Reducing the gender gap in spatial skills in high school physics

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Abstract. Science, Technology, Engineering and Mathematics (STEM) courses in college require intensive use of spatial skills. This research determines the correlation of the high school physics grades and the spatial skills of selected students from the Philippines. To measure the participants’ spatial skills, the Purdue Visualization of Rotations Test (PVRT) was utilized. Results show that these two variables have a moderate positive correlation. The data also reveal a significant difference in the PVRT scores between the male and female participants in this study. The gender gap in spatial skills was significantly removed after the females received an intervention in the form of a special program for improving spatial skills. This suggests the effectiveness of the special program, and the malleability of spatial skills even in adolescence. Recommendations for improving the spatial skills, as well as directions for future research are also discussed.

1. Introduction
Science, Technology, Engineering and Mathematics (STEM) courses in college require intensive use of spatial skills. For example, physics involves the study of illustrations of three-dimensional (3D) vector fields that are printed on two-dimensional (2D) paper. Medical doctors give appropriate medical advice by referring to 2D and 3D images of the human body. In engineering, the visualization of various plans such as schematic plans, floor plans, and factory production flow processes are required. These subjects and their applications are just a few samples that highlight the importance of spatial skills for scientists, technologists, engineers and mathematicians. Research [1–3] shows that success in STEM courses is related to 3D visualization skills. Furthermore, research [1–4] suggests that there is a discrepancy between the spatial skills of female students and their male counterparts.

This study examines the relationship between spatial skills, achievement in science, and STEM careers. A special program [2] was provided as an intervention to female high school students in the Philippines, and this significantly increased their spatial skills. Another angle studied was the correlation of the respondents’ spatial skills to physics achievement. This was in line with extant literature, and the absence of parallel studies conducted in the Philippines.
2. Related Work

2.1. Gender Gap in Spatial Skills
Spatial skills develop progressively [5]. The first stage—in children aged 3 to 5—involves the development of topological skills, which are related to distinguishing the distance between two objects. The second stage—during adolescence—sees the development of projective spatial ability, which is related to how a 3D object will look with respect to different points-of-view. Last to develop is the ability to visualize reflections by combining topological skills with projective spatial ability.

Two factors comprise spatial skills: spatial orientation and spatial visualization [6]. Spatial orientation is involved with mental rotations of objects [7], while spatial visualization is concerned with reconstructing the object after it was deconstructed [8].

Research shows that without intervention, the spatial skills of male students are better than their female counterparts [7]. This is true in middle school and high school [2], and in college [1,2]. Maeda and Yoon’s meta-analysis [7] reveals that when time limits per test item is considered, the gender gap in the results of spatial ability tests increases further. Sorby found that the difference in spatial skills can be attributed to one’s activities performed as a child. Students with well-developed spatial skills performed, as children, activities that generally involve hand-eye coordination such as “playing with construction toys as a young child, participating in classes such as shop, drafting, or mechanics as a middle school or secondary student, playing three-dimensional computer games, participating in some types of sports, and having well-developed mathematical skills.” [2, p. 460].

Spatial skills can be measured using different tests such as the Mental Cutting Test, Differential Aptitude Test – Space Relations, and the Purdue Visualization of Rotations Test (PVRT). PVRT, developed by Bodner and Guay [1], comprises 20 multiple-choice questions. Each item shows an isometric drawing of a three-dimensional object, and beside it a rotated version of the same object. Students then study the amount of rotation, and figure out what another object will look like if rotated the same way. Possible rotated versions of the new object are given as alternatives of the test item. Furthermore, Bodner and Guay found that the PVRT and along with introductory chemistry scores of college students have a moderate positive correlation with each other [1].

College students’ grades in engineering are also positively correlated with spatial skills [2]. Sorby’s study involving engineering students served as a basis of the Spatial Skills Project (SSP) curriculum. Female engineering students who completed the SSP training had increased spatial skills at par with male engineering students. SSP includes topics such as sketching isometric pictorials from coded plans, sketching multi-view drawings of simple objects, 2D to 3D transformations (paper folding), 3D coordinate systems, object transformations including translation, scaling, rotation, and reflection, cross-sections of solids, surfaces and solids of revolution and combining objects by cutting, joining, or intersecting. SSP is available both as a printed book and software [2].

This study was conducted because there is no extant literature on the effectiveness of SSP in improving spatial skills involving high school students from the Philippines.

2.2. Relationship between Spatial Skills and Achievement in Science
Spatial skills are required not only in science, but also in everyday life and work [9]. Hence, it is important to understand the relationship of spatial skills and science achievement. There are several studies that suggest a direct relationship between spatial skills and achievement in science. In college chemistry, the scores of students on a quiz on crystal structures have a moderate positive correlation with spatial skills [1]. The same direction of relationship is shown in studies associating spatial skills with Earth science knowledge [10], high school physics achievement of Turkish students [11], understanding of some astronomy concepts [12], biology [13] and geology [14], among others.

It must be noted though that these correlations should be interpreted with care due to the presence of other variables, like verbal ability, that affect science achievement [15]. In one longitudinal study, the effect of those variables on science achievement were controlled [3]. Despite holding those variables constant, the analysis still shows spatial skills as a significant predictor of science achievement.
3. Research Method

3.1. Research Questions and Designs

Three research questions were explored in this study:
1. Is there a correlation between high school physics achievement and spatial skills?
2. Does the use of SSP improve the spatial skills of female high school students?
3. Is there a significant difference between the spatial skills of male and female high school students?

This study involved an all-male and an all-female group. A correlational method was used in response to the first research question. The high school physics grades of each group were correlated to their PVRT scores. Meanwhile, a quasi-experimental, non-equivalent control group design involving the group of male (control group, \( n = 87 \)) and female (experimental group, \( n = 69 \)) high school students was employed to address the second and third research questions.

3.2. Participants

All participants in this study were grade 12 students, aged 16–17 years old. Respondents came from private, gender-exclusive, urban high schools in the Philippines, and were randomly selected from their respective schools.

3.3. Procedure

First, consent to use PVRT in this study was sought through a personal correspondence with Bodner. Permission to collect the participants’ physics grades and PVRT results was also sought from the administrators of the involved high schools. The students were provided copies of the PVRT and Scantron forms where they could write their answers. As per the recommendation of Bodner, all participants were given 10 minutes to answer the PVRT. The time limit was set to avoid analytic processing.

The spatial skills of the control group, composed of male students, was measured using PVRT only once. On the other hand, the spatial skills of the experimental group, composed of female students, were measured twice—before and after an intervention. The female participants in the study underwent a “shortened” SSP program, given in the form of an elective class. The selected students met with the researcher for a weekly class that was two hours long.

The program is considered a “shortened” SSP program because only two of the nine modules in SSP were used. These modules were: sketching isometric pictorials from coded plans, and sketching multi-view drawings of simple objects. The seven modules that were not used in the intervention are: 2D to 3D transformations (paper folding), 3D coordinate systems, object transformations including translation, scaling, rotation, and reflection, cross-sections of solids, surfaces and solids of revolution and combining objects by cutting, joining, or intersecting. After eight meetings in the intervention, the female participants answered the PVRT again.

3.4. Data Analysis

In response to the three research problems, the data was analysed in three ways. First, the relationship between high school physics grades and spatial skills (from the initial PVRT scores) was measured using Pearson correlation. Second, the gender gap in spatial skills was measured using a t-test for independent means on the PVRT scores of the male students, and the PVRT scores of the female students before the intervention. Third, the effectiveness of the intervention in improving the spatial skills of females was measured using a t-test for dependent means on the pre-intervention and post-intervention PVRT scores. After the female students completed the intervention, the gender gap in spatial skills was again measured. This was performed using a t-test for independent means on the PVRT scores of the male students and the PVRT scores of the female students after the intervention. All statistical tests in this research were performed at the 0.05 level of significance.
4. General Discussion

4.1. Correlation of Physics Achievement with Spatial Skills
Spatial skills are required in physics topics, such as visualization of vectors, fields and paths. For example, the path of an electron in a magnetic field requires an understanding of the three-dimensional nature of the field, and the movement of the electron. This section presents data from a group of high school students from the Philippines. The descriptive statistics are shown in Table 1.

Table 1. Descriptive statistics for the physics grades of the respondents of the study.

|          | n    | Standard deviation | Mean physics grade |
|----------|------|--------------------|--------------------|
| Male     | 87   | 5.6                | 83.3               |
| Female   | 69   | 7.4                | 85.6               |

The Pearson correlation coefficient is $r = 0.33$ for males, and $r = 0.34$ for females. These correlation coefficients are significant for a one-tailed test at 0.05 significance level. Hence, there is a moderate or reasonable positive correlation between the physics achievement scores of students and their spatial skills. The data show that high physics grades are associated with high spatial skills. This finding agrees with existing literature on the relationship of science achievement and spatial skills. College students’ quiz scores on crystal structures, a topic in chemistry, also have a moderate positive correlation with spatial skills ($r = 0.32$) [1]. The same results are shown in studies associating spatial skills with Earth science knowledge ($r = 0.52$) [10], high school physics achievement of Turkish students ($r = 0.45$) [11], understanding of some astronomy concepts [12], biology [13], and geology [14].

4.2. Gender Gap in Spatial Skills
Data from the participants reveal that male high school students have better spatial skills than female students. There is a very small difference in the spread of the scores between the two groups. Table 2 shows descriptive statistics for these data.

Table 2. Descriptive statistics for the PVRT pre-test scores of the respondents.

|          | n    | Standard deviation | Mean PVRT score (%) |
|----------|------|--------------------|---------------------|
| Male     | 87   | 20.4               | 68.5                |
| Female   | 69   | 20.1               | 56.6                |

A two-tailed t-test for independent means was used on the PVRT scores of the male students and the pre-intervention PVRT scores of the female students. The analysis shows a significant difference between the mean PVRT scores of the groups, $t(154) = 3.65, p < .05$. Other studies [1,2] also reveal the same gender gap in spatial skills. A meta-analysis on gender differences in spatial skills [7] enumerates several factors that explain this gender gap. These include biological, strategic, experiential, affective and test-administration constraints. Experiential factors include a person’s engagement in activities that require spatial skills which can improve their spatial skills. Among these are: manipulating construction toys and playing three-dimensional computer games [2]. Existing literature [16,17] suggest that spatial skills are malleable, or can be enhanced and trained. Hence, given the proper training and scaffolding for spatial skill development, the gender gap in spatial skills can be reduced, or even removed. This can be seen in the female participants of this study.

4.3. Using the SSP Curriculum to Improve Spatial Skills
The gender gap in spatial skills shown by the data in this study suggests that an intervention be given to the female participants. The SSP curriculum was provided as an intervention in this study because the curriculum’s effectiveness in improving spatial skills has already been studied on American college and middle school students [2]. Selected female students (33 of the 69 participants in the first study) met
with the researcher in a weekly elective class which lasted for two hours. The use of the printed materials from SSP curriculum significantly increased the mean PVRT scores of the female participants after eight class sessions. Table 3 shows the results of the pre-intervention and post-intervention mean PVRT scores.

Table 3. Summary of pre-test and post-test PVRT scores of female respondents of the study.

|                | n   | Standard deviation | Mean PVRT score (%) |
|----------------|-----|--------------------|---------------------|
| Pre-intervention | 33  | 19.7               | 60.3                |
| Post-intervention | 33  | 17.2               | 69.2                |

Using a two-tailed t-test for two dependent means, the data show that the mean PVRT score of the female respondents in the post-intervention is significantly different than their mean pre-intervention PVRT score, \( t(32) = 3.83, p < .05 \). After completing the intervention, there is a significant increase in the PVRT scores of female Filipino high school students, in agreement with the findings of Sorby [2].

Further analysis of the data confirms no gender gap after the female participants underwent intervention. A two-tailed t-test for independent means was used to compare the mean PVRT score of the male students and the mean post-intervention score of the female students. Descriptive statistics for this comparison appear on table 4.

Table 4. Summary of PVRT scores of the respondents of the study. Scores used for female respondents are from the post-intervention PVRT.

|       | n   | Standard deviation | Mean PVRT score (%) |
|-------|-----|--------------------|---------------------|
| Male  | 87  | 20.4               | 68.5                |
| Female | 33  | 17.2               | 69.2                |

The results show that female and male PVRT scores do not significantly differ from each other after SSP was used as intervention, \( t(118) = 0.18, p = 0.85 \). Females can have spatial skills on a par with males with the help of a spatial skill enhancing program. It should be noted that gender gap was removed even if the study only used two of the nine modules provided in the SSP printed materials.

This finding provides support that spatial skills are indeed malleable [17] and can be enhanced even in adolescence. Formal structures (such as an elective class or a club) for improving spatial skills will likely affect school logistics and academics. However, other courses in the school may integrate the use of spatial skills in their classes, such as the use Geographic Information Systems (GIS) [9] and origami in mathematics [18]. All these efforts to improve spatial skills, added to experiential factors, could greatly impact an adolescent’s decision to pursue a degree in STEM in the future [19].

5. Summary of Findings, Recommendations, and Future Work
The relationship of science achievement with spatial skills has been the focus of several studies. The gender gap in spatial skills is also a concern among researchers. This gender gap can be reduced or removed by implementing appropriate activities; one of which is the SSP. Within the context of Filipino high school students, the current research was able to determine that there is a moderate or reasonable positive correlation between high school physics achievement and spatial skills. The gender gap in spatial skills identified in other studies was also revealed in this research. Lastly - aligned with what existing literature suggests—the gender gap in spatial skills was removed after the female participants of this study underwent an SSP-based intervention.

The importance of spatial skills in learning physics, and science in general, has been studied for decades [3]. Efforts to improve spatial skills, such as the use of SSP, should be encouraged to develop students who have the confidence to pursue STEM careers in the future. In this age where talent from both genders is needed, addressing the gender gap in spatial skills may contribute to the solution of increasing the number of women in the STEM workforce.
The PVRT’s focus on mental rotations of objects can be associated with some topics in physics that require rotating axes and changing points-of-view. For example, in most problem-solving methods involving an object on an inclined plane, the free body diagram of the object must be re-oriented such that the normal force lies along the +y-axis. Also, students must be able to visualize a car’s free-body diagram as seen from the front to understand that friction is the centripetal force on cars moving on banked curves. The right-hand rule, which relates three vectors, is also an important tool in physics that require spatial skills.

Although this study, along with the others mentioned, did not include other variables which may affect physics achievement in the analysis, the PVRT’s psychometric property to measure mental rotation skills, and the spatial nature of some physics topics provide some basis for their relationship. A study involving a specific physics concept that requires spatial skills may provide a better insight on the relationship of physics understanding and spatial skills.

Future researches on spatial skills in the Philippine context require data from other sources such as government-owned schools, private co-educational high schools, and technical schools, both from urban and rural locations. New data from these sources will answer questions related to how spatial skills are affected by socioeconomic status, single-sex or co-educational settings, and location. These data would support a description of the spatial skills of high school students in the Philippines.

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