Spatial Training and Calculus Ability: Investigating Impacts on Student Performance and Cognitive Learning Style

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Despite concerted efforts on the part of educational policy makers, women are still underrepresented in the STEM fields. Researchers have shown that calculus plays a major role in this gender disparity since it requires spatial skills to succeed: skills that women tend to lack compared to men. However, previous studies have shown that spatial ability is malleable and spatial skills can be improved with training. This pilot study employed spatial training in a third-term calculus course and measured the effects of this training on students' calculus ability, spatial rotation ability, and cognitive learning style. Associations between cognitive learning style and task performance were also measured. Preliminary results indicate that spatial training does not significantly impact student performance on a calculus skills assessment or a test of mental rotations, but effects on students' cognitive learning style are present.

Key words: spatial training, calculus skills, cognitive learning style

Introduction & Literature Review

While the call for more graduates in Science, Technology, Engineering and Mathematics (STEM) continues (Executive Office of the President, PCAST, 2012; Stieff & Uttal, 2015), women remain consistently underrepresented in these fields (Schlenker, 2015). The major cause of this gender gap may concern a sequence of courses in calculus. Calculus is universally required for STEM majors and, therefore, often acts as a gatekeeper to student success and continuation into STEM careers (Bressoud et al., 2015). However, women are 1.5 times more likely to change to a non-STEM career pathway after a calculus course than men (Ellis et al., 2016). Women may struggle with concepts in calculus because they rely heavily on visual representations: females to have been shown to have less developed spatial abilities (Ferrini-Mundy, 1987) and to underperform on spatial tasks compared to males, starting as young as four years of age (Levine et al., 1999; Voyer, Voyer, & Bryden, 1995). Other studies indicate that individuals with higher scores on spatial tests are more likely to enjoy STEM subjects and to choose careers in STEM (Wai, Lubinski, & Benbow, 2009).

While the body of literature seems to suggest that women may have a disadvantage in the STEM fields, encouraging evidence exists that practice with spatial concepts can improve spatial ability (Uttal, 2009; Stieff & Uttal, 2015) and that spatial training can decrease the gender gap in spatial thinking (Newcombe, 2010). We refer to this idea in the paper as *spatial training,* which we define as explicit instruction and practice on spatial skills such as rotation, planar views or unfolding of an object. At this time, knowledge about the benefits of spatial training is not conclusive concerning whether an increase in spatial ability has direct effects on performance in the STEM fields. A study conducted with engineering students found an association between spatial training and academic performance, as well as a closing of the gender gap (Sorby et al., 2013). However, very few studies exist that investigate the link between spatial training and mathematical skills. One study by Ferrini-Mundy (1987) required undergraduate students to complete spatial training exercises during a calculus course but did not find significant increases in calculus performance (although female students were better able to visualize solids of revolution than male students). Other research has found that while spatial training does reduce the gender gap in performance on spatial tasks, it fails to eliminate it (Uttal, 2009). Thus, a call has been made in the spatial cognition literature to extend this line of enquiry into the potential for spatial training to close the gender gap in the STEM fields by investigating new mediating variables and extending periods of spatial training (Casey, 2013).

One factor that may be associated with spatial and mathematical ability is the psychological construct of cognitive learning style. A cognitive learning style represents a coherence of a person's manner of cognitive function (i.e., information acquisition and processing) (Harvard Mental Imagery and Human-Computer Interaction Lab, 2013). Because the human visual system distinctly processes properties about objects (color, shape) and space (location and spatial relations), Kozhevnikov, Kosslyn, and Shephard (2005) have used neuropsychological evidence to propose the Object-Spatial-Verbal theoretical model of cognitive style. This model outlines three independent dimensions (object imagery, spatial imagery, and verbalization) to explain that object visualizers prefer to construct vivid, concrete, and detailed images of individual objects, spatial imagers schematically represent spatial relations of objects and spatial transformations, and verbalizers prefer to process and represent information verbally and rely on non-visual strategies (Kozhevnikov, Kosslyn, & Shephard, 2005).

It seems that preference for one of the three strategies has been shown to directly relate to one's performance on either mathematical, object imagery ability, or spatial ability tests (MM Virtual Design, 2016). Thus, cognitive learning styles may assist math educators to tailor material, assignments, and visualization media to students' individual differences in cognitive learning style and decision-making based on visual stimuli. Learning and performance based on visual information presented in a manner congruent to one's cognitive learning style may help close the gender gap in STEM. Indeed, Peters et al. (1995) found that women report using verbal strategies to solve mental rotation tasks more often than men and Casey (2013) points out that one reason why large gender differences are found for mental rotation tasks is because verbal strategies are often less effective than holistic mental rotation approaches used more often by men. Thus, measuring cognitive learning style in association with spatial ability and an understanding of calculus may afford information about whether those with predominant verbal cognitive learning styles are women, as well as whether their performance in calculus improves with spatial training.

This study targets the lack of literature investigating effects of spatial training on mathematical skills and seeks to answer the following research questions: (1) What are the impacts of spatial training on undergraduate students' performance in calculus? (2) Are differences present in the effects of spatial training between male and female students? And (3) What are the impacts of spatial training on students' cognitive learning style?

Methods

Context

The study took place at a mid-sized state-funded university in the northwestern United States in a summer 2016 quarter. All student participants were enrolled in a third-quarter calculus course covering the calculus of sequences and series, vectors equations, and multi-variable functions. The course was taught using an inquiry-based learning pedagogy; spatial training was incorporated during class time.

Spatial training was conducted for, on average, 10 minutes during every class meeting (twice per week for 10 weeks). Students completed exercises from a spatial training workbook developed by Sorby et al. (2013; and used with permission). Exercises in the workbook ranged from assessments of what a given shape would look like when rotated around a given axis, to asking students to draw an object from different angles using different cross-sections, to showing 2-D views of an object and asking students to draw the 3-D object. During the spatial training portion of class, students were asked to discuss the exercises in small groups and come to a consensus on the correct answer before answers were discussed with the whole class.

Participants

Participants had already completed two quarters of undergraduate calculus and spent an average of 12 hours a week (*SD* = 3.70) studying course material. Seventeen students (8 males, 9 females) attended class for both rounds of data collection and all but one took part in the study ($n = 16$; 8 males, 8 females, mean age = 21 years). Five (31%) participants reported enrollment in another math course during the quarter while 11 participants (69%) reported that they were not receiving other forms of math training at the time of the study.

Data Collection

Participants were given three separate instruments in a pre-post data collection model that measured spatial ability, calculus ability, and preferred cognitive learning style. The measurement of spatial ability was obtained using a 15-item version of the Purdue Spatial Visualization Test: Rotations (PSVT:R) (Guay, 1977). This multiple-choice instrument gives an example of an object and a rotation of the same shape and asks participants to choose (from 5 possibilities) the result of the same rotation on a new object. The PSVT:R was used to obtain a baseline measure of spatial ability and to quantify improvements from the spatial training. The Calculus Concept Inventory (CCI) was administered to measure calculus ability. This instrument, designed by Epstein (2013), measures students' understanding of the basic concepts of differential calculus. The CCI contains 22 questions about limits and derivatives, many of which require interpretation of a graph or visual aid. The Object-Spatial Imagery and Verbal Questionnaire (OSIVQ) developed by Blazhenkova and Kozhevnikov (2009) was used to measure students' predominant cognitive learning style. The OSIVQ consists of 45 questions to assess object imagers, spatial imagers, and verbalizers and takes approximately 10 minutes to complete. Each item asked students to rate their agreement on a 5-item Likert scale ranging from "totally disagree" (1) to "totally agree" (5) with statements of preference or ease of performing various tasks.

Additionally, basic demographic questions, such as age, gender, and the number of courses related to mathematics taken at the post-secondary level were asked. To gain an understanding of students' concurrent exposure to mathematical and spatial concepts outside of the training, and the course in general, students were asked to report whether they were receiving (or intended to receive) alternative instruction or tutoring during the term (e.g., enrollment in a different math course or spending time at the learning and teaching center), as well as the number of hours of this additional instruction per week.

All instruments were administered to participants during class time and no significant time pressure was placed on the students. Tasks were administered to participants in the following order: consent form; OSIVQ; Visualization and Rotation Purdue Spatial Visualization Test; Calculus Concept Inventory. Thus, the tasks were not completed simultaneously: only when a task was completed was the next task offered to a participant by one of the authors. No calculators or other electronic devices were used during task completion.

Results

The CCI and PSVT:R were scored by assigning 1 point for a correct answer and 0 points for an incorrect answer. Descriptive statistics for each inventory separated by gender are given in Table 1. To answer our first research question, students' pre- and post-test scores were computed and a paired-samples *t*-test was performed to determine significant improvements in calculus ability. No significant improvement was revealed over the term ($p > .05$). While male participants' average scores were higher on the CCI than women at the start of term ($M = 9.63$, $SD = 4.47$ and $M = 7.75$, $SD = 7.75$, respectively), they were not significantly higher ($p > .05$). This result was also borne out at the end of term whereby male students' average scores on the CCI were insignificantly higher than female students' scores ($M = 10.25$, $SD = 2.09$ and $M = 8.25$, $SD = 1.40$, respectively).

Table 1:
Descriptive Statistics for Test Variables Per Gender Type

Variable	Gender	Mean *Round 1*	Standard Deviation *Round 1*
CCI (scored out of 22)	Male	9.63	4.47
	Female	7.75	3.45
PSVT:R (scored out of 15)	Male	9.88	4.29
	Female	9.75	2.05
OSIVQ: Spatial (scored out of 75)	Male	49.75	2.74
	Female	46.13	3.44
OSIVQ: Object (scored out of 75)	Male	47.00	2.67
	Female	50.13	2.26
OSIVQ: Verbal (scored out of 75)	Male	42.75	1.40
	Female	39.50	1.58
		Round 2	*Round 2*
CCI (scored out of 22)	Male	10.25	2.09
	Female	8.25	1.40
PSVT:R (scored out of 15)	Male	10.5	1.45
	Female	9.25	1.24
OSIVQ: Spatial (scored out of 75)	Male	54.00	2.19
	Female	47.50	3.70
OSIVQ: Object (scored out of 75)	Male	52.38	3.42
	Female	49.25	2.04
OSIVQ: Verbal (scored out of 75)	Male	45.38	0.80
	Female	40.13	1.42

To determine an association between students' spatial ability and mathematical ability, a correlation coefficient for a student's final grade in Calculus III and their final PSVT:R score was calculated. This correlation ($r = 0.4283$) was not significant ($p > .05$). Additionally, a paired-samples *t*-test did not determine a significant improvement in students' rotational ability during the term ($p > .05$). Consistent with previous studies (Levine et al., 1999; Voyer, Voyer, & Bryden, 1995), male participants' average scores were higher on the PSVT:R than women at the start of term ($M = 9.87$, $SD = 4.29$ and $M = 9.75$, $SD = 2.05$, respectively), and at the end of the term ($M = 10.5$, $SD = 1.45$ and $M = 9.25$, $SD = 1.24$, respectively). However, these differences were not significant ($p > .05$).

On average, more students at the start of the term self-identified as object learners ($M = 48.56$, $SD = 7.00$) than they did as spatial learners ($M = 47.94$, $SD = 8.69$) or verbal learners (M

= 41.13, $SD = 4.41$). Indeed, scores on the spatial sub-scale were significantly higher than on the verbal sub-scale, $t(15) = 3.97$, $p = .001$. In addition, scores on the spatial sub-scale were significantly higher than those on the object learner sub-scale, $t(15) = -2.98$, $p < .01$.

After 10 weeks, the object cognitive learning style remained the predominant style for the class as a whole ($M = 50.81$, $SD = 7.87$) and, similar to the start of term, the second-most common learning style among the class was spatial ($M = 50.75$, $SD = 8.96$), followed by verbal ($M = 42.75$, $SD = 4.16$). However, unlike at the start of the term, these differences were significant: students sscored significantly higher on the object learning style sub-scale compared to the verbal learning style sub-scale, $t(15) = -3.57$, $p < .01$. They also self-scored significantly higher on the spatial sub-scale compared to the verbal sub-scale, $t(15) = -3.55$, $p < .01$.

Although mean scores on each of the three sub-scales increased over the term, paired-samples *t*-tests revealed only one significant difference between sub-scale scores over time. Students did not self-score significantly better or worse on the object or verbal subscales over time (all *p*s > .05). They did self-score significantly higher on the spatial sub-scale at the end of the term after receiving spatial training, $t(15) = -2.59$, $p < .05$.

At the start of the term, the men in the sample identified most, on average, as spatial learners ($M = 49.75$, $SD = 2.74$) and least as verbal learners ($M = 42.75$, $SD = 1.40$). This was also the case at the end of the term (see Table 1). In contrast, the highest average score among the three cognitive learning styles for women was on the object sub-scale ($M = 50.13$, $SD = 2.26$) while the lowest was on the verbal subscale ($M = 39.50$, $SD = 1.58$) and remained so at the end of term.

While participants' general perceptions of dominant learning styles remained stable over 10 weeks, each gender's scores increased on each sub-scale -- except that women's scores on the object learning style sub-scale decreased slightly (but insignificantly, $p > .05$) over time.

After the first round of data collection, independent samples *t*-tests revealed no significant differences between male and female participants' scores on the three OSIVQ sub-scales (all *p*s > .05). However, at the end of the term, a significant difference between men and women's scores on the verbal sub-scale of the OSIVQ was revealed, $t(14) = 3.22$, $p < .01$.

Finally, scores on the spatial sub-scale of the OSIVQ did not correlate significantly with high scores on the PSVT:R at the start of the term ($p > .05$) but did so at the end of term ($r = .62$, $p = .01$). No other significant correlations were revealed between scores on the PSVT:R and other sub-scales of the OSIVQ, nor were there any significant associations between scores on the OSIVQ sub-scales and the CCI at the start or end of the term.

Discussion & Future Work

This pilot study revealed that students who self-identified more as object or spatial learners than verbal learners did so significantly more strongly after spatial training. In particular, a strong identification as a spatial learner linearly associated with mental rotation ability after spatial training. However, spatial training alone did not significantly impact the calculus or mental rotation abilities of undergraduate students. The results of this research will inform an adjustment to the methods before a second study is undertaken with a second-term calculus course. Since the present study was done during a summer term, only a total of 18 classes occurred, with approximately 15 minutes of spatial training done per class. This may not be sufficient for students to be influenced by the training: indeed, less than half of the items in the workbook were completed during the term. Thus, the next iteration of this research will require students to complete some training modules independently to allow more time for an effect.

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