Preparing Students for Engineering Success through Improving 3-D Spatial Skills

Abstract

Three-dimensional spatial skills have been shown to be critical to success in variety of STEM fields. In particular, spatial skills have been linked to success in engineering and in learning to program in computer science. Unfortunately, of all cognitive processes, 3-D spatial skills exhibit some of the most robust gender differences, favoring males, which could have serious implications as we attempt to increase gender diversity in our engineering programs. Spatial skills are not usually a part of the formal instruction in the pre-college classroom, meaning that many of our students enroll in our engineering programs deficient in these skills. A course for developing 3-D spatial skills has been offered at various universities in the US over the past two decades. Outcomes for this course include improved grades and graduation rates for the students who participate in it, particularly for the women. Based on these successes at the university level, attempts are being made to incorporate spatial skills training into pre-college classrooms. In order to explore whether links between mathematical ability and spatial ability are evident in a pre-college cohort, the authors are involved in a collaborative study regarding the impact of spatial skills training at the pre-college level. Data relating to math performance and various psychological constructs are being gathered using the Math Motivation Questionnaire. This paper describes the study and outlines key findings to date, examining data from 1182 participants gathered in co-operation with 22 practicing middle school teachers. The implications for engineering access and success will be discussed.

Introduction

Over the past three decades a growing body of research has demonstrated considerable links between 3D spatial skills and performance in a diverse range of disciplines [1, 2]. In addition, increases in spatial skills that are the result of an intervention have demonstrated considerable links to increased retention and
performance in University level degree programs[3]. This is especially true for females who tend to demonstrate lower levels of spatial skills than those of their male counterparts. Females who complete spatial interventions not only demonstrate rapid development of spatial skills but demonstrate increased performance in fields that one would not typically directly associate with spatial ability, such as mathematics. More recent studies have moved beyond correlation-based observations to experimental style studies [1]. Within these experimental designs, improvements in spatial skills were found to be concomitant with positive STEM relevant outcomes. Lowrie, Logan, and Ramful (in press) [4] conducted a study with sixth grade students (Australian system) and found that an intervention not only improved spatial skills, but also improved mathematics outcomes for the students in the experimental group when compared to a control group that received standard mathematics instruction. Noting the considerable benefits arising from completion of a spatial skills intervention, this study set out to examine whether similar positive outcomes would be observed in a pre-college cohort.

One of the most valuable outcomes from previous studies examining spatial skills development were the associated increased retention rates of female participants [5]. Increasing female presence in STEM related fields remains a priority for national and international policy and has obvious societal benefits [5-7]. Discussions arising from the results of these studies have suggested that this could be attributed to increased perceptions of competence in the spatial domain or a breakdown of gender based preconceptions. This is particularly relevant when considered alongside Newcombe [8] who highlights these factors as being influential in the selection of STEM career paths. A study by Britner and Pajares [9] examining the beliefs of middle school students relative to science further emphasizes the influence of self-efficacy, one's belief in one's ability to succeed in specific situations, in terms of performance but also self-direction. This suggests that positive outcomes resulting from completion of the spatial skills intervention, previously observed with University student cohorts, have the potential to
increase STEM career path selection by females who have completed the intervention at the pre-college level. While the next round of the current study is designed to explore this potential, the current round first seeks to establish whether desirable outcomes related to mathematical ability, previously observed in university level students, are evident in a younger cohort. Previous research has examined the suitability of the spatial intervention for use with younger students [1]. In order to examine these outcomes, participants will complete pre and post-testing in order to establish improvements in spatial skills attributed to the intervention. In addition, participants also complete pre and post-tests examining various mathematical domains.

**Research Design**
The research project will take place over a four year period with data gathered from 7\textsuperscript{th}-9\textsuperscript{th} grade students. Currently the first year of data collection has been completed; this first year data will be the focus of this paper. However, in order to situate this paper within the broader context of the overall project a brief overview of remaining years is included:

- Year 1 will be used to gather baseline data relating to the initial ability in mathematical and spatial domains of 7\textsuperscript{th} grade students.
- Year 2 incorporates a spatial skills development intervention in half of the total class group with the remaining half acting as a control. The experimental and control groups will be randomly assigned.
- Year 3 will repeat the experimental and control groups for a second cohort of students. Data will also be gathered from 8\textsuperscript{th} grade students who completed the intervention the previous year relating to their achievement and motivation for STEM.
- Year 4 will gather data on all participants in our experimental and control groups. Some of these students will be in 8\textsuperscript{th} grade; others will be in 9\textsuperscript{th} grade at this time. This will focus on mathematical achievement, motivation, and pursuit of advanced math classes.
The intervention will be conducted by trained teachers. In addition teachers will keep logs detailing their execution of the intervention and will be observed at multiple points throughout this execution. The intervention takes the form of 8-9 modules, each lasting 1-2 class periods. In addition to allowing for baseline data gathering, year 1 also allowed for considerable training and feedback opportunities with the teachers involved in the study.

As previously stated the study is currently in its second year. The baseline data gathered from the year 1 non-intervention students will provide useful longitudinal comparisons with later math achievement and motivation based data. Year 1 students completed 10-item versions of the Purdue Spatial Visualization Test:Rotations, Differential Aptitude Test, Lappan Spatial Visualization Assessment and the Mental Cutting Test. In addition participants completed a Mathematics Assessment as well as a Math Motivation Questionnaire. The mathematical assessment is comprised of 7 items taken from released items from the Colorado State Assessment Program test originally designed for use with 7th grade students [10]. The Math Motivation Questionnaire was adapted from Glynn, Taasoobshirazi [11] and features 6 subscales; Intrinsically Motivated Math Learning, Extrinsically Motivated Math Learning, Relevance of Math Learning to Personal Goals, Responsibility (Self-Determination) for Learning Math, Confidence (Self-efficacy) in Learning Science and Anxiety About Math Assessment. Baseline data was gathered in March 2016. The subsequent results section of this paper outlines data gathered from 1182 7th grade participants with the co-operation of 22 practicing teachers. Currently it is envisioned that future rounds will encompass over 4000 participants.

Results
Table 1 outlines spatial test data from baseline testing. In line with existing research, females demonstrated lower spatial ability in all tests. Cohen’s $d$ effect sizes are presented expressing the magnitude in difference of means across gender.
Table 1. Baseline Spatial Results

<table>
<thead>
<tr>
<th></th>
<th>Female (n = 443)</th>
<th>Male (n= 517)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\bar{x}$</td>
<td>$\sigma$</td>
<td>$\bar{x}$</td>
<td>$\sigma$</td>
<td>Cohen's $d$</td>
<td>$t$</td>
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<tr>
<td>DAT</td>
<td>4.25</td>
<td>2.144</td>
<td>4.69</td>
<td>2.343</td>
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<td>PSVT</td>
<td>3.67</td>
<td>2.135</td>
<td>4.38</td>
<td>2.438</td>
<td>0.309</td>
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<td>LAP</td>
<td>2.73</td>
<td>1.945</td>
<td>3.39</td>
<td>2.3</td>
<td>0.31</td>
<td>5.016</td>
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<tr>
<td>MCT</td>
<td>2.81</td>
<td>1.723</td>
<td>2.91</td>
<td>1.71</td>
<td>0.058</td>
<td>.844</td>
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</table>

Figure 1 outlines this data and demonstrates a consistent pattern across all spatial tests employed within baseline testing.

Mean scores outlining the 6 subscales that make up the MMQ [11] are presented in Table 2. Independent sample T-tests showed no significant difference in means across gender for Intrinsic Motivation ($t = .048, p = .962$), Extrinsic Motivation ($t = 1.592, p = .112$), Personal goals ($t = .751, p = .453$) or Self-Efficacy ($t = .707, p = .09$). However, statistically significant differences in means were observed for the Self-Determination ($t = 2.551, p = .011$) and Anxiety ($t = 5.978, p < .001$) subscales.
Table 2. Baseline MMQ Subscales

<table>
<thead>
<tr>
<th></th>
<th>Intrinsic</th>
<th>Extrinsic</th>
<th>Personal Goals</th>
<th>Self-Determination*</th>
<th>Self-Efficacy</th>
<th>Anxiety*</th>
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<tbody>
<tr>
<td>Female</td>
<td>15.94</td>
<td>19.08</td>
<td>15.27</td>
<td>17.5</td>
<td>17.59</td>
<td>13.01</td>
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<td></td>
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<td>457</td>
<td>450</td>
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<td></td>
<td>σ</td>
<td>4.04</td>
<td>3.7</td>
<td>4.15</td>
<td>3.24</td>
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<tr>
<td></td>
<td>x</td>
<td>15.93</td>
<td>18.7</td>
<td>15.48</td>
<td>16.97</td>
<td>18.11</td>
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<tr>
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<td>15.93</td>
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</tr>
</tbody>
</table>

* = statistically significant difference across gender

Associated math assessment data is presented in Table 3. The assessment produced data that demonstrated a statistically significant difference in means between genders ($t = 2.199, p = .028$).

Table 3. Baseline Math Assessment

<table>
<thead>
<tr>
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<th>Female</th>
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<tbody>
<tr>
<td>x</td>
<td>2.812</td>
<td>2.619</td>
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<tr>
<td>n</td>
<td>465</td>
<td>539</td>
</tr>
<tr>
<td>σ</td>
<td>1.411</td>
<td>1.36</td>
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</tbody>
</table>

Math performance demonstrated statistically significant correlations with DAT ($r = .263, p < .001$), PSVT ($r = .28, p < .001$), LAP ($r = .316, p < .001$) and MCT ($r = .217, p < .001$).

Discussion

Data relating to spatial tests supports previous studies that highlight the difference in ability with respect to gender [1, 5, 12-14]. On average, female participants achieved lower scores across all spatial tests. The difference between gender means is calculated and expressed as Cohen’s d effect size in Table 1. The MCT test demonstrated the lowest difference between genders and also demonstrated markedly lower standard distributions than the other tests. This echoes concerns
of teachers who suggested that the MCT test was too difficult in its current form resulting in reduced discriminant validity. This version of the test will not be included in future testing.

The MMQ data suggests considerable differences in means across gender, the most striking of which is the anxiety subscale. This reverse scored subscale suggests that female participants experienced statistically significantly increased anxiety relative to math ($t = 5.978$, $p<.001$) (see Table 2). When Cohen’s $d$ is calculated an effect size of 0.39 is observed. This is representative of the majority of research in the last two decades [15, 16] The anxiety subscale also demonstrated the highest correlation to math performance in wave 2 ($r = .276$, $p<.001$). In the context of statistically significantly higher performance for females ($t = 2.199$, $p = .028$) in math assessments, this data raises interesting questions relating to belief and performance across genders. Even though females are performing at an equivalent or better level, they are significantly more anxious about math compared to males. When math performance is considered, relative to performance in the four spatial tests employed in this study, a statistically significant correlation is evident for all four tests: DAT ($r = .263$, $p <.001$), PSVT ($r = .28$, $p <.001$), LAP ($r = .316$, $p <.001$) and MCT ($r = .217$, $p <.001$). This echoes previous studies which previously observed co-variance between the two domains [17, 18]. Future rounds of this study which incorporate interventions, and as a result alter spatial ability, will seek to explore whether ability increases within these domains are concomitant.

**Conclusion**

As previously stated, the purpose of year 1 of the current study was to establish baseline data, but also to examine potential links between spatial and mathematical ability in a 7th grade middle school population. Preliminary results of the study highlight similar patterns observed in terms of spatial ability and gender to those observed in University level populations. Additional math assessment data supports covariance between spatial and mathematical ability.
Future rounds of the current research project which aims to enhance spatial ability through an intervention, will allow for an examination of whether ability increases within these distinct domains are concomitant.

Implications relating to the impact of gender are evident in math assessment, math motivation and spatial ability data sets. Female participants demonstrated markedly lower levels of spatial ability relative to their male peers and higher math anxiety. The negative impacts of this under-developed ability are well established [19] and further support the need for spatial skill development at a pre-college level. Future rounds of this study will examine how participants develop spatial abilities through an intervention and has the potential to provide insight into whether the many advantages observed for females who completed a similar intervention at the University level are evident in a younger population. This has considerable implications for performance within STEM areas but also has implications for STEM career selection.

Links between spatial ability and mathematical ability were also observed. In addition, the relationship between motivation and ability level in the domain of mathematics was highlighted. Increased anxiety relative to math assessment for female participants was a particularly interesting result especially in the context of females out-performing males in the math assessment. This warrants further attention and will be explored using increased sample sizes as well as revised instruments in future rounds of the study. As previously mentioned, round 1 of the current study was primarily designed as a means of gathering baseline data. Data gathered relating to spatial ability, math ability and related motivation constructs has provided a useful initial insight, but also facilitated the refinement of instruments and practices which will benefit future rounds.

Acknowledgement
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Reference List