included $n = 29$ physical science students, $n = 30$ natural science students, and $n = 23$ non-science students, classified by primary major and experience in physical sciences. Physical science students included chemistry majors, biochemistry majors, and biology majors with organic chemistry experience (which included pre-requisite general chemistry experience), while the natural science students were biology majors without organic chemistry experience, environmental science majors, and exercise science majors. We obtained informed consent before participants accessed the experiment.

2.2. Stimulus Materials

The participants were presented with an online experiment that was divided into two parts, the first of which consisted of 10 MR tasks selected from the Purdue Visualizations of Rotations Test (PVRT; Bodner & Guay, 1997). Each of these tasks presented a model three-dimensional shape, then the same shape rotated side-to-side and up-and-down. Participants were then shown a new three-dimensional shape and were tasked with rotating this shape the same way the model shape had been rotated; they then selected the correct resulting shape from five options. The PVRT was scored by number correct.

2.3. Dependent Measures

Task performance. After the PVRT, participants completed a series of self-report measures about the tasks, all of which were reported on seven-point bipolar scales with endpoints of 1 and 7. We evaluated how pressured the participants felt to complete the tasks well and how pressured they felt to complete the tasks quickly, both of which were bound by endpoints were 1 *I didn't feel pressured* to 7 *I felt very pressured.* Other questions were how difficult the tasks were (*extremely difficult*/*not difficult at all*), perceived success on the task completion (*I did very poorly*/*I did very well*), previous experience with mental rotation (*No experience at all*/*A lot of experience*) effort on the tasks (*I didn't try very hard/I tried very hard*), frustration with the tasks (*not very frustrating/very frustrating*), and how much the skills are used to complete tasks daily (n*ot at all/very much*).

Background and science experience. We also included self-report measures about how many hours (per week) participants painted or drew, as well as how many hours (per week) they played video games (both from options 0 - 2, 3 - 6, 7 - 10, 11 - 14, 15+). Additionally, they indicated their years of athletic experience in organized sport at the collegiate level. Lastly, participants revealed their college major, experience in college science classes, self-identified sex or gender, and how many of their parents were employed in a STEM field.

2.4. Procedure

After students signed up to participate, we sent them a link to the experiment, which was presented via Kwik Surveys software. Informed consent was obtained on one of the first pages presented by the program. We asked that participants mute their cell phones and find a quiet, isolated place to complete the tasks to help minimize any possible distractions. The 10 tasks obtained from the PVRT were presented in a random order, followed by the dependent measures, which were presented in one of two counterbalanced orders within type of scale (perceptions of the tasks, participant background). We directed participants to answer each question to the best of their ability and told them to take as much time as needed. We debriefed them at a later time.

3. Results

Data Reduction

Given that some of our self-report measures may have assessed the same constructs, we reduced our data using factor analysis. A principal components factor analysis with varimax rotation was first calculated on self-report measure of life activities that may impact MR ability, such as the number of parents in STEM, frequency of participation in art and video games, and status as a competitive athlete. This analysis produced two factors that accounted for 60.9% of the variance. These factors and their loadings are presented in **Table 1**. The two resulting factors were named *non-Science MR experience*, including athletic experience (.75) and art experience (.77) and *non-Science focus*, including video game experience (.79) and lack of parents in STEM (−.75).

A second factor analysis with varimax rotation was calculated on participants' self-report measures of task difficulty, pressure to perform, previous experience, and effort put into completing these tasks. The analysis produced two meaningful factors that accounted for 65.3% of the variance. The factors and their loadings are presented in **Table 2**. The factors were *self-handicapping*, which included perceived task difficulty (.68), perception of poor performance (.85), lack of previous MR experience (.66), and frustration with MR tasks (.75). The second was *effort toward task*, including pressure to do well (.71) and effort put into task (.82). Daily use of MR was revealed as a potential third factor, but its Eigenvalue was exactly 1, it was the only variable to load, and it did not account for much added variability (12%). Thus, we did not include that as a separate factor in subsequent analyses.

Surprisingly, men (M = 6.14, SD = 2.37) did not outperform women (M = 5.08, SD = 2.30) at a statistically significant rate, $t(80) = 1.81$, $p = .074$. Therefore, we did not include sex as a predictor in our analysis. A forced entry regression analysis was used to examine how well science experience (biology courses and chemistry/physics courses) and the factors produced from our data reduction (non-science MR experience, non-science focus, self-handicapping, effort

Table 1. Results of factor analysis on measures of mental rotation.

Factor	Variance	Measure
Non-Science MR Experience	29%	Athletic Experience (.75) Art Experience (.77)
Non-Science Focus	32%	Video Game Experience (.79) Number of Parents *not* in STEM (−.75)

Note. Based on N = 82.

Table 2. Results of factor analysis on self-report measures of efficacy and performance.

Factor	Variance	Measure
Self-Handicapping	35%	Perceived Task Difficulty (.68) Lack of Previous MR Experience (.66) Frustration with MR Taks (.75)
Effort Toward Task	18%	Perceived Pressure to Do Well (.71) Effort Put into MR Tasks (.82)

Note. Based on N = 82.

toward task, and daily use of MR) predicted MR performance. The results from this regression analysis are located in **Table 3**; *df* do not equal total *N* due to missing data. The equation was significant, $F(6, 67) = 5.05$, $MSE = 3.99$, $p = .001$, $R^2 = .31$, and results showed that taking chemistry and physics classes ($\beta = .29$, $p = .026$), having had fewer biology courses (i.e., less non-physical science; $\beta = -.40$, $p = .003$), and lack of self-handicapping ($\beta = -.35$, $p = .006$) all predicted MR.

4. Discussion

The results of this study showed that *physical* science experience, as well as lack of self-handicapping, predicted MR. Participants who took more physical science classes (including general chemistry, organic chemistry, and physics) were more successful on the tasks, but that taking more biological science classes led to a lower completion rate on MR. Participants who self-reported high levels of self-handicapping, including perceived poor performance on the tasks, frustration with the tasks, high perceived task difficulty, and low previous experience, had fewer correct responses on the 10 PVRT items. Non-science MR experience, non-science focus, and self-reported effort put towards the tasks were not accurate predictors of the participants' MR performance. Although sex differences are well established among studies of MR and spatial ability (Boone & Hegarty, 2017; Heil et al., 2018; Voyer et al., 1995), our findings did not show that men significantly outperformed women on MR (although on a practical level men completed one rotation more out of 10 than women). However, we did have highly unequal *n*s in our groups and relatively few men participants compared to women.

Our results indicated that the number of physical science classes taken is a good predictor of MR. Participants who had more experience in chemistry and physics classes performed better on the experimental tasks than those who did not have experience in these classes. These findings parallel those of Brownlow and Miderski (2002), who also found that students with chemistry experience

Table 3. Regression coefficients of experimental variables on MR ability.

Variable	*B*	β	*SE*	*t*	*p*
Constant	9.54		1.82	5.23	.001
#Biology Classes	−.40	−.40	.13	−3.08	.003*
#Chemistry/physics Classes	.28	.29	.13	2.27	.026*
Self-Handicapping	−.18	−.35	.06	−2.84	.006*
Non-Science MR Focus	.03	.00	.36	.07	.942
Non-Science Focus	−.10	−.05	.24	−.42	.677
Effort on Task	−.04	−.04	.11	−.33	.740

Note. Equation was significant, $F(6, 67) = 5.05$, $MSE = 3.99$, $p = .001$, $R^2 = .31$. Significant *p*-values are marked with a *.

(or STEM experience in general; Sharobeam, 2016) successfully completed more MR tasks that students without similar experience. Chemistry courses frequently require the rotation of three-dimensional molecules, which may serve as practice for MR, and practice on parallel tasks is a reliable means of improving MR (Uttal et al., 2013). The spatial skills required for success in chemistry and physics courses are very similar to those required to successfully complete the tasks asked of our participants, which may explain why these students performed better, and why physical science experience predicted MR ability.

Our most intriguing finding was that participants who had taken more biological science classes were less successful in completing mental rotation tasks, which was the opposite of our hypothesis. While many biological sciences do not require the same spatial skills as chemistry and physics, that alone does not explain the negative relationship with mental rotation success. Brownlow et al. (2003) found that men well outperformed women on MR among students with limited science experience, while men and women with no science experience and organic chemistry experience were similar. Because women's performance can be increased by training (particularly if it builds confidence; Lourenco & Liu, 2023), and decreased by stereotypes of women in STEM (Kanoy et al., 2012; Ortner & Sieverding, 2008), this group of participants (i.e., heavy biological science focus) may have had enough science experience to know about the hindering stereotypes, but not enough experience to practice MR. These unique conditions may have led to this negative relationship between biological science experience and MR ability.

Lastly, self-handicapping, which was one of four factors we analyzed based on the self-report measures and the demographic information collected from participants, also predicted poorer MR. Participants who reported having more difficulty and frustration with the tasks were less successful than those who did not report these issues. Research by Kanoy et al. (2012) suggests that women may be affected by stereotype threat when completing MR and may therefore be more likely to claim these tasks as difficult or frustrating—yet, even if that were the case, men did not significantly outperform women on the task. Furthermore, lack of previous experience with MR (which could be gained through chemistry and physics courses) decreased, suggesting that experience with spatial tasks may reduce self-handicapping and in turn, increase performance. Ortner & Sieverding (2008) also indicated that the pressures of previously established stereotypes about women may hinder performance on MR tasks and may also increase their perceived difficulty. Because we were unable to recruit more men to the study, we had a much larger share of women participants (reflecting to some degree the population of students in the science courses from which we recruited), and thus it is not surprising that self-handicapping (which may have been more common in the women who were likely to experience stereotype threat) was important to success on the task. More men participants are needed to better examine the importance of self-handicapping and the other self-report measures to MR.

In addition to including more men, further research in this area may look to disentangle physics from chemistry, as the majority of the existing research about science experience revolves specifically around chemistry. Additionally, many biology students need chemistry in their curriculum but in our sample the biology students take chemistry later in college, i.e., generally not in the first year, and many of our sample had not had a lot of biology ($M = 2.06$ courses). Yet, many students need both for medical, veterinary, and other professional science-related post-secondary education. Thus, it is important to look at students who have both biology and chemistry, as our results show their effects on MR are contradictory.

5. Conclusion

The results of this study revealed that physical science experience predicted MR success, while both biology experience and self-handicapping predicted poorer performance. These results further support the idea that MR is increased with practice and experience using these kinds of spatial skills. Moreover, practicing these skills and increasing MR abilities at a younger age may help to give women the experience necessary for success in the sciences, and perhaps in turn decrease their negative ideas about being in STEM. Should education systems give younger students the chance to practice MR skills, women may become more involved in the sciences, and increase their participation in career fields that contribute to societal advancement.

Conflicts of Interest

The authors declare no conflicts of interest.

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