Engaging STEM Learners with Hands-on Models to Build Representational Competence

Abstract

Modern 3D printing technology makes it relatively easy and affordable to produce physical models that offer learners concrete representations of otherwise abstract concepts and representations. We hypothesize that integrating hands-on learning with these models into traditionally lecture-dominant courses may help learners develop representational competence, the ability to interpret, switch between, and appropriately use multiple representations of a concept as appropriate for learning, communication and analysis. This approach also offers potential to mitigate difficulties that learners with lower spatial abilities may encounter in STEM courses. Spatial thinking connects to representational competence in that internal mental representations (i.e. visualizations) facilitate work using multiple external representations. A growing body of research indicates well-developed spatial skills are important to student success in many STEM majors, and that students can improve these skills through targeted training.

This NSF-IUSE exploration and design project began in fall 2018 and features cross-disciplinary collaboration between engineering, math, and psychology faculty to develop learning activities with 3D-printed models, build the theoretical basis for how they support learning, and assess their effectiveness in the classroom. We are exploring how such models can support learners' development of conceptual understanding and representational competence in calculus and engineering statics. We are also exploring how to leverage the model-based activities to embed spatial skills training into these courses. The project is addressing these questions through parallel work piloting model-based learning activities in the classroom and by investigating specific attributes of the activities in lab studies and focus groups.

To date we have developed and piloted a mature suite of activities covering a variety of topics for both calculus and statics. Class observations and complementary studies in the psychology lab are helping us develop a theoretical framework for using the models in instruction. Close observation of how students use the models to solve problems and as communication tools helps identify effective design elements. We are administering two spatial skills assessments as pre/post instruments: the Purdue Spatial Visualizations Test: Rotations (PSVT:R) in calculus; and the Mental Cutting Test (MCT) in statics. We are also developing strategies and refining approaches for assessing representational competence in both subject areas. Moving forward we will be using these assessments in intervention and control sections of both courses to assess the effectiveness of the models for all learners and subgroups of learners.

Introduction

This NSF-IUSE Exploration and Design track project focuses on using hands-on models and manipulatives to improve student learning and success rates in integral calculus and engineering statics. These two courses include key prerequisite concepts and skills that are foundational to many engineering disciplines. Many of these concepts are spatial in nature [1], [2] and likely require well-developed visualization skills to understand. The importance of spatial visualization skills for STEM majors in general is well-established [3]. A number of targeted training approaches can improve these skills as measured on validated instruments such as the Purdue Spatial Visualizations Test: Rotations (PSVT:R) [1] and can improve grades in introductory calculus [4]. Targeted spatial training offers potential to increase overall student success in STEM, but studies have yet to show causality in improvements to retention and degree attainment [5]. Women generally enter college engineering programs with lower spatial abilities [4], so interventions targeting spatial skills may help increase the percentage of women in the engineering workforce. We view the spatial skills challenge as a subset of a larger goal, namely improving students' conceptual understanding. Multiple studies have shown that many students who can solve quantitative problems struggle to answer concept questions on the very same topic [6].

Conceptual knowledge in engineering sciences and the underlying mathematics is a critical part of engineering expertise and associated competencies [7]. Engineers communicate and apply concepts using a language of multiple representations that include pictorials, diagrams, graphs, symbols, numbers and narrative language [8]. Students build conceptual knowledge by thinking through multiple representations and translations. Through this process, they resolve misconceptions (or naïve conceptions) and build mental models of the underlying meaning the representations communicate [9]. We have identified the framework of representational competence as useful for thinking about students' conceptual knowledge in calculus and statics. Kozma and Russel [10] used the term representational competence in the context of chemistry education to describe the ability to use multiple representations of a concept as appropriate for learning, problem solving, and communication. While there is still no consensus on representational competence as a unified theoretical framework [11], the construct is commonly used in the science education literature and is identified as a marker of true conceptual understanding [12], [13], [14]. Studies of representational competence (or fluency) also exist in the engineering education literature, though to a lesser extent [9]. Well-developed spatial abilities relate to the development of representational competence in many content domains because these skills connect to the ability to form and manipulate mental representations. These skills are also helpful for to drawing accurate diagrams (e.g. free-body diagrams) that are important to coordinating information and solving problems of increasing complexity [4].

Modern 3D printing technology makes it relatively easy and affordable to produce physical models that offer learners concrete representations of otherwise abstract concepts and representations. Studies in chemistry education demonstrate the promise of hands-on models and manipulatives to serve as scaffolds for novice learners to develop representational competence when working with multiple 2D representations in chemistry [12], [15].

Project Description

We hypothesize that integrating active learning activities with hands-on models will help learners develop representational competence in engineering mechanics and mathematics and are leveraging 3D printing technology to test this idea. The project team consists of an engineering professor and a math professor at a community college working in close collaboration with a psychology professor at a nearby university. Our approach also has potential to mitigate difficulties that learners with lower spatial abilities may encounter with spatial concepts and embed spatial skills training exercises throughout both courses. The following project goals and associated research questions guide our work.

Goal 1
Develop physical models and associated learning activities that embed practices thought to develop representational competence in multiple content areas in Statics and Integral Calculus.

Goal 2
Assess the effectiveness of the models and activities on improving representational competence in the context of traditional coursework.

> RQ1a. Do the model-based learning activities lead to increased gains in representational competence compared to traditional instruction?
>
> RQ1b. Does guided work with the models lead to more improvements in students' spatial skills compared to traditional instruction?
>
> RQ1c. Does use of the models improve student success rates and outcomes in the course in which the intervention took place?
>
> RQ1d. Does use of the models improve student success rates and outcomes in follow-on courses (Calculus 3 and Mechanics of Materials) in which the intervention is no longer being conducted?

Goal 3
Identify the characteristics of modeling activities that make them effective for all learners and/or subgroups of learners.

> RQ2a. What specific attributes of a model-based learning activity contribute to the development of representational competence in students?
>
> RQ2b. What specific attributes of a model-based learning activity help develop students' spatial skills?
>
> RQ2c. Does the effectiveness of the model-based activities depend on frequency and/or duration of student exposure?
>
> RQ2d. Does the effectiveness of the model-based activities depend on students' prior experiences, STEM confidence, or vary for specific student populations such as women and students of color?

The project is currently in its second year. Work during the first year focused on development and refinement of the models and associated activities through pilots in classroom, focus groups, and one-on-one sessions in the psychology lab. Close observation of how students use the models to solve problems and as communication tools helped identify effective design elements. We also developed assessment strategies for representational competence, including work on a new instrument to measure students' fluency with vector concepts in a statics context [16].

Models and Activities

Our mature collection of eight calculus activities cover the topics of accumulation, centroids (center of mass), volumes with discs/washers, volumes with cylindrical shells, and volumes by slicing. The ten statics activities cover vectors, concurrent force systems, moments and couples, statics equivalency, rigid body equilibrium in two and three dimensions, support models, static friction, and frame analysis. Manipulatives include concrete physical models of graphs and problem figures as well as concrete embodiments of abstractions such as differential areas used in formulating integrals, couple-moment vectors and 3D coordinate axes. We piloted versions of all activities in at least one class session during 2018-19. Figures 1 and 2 show some of the models that we have developed for calculus and statics respectively.

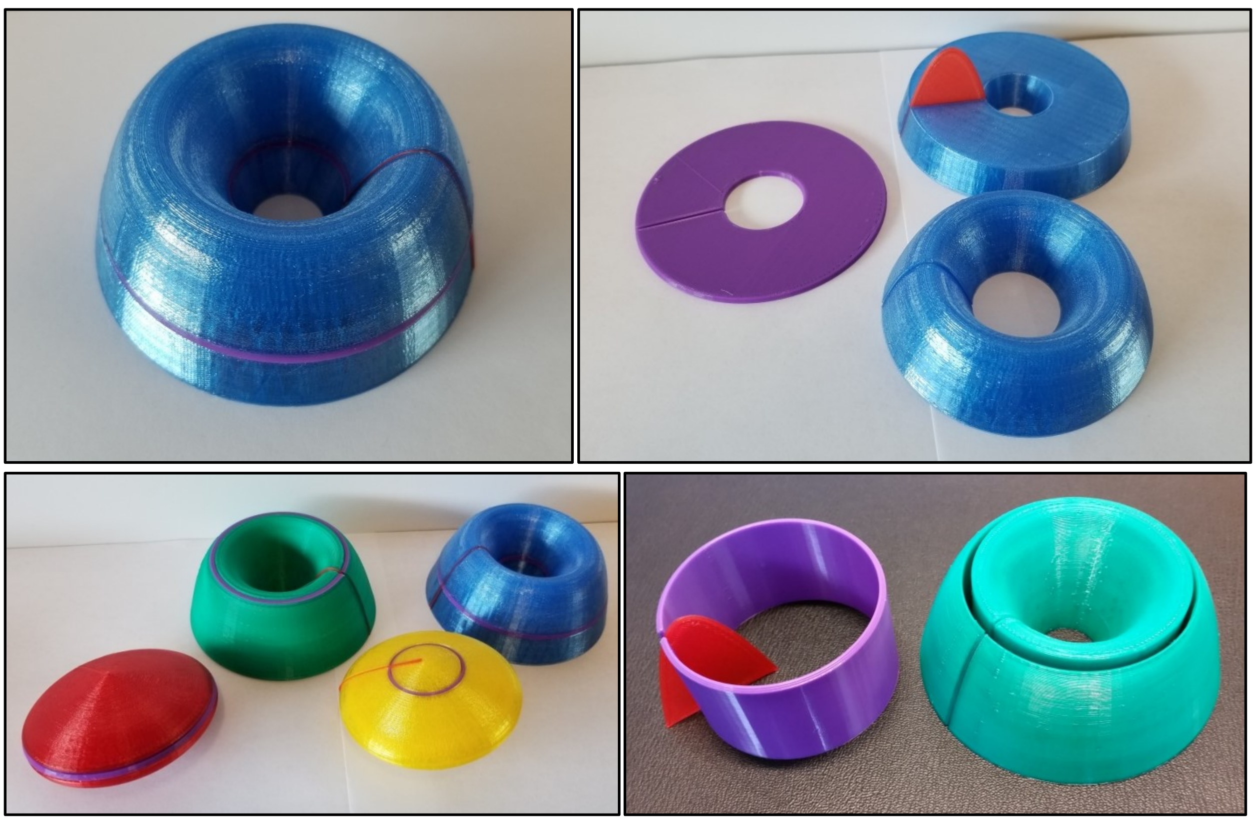

Figure 1. Volume of revolution models used in calculus: assembled model of a revolved parabola (top left), disassembled for investigating the method of washers (top right), collection of models for parabola revolved around x or y axis (bottom left), disassembled for investigating method of shells.

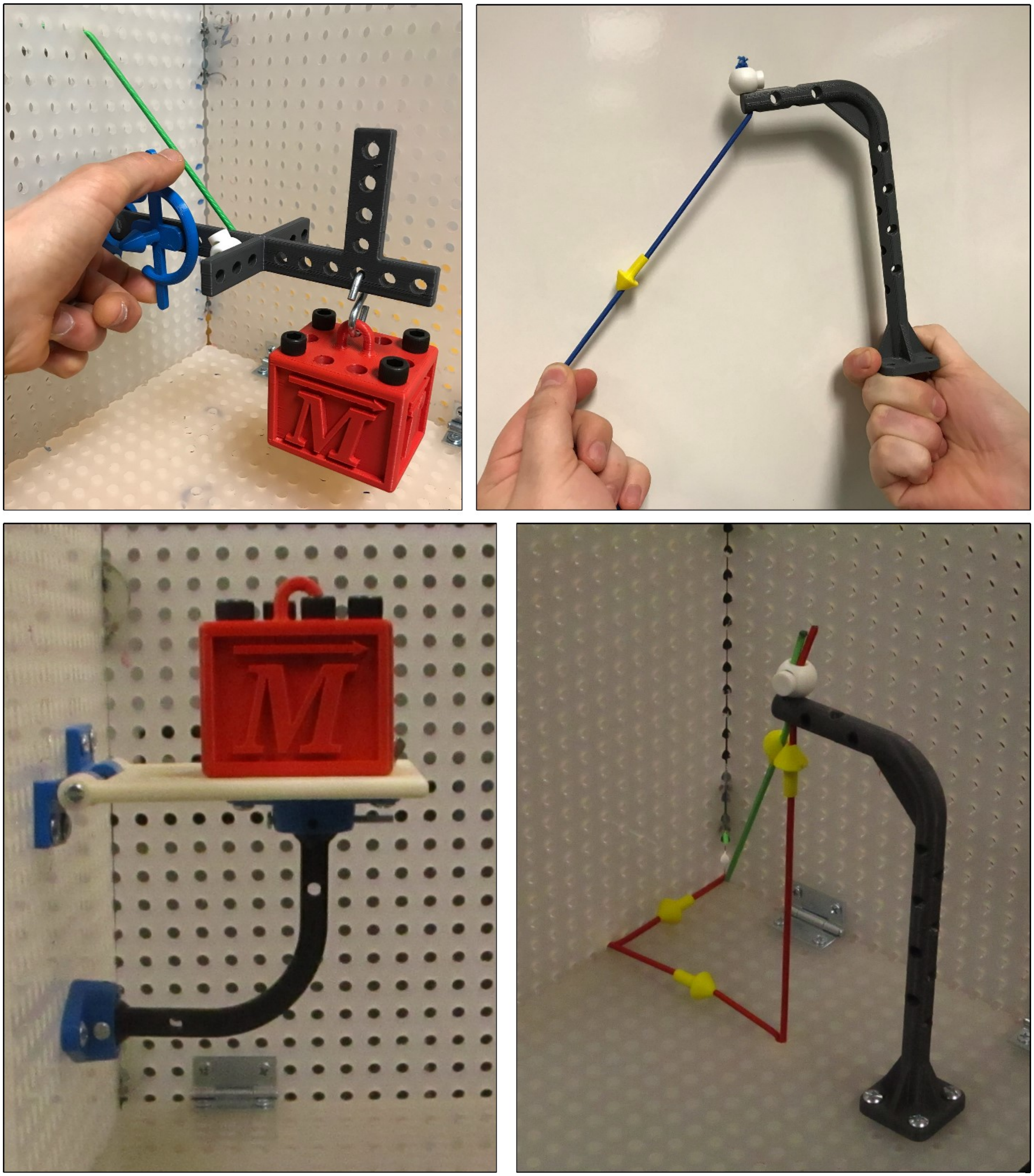

Figure 2. Example statics models for the topics of static equivalency (top left), rigid body equilibrium and support models (top right), two-force members (bottom left), and 3D vector components (bottom right).

Research Design

The next phase of the project features a longitudinal study to assess the impact of the models in the classroom with focus on investigating RQ1a-d and RQ2c-d through statistical analysis of student performance on targeted assessments. We also look at overall course outcomes in integral calculus and statics as well as follow on courses. We will run intervention and control sections in both of the target courses as shown in Figure 2. Since the calculus course is a prerequisite for statics, we will develop a data set with four conditions to help gain insight into any compounding effects of repeated exposure to the model-based pedagogy (relevant to RQ2c):

1. Students who learn with models in both calculus and statics.
2. Students who learn with models in calculus but not statics.
3. Students who learn with models in statics but not calculus.
4. Students who learn with models in neither course.

We plan to expand this project to three other community colleges starting fall 2020 in order to increase the size of the overall study population. We are particularly interested in increasing the statistical power of the demographic subgroups of interest in RQ2d.

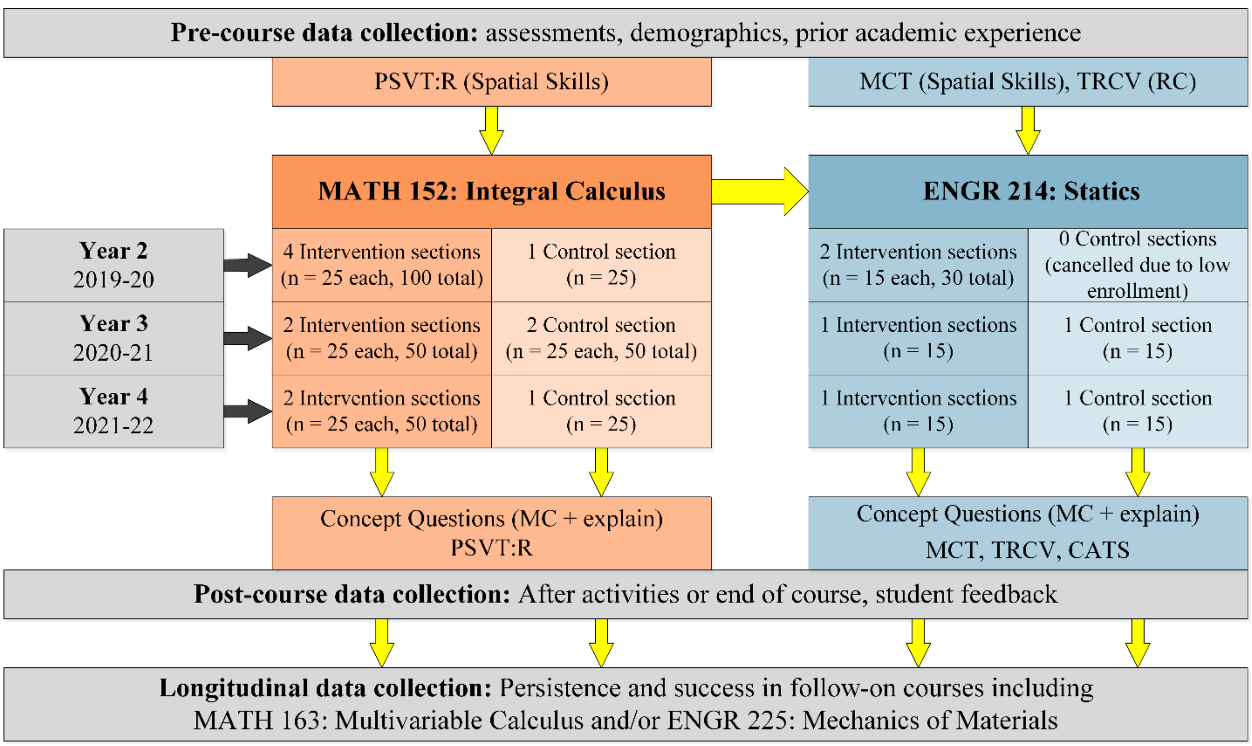

Figure 2. Research design for longitudinal study assessing the impact of the model-based learning activities.

Ongoing class observations and complementary studies in the psychology lab continue and are shifting toward the goal of develop a theoretical framework for using the models in instruction and addressing RQ2a and RQ2b.

Assessments

There are several validated assessments available for testing spatial abilities [17]. As shown in Figure 2, we have chosen to use the PSVT:R and the Mental Cutting Test (MCT) to assess spatial skills preparation and development in calculus and statics respectively. The choice of the

PSVT:R for calculus was driven by its prevalence of use in other studies and available comparison data correlating to calculus performance in other contexts [4]. We chose the MCT for statics for two reasons. First, the skills of sectioning (mental-cutting) and interpreting proportion are relevant to many statics concepts. Second, there may be a "ceiling effect" that limits the ability of the PSVT:R to detect gains in spatial skills in statics [18]. We developed the TRCV (Test of Representational Competence with Vectors), a multiple-choice assessment of vector representations and concepts, as part of this project [16]. The "Concept Questions (MC + explain)" assessment referenced in Figure 2 refers to targeted concept questions we ask both immediately following the activities and embedded in course exams. We ask students to explain their answer choices and code the justifications for evidence of representational competence. The CATS acronym refers to the Concept Assessment Test in Statics [19], [20].

Conclusion

This project seeks to leverage 3D printing to develop relative low cost and easily distributed models and manipulatives to improve students' conceptual understanding in integral calculus and engineering statics. Collaborative work between engineering, math, and psychology faculty has focused on designing activities that will provide effective scaffolding for students to learn concepts and promote development of representational competence in both disciplines. We hypothesize that work with the models may also provide some spatial skills training and/or help students with lower spatial abilities to better engage with spatially intensive concepts. Going forward, a longitudinal study of intervention and control sections of the two courses will investigate research questions around the effectiveness of the models for all learners and for demographic subgroups.

Acknowledgements

This material is based upon work supported by the National Science Foundation under grant numbers DUE #1834425 and DUE #1834417. Any opinions, findings, and conclusions or recommendations expressed are those of the authors and do not necessarily reflect the views of the NSF.

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