Implementation and analysis of a spatial skills course for Secondary level STEM education

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ABSTRACT

High spatial skills have been directly linked to enhanced performance in STEM disciplines, with improvements in spatial skills linked to an increase in female retention at the university level. Spatial skills development and direct training are well researched and implemented within university level engineering education but are less defined at earlier stages of education. It is hypothesised that a spatial intervention implemented at the secondary level could be beneficial in order to boost student performance in STEM, where it still influences their interest in subjects and future career paths. The purpose of this paper is to present the implementation process of a spatial intervention in Irish secondary schools and the initial analysis of combined teacher and student data. The intervention was implemented with Transition Year (aged ~15 to 16 years old) students. Fifty teachers undertook a tailored professional development training to prepare them to deliver the spatial skills intervention, some of which then took part in various qualitative data gathering activities. The intervention was delivered to approximately 1500 students. They were administered a range of psychometric tests, including multiple spatial tests and a fluid reasoning test to investigate their development in a variety of cognitive aspects. This paper will focus on investigating the possible relationships between teacher spatial ability and student gains in spatial ability. The findings of the study were positive, indicating the successful implementation of the intervention and showing promise for future iterations.

Key Words: Spatial skills, professional development, pedagogy, secondary education, student outcomes, student participation

1. INTRODUCTION

Traditionally, it was believed that STEM (Science, Technology, Engineering, Mathematics) success was primarily supported by the development of mathematical and verbal skills (Marrero et al., 2014). However, a longitudinal study conducted by (Wai et al., 2009) showed that spatial skills are strongly predictive of STEM participation and attainment – even more so than the development of mathematical and verbal skills. Additionally, it displayed the importance of developing spatial skills by the age of 13, as this may impact students' career choices. Research from the Technology and Engineering field has established the importance of spatial skill development in student thinking when problem-solving (Duffy, 2017), increasing their working memory capacity when working with graphical problem-solving tasks (Buckley et al., 2019; Delahunty et al., 2020), supporting female participation in Engineering, and increasing students' performance in subsequent engineering courses (Sorby & Veurink, 2010).

An Irish national study (Bowe et al., 2016) highlighted the underdevelopment of spatial skills in secondary schools. Therefore, the purpose of this study is to develop spatial skills at secondary level by implementing an established course, named Developing Spatial Thinking (DST), initially designed for undergraduate engineering students (Sorby & Baartmans, 2000). This course has been chosen due to its previously determined effectiveness in developing secondary school students spatial skills and motivating more female students to enrol in science and mathematics subjects (Sorby, 2009). Since teacher Professional Development Programs (PDPs) are essential in developing in-service teacher's expertise (Garet et al., 2001), a spatial intervention has been implemented in collaboration between the Professional Development Service for Teachers (PDST), two Irish Higher Education Institutions co-authoring this paper, and the University of Cincinnati (UC). This approach was adopted to not only investigate the effectiveness of the course in an Irish secondary level context, but to provide the necessary support for the teachers involved.

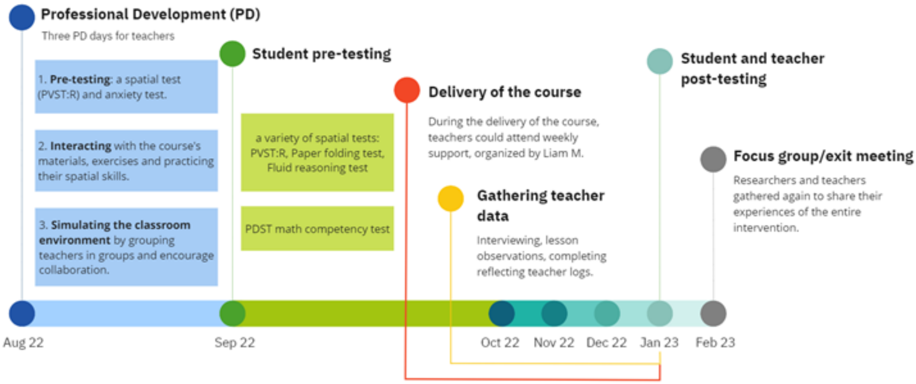
In this study we aimed to answer the following research questions with the objective to better understand teachers' impact on the effectiveness of the course:

- RQ 1: What is the relationship, if any, between teachers' spatial ability and the extent to which their students develop their spatial skills?
- RQ 2: What is the effect, if any, of the spatial intervention on teacher spatial skill level?
- RQ 3: What is the effect, if any, of the spatial intervention on student spatial skill level?

2. INTERVENTION DESIGN

The spatial intervention was based on the original DST course, with reduced content, along with professional development provided for teachers involved. The intervention consisted of the professional development and testing activities shown in Figure 1., supportive of the core elements of effective PDPs, which had been trialled during the pilot study from the academic year 2021/2022 (Maquet et al., 2023).

Figure 1.
Description of intervention activities and timeline



This research was conducted in collaboration between Technological University of the Shannon: Midlands Midwest (TUS), Technological University Dublin (TUD), UC, and the PDST. The PDST managed the school recruitment for the project and the organization of professional development (PD) days. These PD days were delivered by both the PDST and experts in the field of technology education from TUS, who added their knowledge and connected the spatial course to graphics education. Educational goals and practical implications of the spatial course were explicitly pointed out to teachers during the PD days and reinforced through suggested lesson plans for individual modules. There was also an attempt to build a stronger teacher community of practice through the spatial course's website, but that has been proven to be difficult to establish (Maquet et al., 2023).

3. DESCRIPTION OF THE SPATIAL COURSE

Based on the key concepts of Piaget's theory of cognitive development (Piaget, 1952), embodied cognition (Leung et al., 2011), self-directed learning (Du Toit-Brits & Van Zyl, 2017), and the benefits of online learning support (Panigrahi et al., 2018), the implemented spatial course comprised of:

- A workbook with spatial exercises where students develop their thinking with the help of hands-on manipulatives (snap cubes and Knex) and sketching activities.
- Online software with simulations and interactive exercises.
- Online mini lectures with video demonstrations and additional resources for self-directed learning and differentiation.
- A teacher guidebook, including answers, sample lesson plans, and module objectives.
- Sample presentation slides for the teacher to use.

The original course consists of ten modules, while only the following six were used for this study: *Surfaces and Solids of Revolution, Combining Solids, Isometric Sketching and Coded Plans, Flat Patterns, Rotation of Objects about a Single Axis, and Reflection and Symmetry*.

4. PARTICIPANTS AND METHODS

The intervention was implemented with Transition Year (TY) (aged from 14 to 16 years old) students and their mathematics teachers. This year is unique to the Irish education system and is meant to promote students' independence and general skill acquisition needed for their desired future careers (Professional Development Service for Teachers, 2023). This school year was chosen due to its fluid curriculum which supported the adoption of the intervention, previously discussed by Maquet (2023). A quasi-experimental study design was implemented to evaluate the impact on spatial skills of the spatial thinking intervention. This paper includes data from a group of 1199 TY students across Ireland. The participating students completed the provided spatial thinking coursework in place of their usual math instruction. This cohort included 488 male and 711 female participants. Participants who self-identified as genders other than male or female were excluded from this paper due to the low numbers (n = 57) which would not result in a meaningful statistical analysis. Recruitment letters were distributed to schools by the PDST, and expressions of interest were then collected from willing schools. 50 expressions of interest were received but only 25 schools were selected due to the available budget. The 25 schools around Ireland were chosen based on a number of factors to ensure that there was as little bias towards any one group as possible. These factors included single-sex or coeducational schools, school socio-economic status (SES), School population, sex of the teacher, and location of the school. Schools were excluded from the study if they had only one TY math class as all schools were required to have both a control and experimental group. The control group consisted of 413 participants and the experimental group consisted of 786 participants, these were grouped based on the pre-existing classes within each school. The experimental group engaged with the spatial intervention for up to 3 hours a week while the control group engaged in their normal schooling and had no contact with the intervention.

Fifty teachers undertook a tailored professional development training to prepare them to deliver the spatial skills intervention. Half of these teacher participants chose to be in the experimental group who delivered the spatial course to their students. Others, in addition to teachers who did not attend any of the spatial training, were a part of the control group. This group was "business as usual" and delivered regular mathematics classes to their students. Thirty-five teachers of the initial group completed the pre- and post- Purdue Spatial Visualization Test: Visualization of Rotations (PSVT:R) (Guay, 1976) to determine their spatial skill levels based on the rotations factor of spatial ability. This study focuses on those, more quantitative results in order to compare them with their students' spatial skill levels.

All student participants completed the PSVT:R as part of pre-testing before taking part in the intervention, and post-testing after completing the intervention. Approximately 300 student participants completed paper-based testing for all tests, while the remaining participants completed online based testing. This approach was used to determine the validity of the online PSVT:R as a measure of spatial ability, which will be investigated in future research. The online testing was conducted through the use of Google forms and could be completed on a PC, laptop, or tablet. The order in which the tests were administered was randomised for each school to account for any order bias, however all participants had equal time to complete the testing. The participants were given a time limit of 20 minutes for the PSVT:R.

Other student measures included the paper folding test, fluid reasoning test, and math competency test, while other teacher measures included classroom observations, reflective teacher logs, interviews and completing the pre- and post-anxiety test to determine their anxiety levels when working with spatial problems. These were conducted as part of a larger study which is outside the remit of this paper and so will not be investigated here.

5. RESULTS

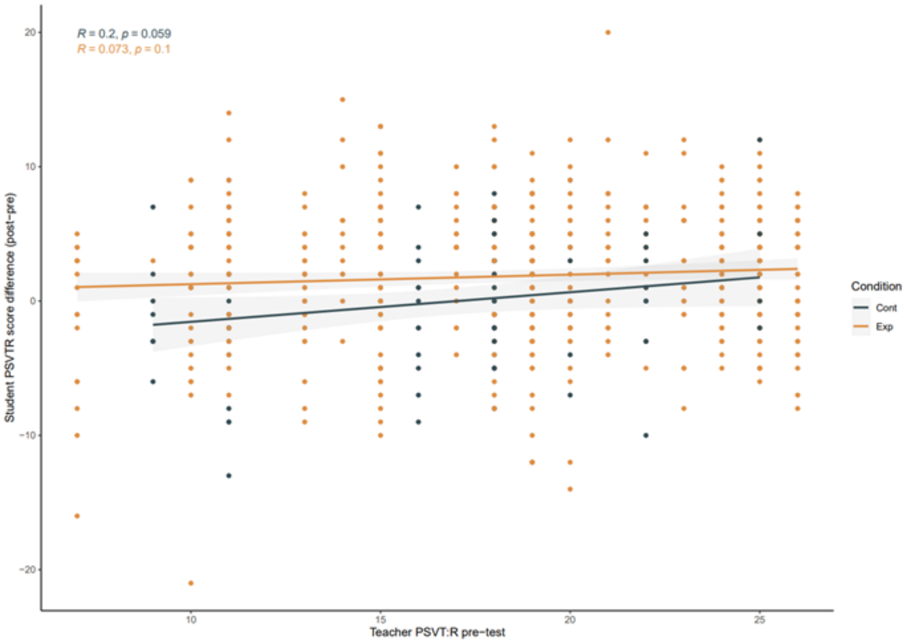
5.1. Pre-test conditions

Before discussing post-intervention impacts, it is important to understand the pre-intervention conditions. Prior to engaging with the spatial skill intervention, the control group students had a mean score of 13.29 while the experimental group students had a mean score of 13.39 on the PSVT:R. A t-test was conducted to determine if there was a significant difference that could be found between the groups ($t = -0.238$, $df = 740.12$, $p > 0.05$), this indicates that there was no significant difference between the two groups. From this we can determine that participants among the two groups scored very similarly on average. Female participants achieved a mean score of 12.56 while male participants achieved a mean score of 14.55. A t-test was conducted on these groups also ($t = -5.1291$, $df = 801.24$, $p < 0.05$), indicating a statistically significant difference between the two groups with male participants outperforming female participants by an average of 2 points on the PSVT:R. Students attending DEIS schools (‘Delivering Equality of Opportunity In Schools’ – this refers to schools of a lower SES in Ireland) achieved a mean score of 12.95 while students attending non-DEIS schools achieved a mean score of 13.61. A t-test was conducted to compare the groups ($t = -1.7731$, $df = 965.47$, $p = > 0.05$) and while the difference was not statistically significant, there is still a noticeable underperformance from the DEIS school participants.

5.2. RQ 1: What is the relationship between teachers’ spatial ability and the extent to which their students develop their spatial skills?

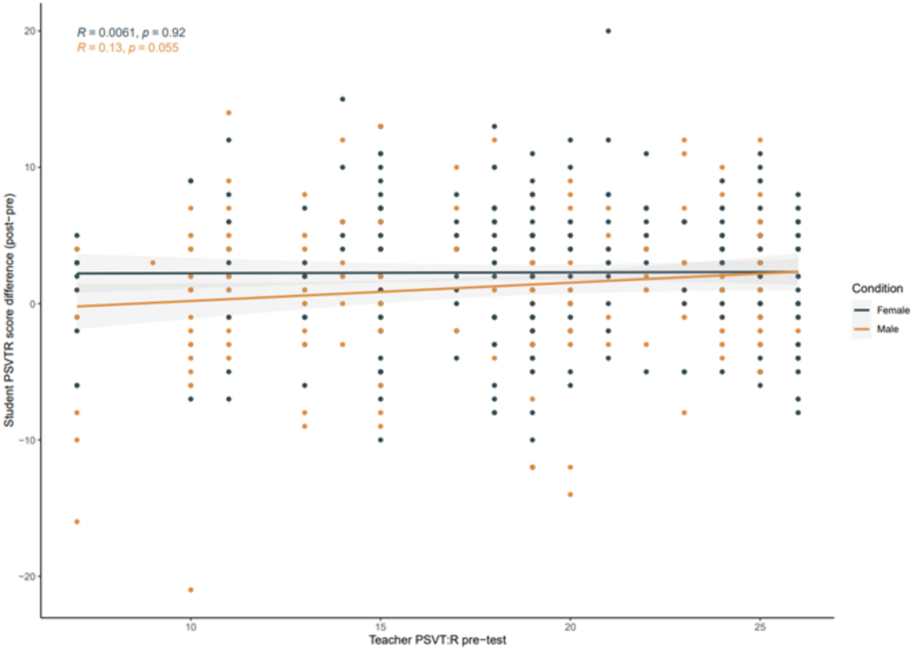
To answer this question, correlations between teacher pre-test ability and student score change on the PSVT:R were investigated. Multiple perspectives were taken while conducting these correlation analyses but due to the scope of this paper, only some of the relationships will be commented on here. The first graph (Fig. 2) shown below indicates the relationship between teacher pre-test performance and student performance change, separately for the control and experimental group. There was a weak correlation for each group, (control ($r = 0.2$, $p > 0.05$), experimental ($r = 0.073$, $p > 0.05$)), with neither being statistically significant.

Figure 2.
Correlation between teacher pre-test spatial scores and student difference in scores (post-test minus pre-test) in the PSVT:R for all participants



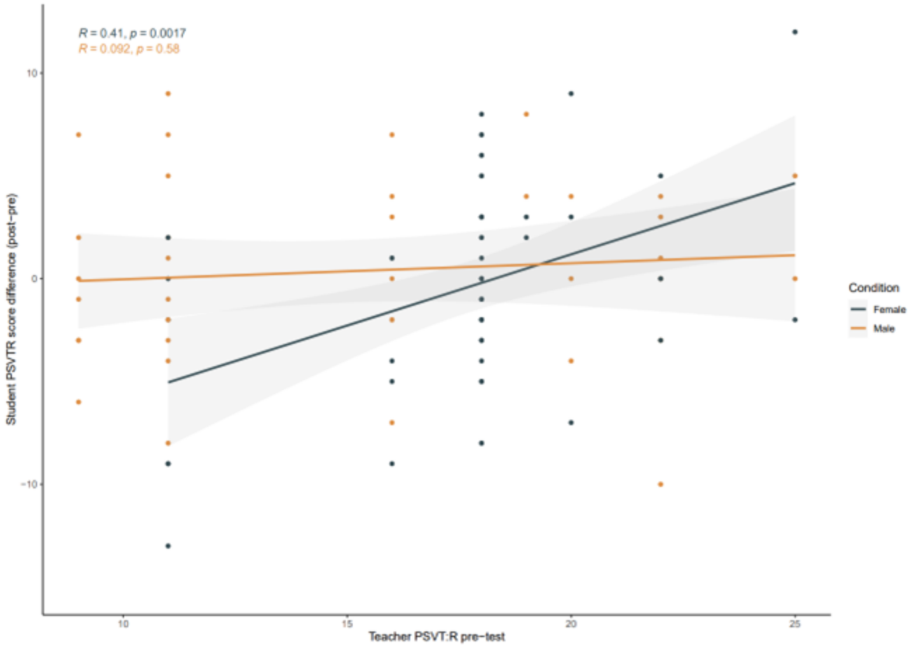
After this analysis, the authors decided to look at each group (control and experimental) in more depth. The next graph (Fig. 3) shown below describes the relationship between teacher pre-test scores and student performance change separately for male and female participants within the experimental group. As can be seen below there is a weak positive correlation for each group (female ($r = 0.0061$, $p > 0.05$) and male ($r = 0.13$, $p > 0.05$)). This suggests that teacher's initial spatial ability does not have significant impact on student performance after completing the spatial intervention.

Figure 3.
Correlation between teacher pre-test spatial scores and student difference in scores (post-test minus pre-test) in the PSVT:R. Looking at differences among genders for the experimental participants only.



The next graph, (Fig. 4) shown below, describes the relationship between teacher pre-test scores and student performance change separately for male and female participants within the control group. As can be seen there is a weak positive correlation among male participants ($r = 0.092$, $p > 0.05$) whereas there is a moderately strong correlation among female participants ($r = 0.41$, $p < 0.05$), which is also deemed statistically significant. Interestingly this result suggests that female student spatial skill development in a non-intervention setting (normal school activity) is linked to the teachers own spatial ability.

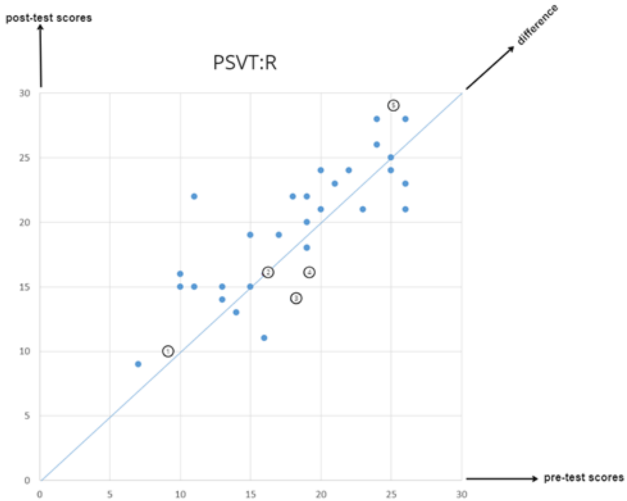
Figure 4.
Correlation between teacher pre-test spatial scores and student difference in scores (post-test minus pre-test) in the PSVT:R. Looking at differences among genders for the control participants only.



5.3. RQ 2: What is the effect of the spatial intervention on teacher spatial skill level?

Thirty-five teachers completed the pre- and post- spatial testing. Their pre-test average score was 18.1 points out of 30 and their post-test average score was 19.3 points out of 30. The scatter graph below (Fig. 5) shows teacher's change when completing the spatial testing.

Figure 5.
Scatter plot showing the relationship between teacher pre-test and post-test scores on the PSVT:R. The circles with numbers represent the teachers from the control group and the rest is from the experimental group.

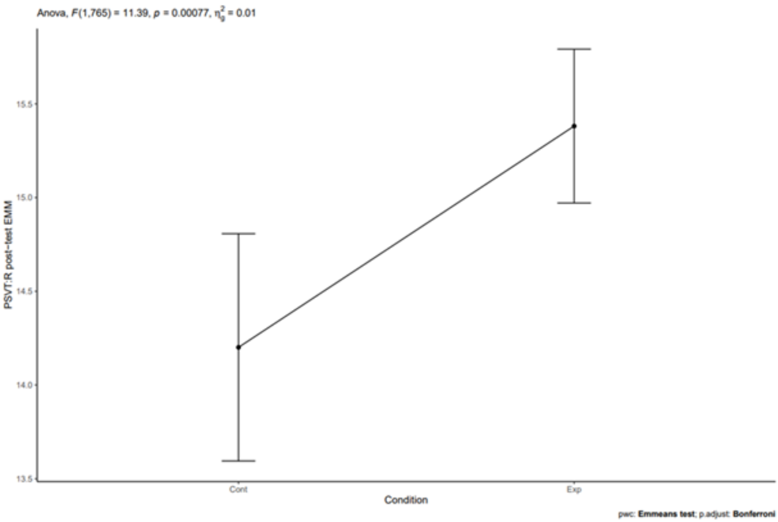


Two paired t-tests were conducted to determine if there was a statistically significant difference between pre-test and post-test performance on the PSVT:R, for control and experimental teachers separately. The control group teachers achieved a mean score of 17.4 on the pre-test and a mean score of 17 on the post-test. A paired t-test indicated ($t = 0.27869$, $df = 4$, $p > 0.05$) that there was no statistically significant difference between pre-test and post-test performance for the control group. The experimental group teachers achieved a mean score of 18.2 on the pre-test and a mean score of 19.6 on the post test, with a paired t-test ($t = -2.3408$, $df = 29$, p-value < 0.05) indicating that there is a statistically significant difference between pre-test and post-test performance for the experimental group teachers. This indicates that engaging with the PD days, along with delivering the spatial intervention has a positive impact on the spatial skills of the teacher.

5.4. RQ 3: What is the effect of the spatial intervention on student spatial skill level?

To determine the effect of the spatial intervention on student spatial skill development, post-test performance between the experimental and control groups were compared, with variances in their pre-test spatial performance being taken into account. Correlational analyses were firstly conducted to investigate if there was an association between pre and post-test performance on the spatial measure for the groups: control ($r = 0.73$, $p < 0.05$) and experimental ($r = 0.7$, $p < 0.05$). The correlations found were all statistically significant, indicating that those who performed high on the pre-test performed high on the post-test also, and vice versa for the lower achieving participants. This was also used to visually inspect the assumption of homogeneity of slopes, which was deemed to be met. An ANCOVA was performed to test the effect that the intervention had on post-test spatial performance as measured by the PSVT:R by comparing groups, while controlling for pre-test spatial scores. The numerical ANCOVA results can be seen below each related estimated (adjusted) mean plot (Fig. 6).

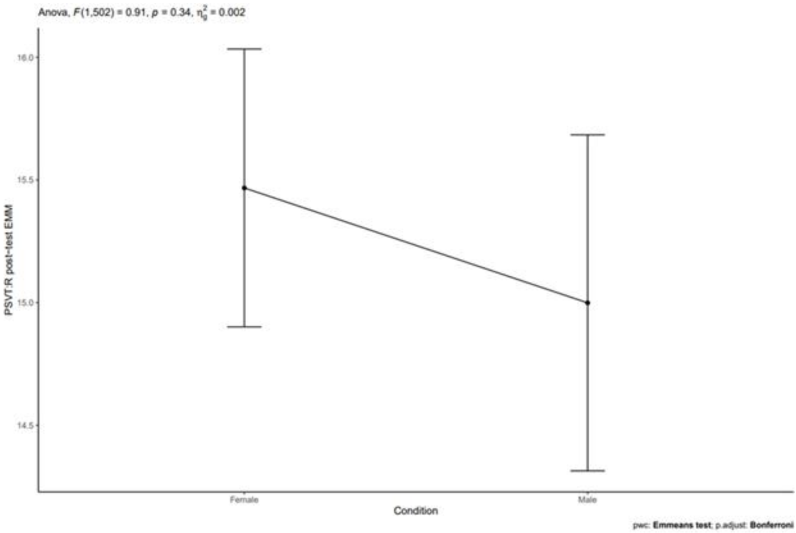
Figure 6.
Estimated (adjusted) marginal means plot for the control and experimental groups on the PSVT:R post-test after controlling for student and teacher performance on the pre-test PSVT:R



There was a significant difference in performance on the PSVT:R in the post test ($F(1,765) = 11.39$, $p < 0.05$), between the control ($M_{adjusted} = 14.2$) and experimental ($M_{adjusted} = 15.4$) groups. Therefore, evidence was found to suggest that the intervention had a positive effect on spatial test performance, having accounted for participant pre-test performance.

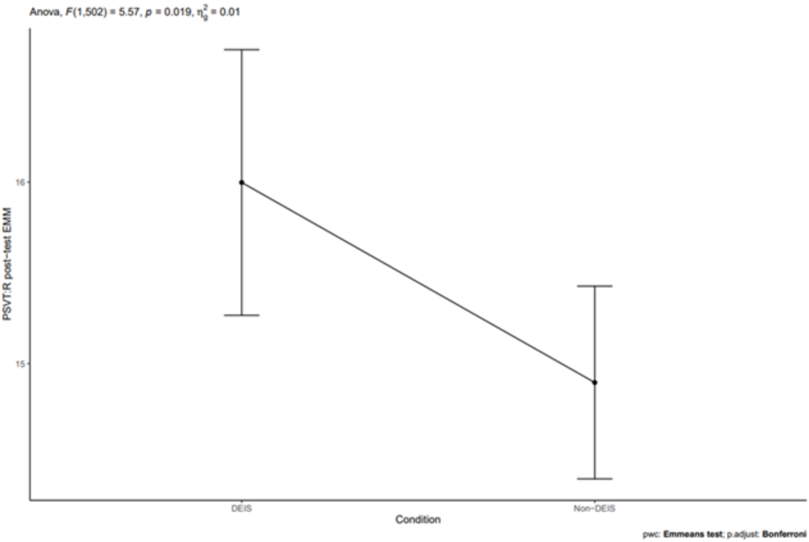
To determine the impact of gender and SES on spatial skill development only data from the experimental group was taken into account, post-test performance between the male and female groups, and DEIS and non-DEIS groups were compared, with variances in the pre-test spatial performance of both student and teachers being taken into account. Multiple correlational analyses were firstly conducted to investigate if there was an association between pre and post-test performance on the spatial measure separately for the groups: female ($r = 0.66$, $p < 0.05$), male ($r = 0.74$, $p < 0.05$), DEIS ($r = 0.69$, $p < 0.05$), and non-DIES ($r = 0.71$, $p < 0.05$). The correlations found were all statistically significant, indicating that those who performed high on the pre-test performed high on the post-test also. This was also used to visually inspect the assumption of homogeneity of slopes, which was deemed to be met. An ANCOVA was performed to test the effect that the intervention had on post-test spatial performance as measured by the PSVT:R by comparing genders (Fig. 7), and DEIS (Fig. 8), while in both cases controlling for pre-test spatial scores. The numerical ANCOVA results can be seen below each related estimated (adjusted) mean plot.

Figure 7.
Estimated (adjusted) marginal means plot for the male and female groups on the PSVT:R post-test after controlling for student and teacher performance on the pre-test PSVT:R



There was not a significant difference in performance on the PSVT:R in the post test, $F(1,502) = 0.91$, $p > 0.05$, between the female ($M_{adjusted} = 15.5$) and male ($M_{adjusted} = 15$) groups. Therefore, no evidence was found to suggest that the gender had an effect on post intervention spatial test performance.

Figure 8.
Estimated (adjusted) marginal means plot for the DEIS and non-DEIS groups on the PSVT:R post-test after controlling for student and teacher performance on the pre-test PSVT:R



There was a significant difference in performance on the PSVT:R in the post test, $F(1,502) = 5.57$, $p < 0.05$, between the DEIS ($M_{adjusted} = 16$) and non-DEIS ($M_{adjusted} = 14.9$) groups. Therefore, evidence was found to suggest that the SES had an effect on post intervention spatial test performance.

6. DISCUSSION

Our study demonstrated the impact of a spatial skills intervention on the spatial skill development of secondary level learners in Ireland. As can be seen above the experimental group outperformed the control group on the PSVT:R, with a statistically significant difference evident among the two groups. It is important to note that the control group did improve their average score on the PSVT:R but not to the same extent as the experimental group. The cause of this improvement is not known to the researchers, but it is hypothesised that this may be due to test-retest memory. When looking at the experimental group only results it is interesting to note that that the female participants outperformed the male participants, with this being opposite of the pre-test performance. A statistically significant difference between the two groups could not be found in the post-test data suggesting that taking part in this intervention supported bridging the gap between gender performance on the PSVT:R. When looking at the PSVT:R performance based on SES, it is important to note that after completing the intervention the DEIS school participants moved from underperforming in the test, to outperforming in the test, with a statistically significant difference emerging between the groups after the intervention. The reason behind this change in performance between the two groups is unclear to the researchers and further work is needed to investigate this relationship.

Although a strong correlation between teachers' spatial ability and student improvement on a spatial skills measure was not found for those taking part in the intervention, our study highlighted the impact of teacher's spatial ability on female participants spatial skills in a non-intervention environment. The reasoning behind this is unclear at this time but it is hypothesised that this may be linked to innately spatially supported teaching strategies employed by teachers of higher spatial skills. This finding is supported by previous research conducted by Krauss et al. (2008), which focused on secondary school mathematics teachers and displayed the significant impact of their mathematical content knowledge (CK) in developing efficient pedagogical content knowledge (PCK) in the area which consequently affects their students' achievements (Hill et al., 2005). This displays the importance of giving teachers enough opportunities and support to develop their own spatial thinking and reflect upon their teaching approaches since that will impact the quality of spatial education in secondary schools. Since pre-service and in-service Irish teachers are currently not being directly trained in their spatial ability development, their own abilities are still in question. The researchers suggest that spatial skills development courses may be of benefit to in-service teachers to support spatial skill development within secondary level education.

Overall, this study provides insights into the impact of an explicit spatial skills intervention on secondary level students spatial skills as measured by the PSVT:R, while also commenting on the impact of teachers' spatial ability on student development in the area. This paper also highlights the importance of supporting teachers in their own professional development to improve the quality of spatial skill development in secondary schools. Results from the study indicate the need to develop spatial skills in secondary school teachers which will later impact their ability to develop it within their students. Spatial professional development programs are a good way to achieve this with in-service teachers. When designing a new program, we need to consider many factors such as teacher's initial spatial ability levels, the selection of appropriate content, structure of the program, organizing continuing teacher support throughout the process, determining a long term vision for the intervention, collaborating with professional instructors, including diverse materials, presenting a clear picture of the practice, integrating spatial content with the existing curriculum, and thinking of ways to record teachers' instruction and provide feedback (Maquet et al., 2023).

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