Learning Spatial Visualization: Beyond Drills and into Early Mastery

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INTRODUCTION

In the College of Engineering at Cornell University, the goal of the Office of Diversity Programs in Engineering (DPE) is to support students, especially those from backgrounds traditionally underrepresented in engineering, and to provide the programming necessary to assist them in being successful. Consequently, we created a new spatial visualization course, entitled Spatial Visualization/Thinking for Engineers. This course was one of three interventions outlined in a grant awarded by the the National Science Foundation (NSF) and the Science, Technology, Engineering, and Mathematics Talent Expansion Program (STEP) (award: DUE #1317501).

During our course preparation and development, we noticed that the range of definitions for "spatial visualization" (SV) is wide and varied. Perhaps the simplest definition is "the ability to mentally manipulate, rotate, twist, or invert pictorially presented stimuli" [1]. Others define it as "the ability to manipulate complex spatial information when several stages are needed to produce the correct solution" [2] The first definition represents spatial visualization as a kind of mental exercise; the second as a response to a particular problem or project. Other schools of thought refer to "spatial ability" or "representing, transforming, generating and recalling symbolic, nonlinguistic information" [3], and that relation to "spatial thinking" or "a constructive amalgam of three elements: concepts of space, tools of representation and processes of reasoning" [4]. These different terms are often used interchangeably,

For the purposes of this paper, our team defines SV skills more generally as *spatial intelligence*, a term that contains for us the ideas of spatial visualization and spatial perception, including the activities of mental rotation of objects, spatial relation between objects, and overall spatial orientation [5]. As with mastery of any set of complex skills, doing one type of activity repeatedly does not develop that mastery; instead, a variety of sub-tasks or related tasks will move practitioners towards mastery [5].

Three groupings of research have emerged regarding the development of SV skills in students. First, some studies record group differences, often related to gender; these studies document findings related to particular kinds of SV skills, e.g., 3D mental rotations. The strongest explanation for these differences is dissimilar socialization processes [3, 4, 5]. Second, other findings report that it is possible to reduce or even eliminate these differences through direct instruction [6, 7, 8, 9]. Third, reducing or eliminating these differences or simply enhancing SV skills generally seems to be predictive of student success, typically defined as retention in the STEM fields [6, 8, 10, 11]. There is an important caveat related to the third of these understandings. We did not find in the literature empirical evidence or investigations that describe how students actually use or apply their newly-won SV skills in authentic engineering projects or to solve real engineering problems. While there may be some suggestive correlations that SV skills vary according to socialization, and that these variances can be reduced or eliminated, there is little if any evidence of what that "success" actually entails other than retention at the academic organization.

It was with all three of these understandings and this final important caveat in mind that the Engineering Communications Program (ECP), DPE, the Cornell University Engineering Success (CUES) program, and two Ph.D. graduate students from Biomedical Engineering designed and implemented an innovative active-learning, project-based course to teach Under Represented Minority (URM) and First Generation at College (FGC) students SV skills. Along with improving their SV skills, we were equally (actually more) interested in developing their spatial intelligence as applied to authentic engineering projects.

1 Course Description and Research Methodologies

The cohort of students involved in this first iteration of our SV course were pre-registered based on their invitation to and voluntary enrollment in the Robert L. Ryan Scholars Program (first-year students who have demonstrated potential despite a variety of educational risk factors). These factors include low resourced high school, low socioeconomic status (SES), FGC student, English as a second language, single parent household, and limited access to rigorous advanced placement math and science coursework. In the fall semester, all of the Ryan Scholars (31 students) were pre-registered for the spatial visualization course regardless of their score on the Purdue Spatial Visualization Test (PSVT).

Our SV course was taught weekly for 14 weeks in the fall semester of 2013 at Cornell University. Following the NSF ENGAGE curriculum [13], the first six lectures instilled SV skills, including rotations, reflections, flat-patterns, cutting planes, combining objects, and isometric/orthographic sketching. We used the PSVT to conduct pre- and post-testing of spatial visualization tasks. The pre-test was administered prior to the beginning of the course; the post-test was administered in week 6. Then, the course's second phase consisted of team projects, each with a *client* from Cornell biomedical engineering faculty. Instructors had worked prior to the course with those faculty to frame a visualization request that would extend students' SV skills using the faculty's own cutting-edge engineering research data. These projects were to challenge the students' ability to understand, manipulate, and communicate complex SV concepts by requiring them to create clear and accurate visuals. Final deliverables to faculty included formal team presentations where they were evaluated by their peers, the instructors, and the faculty clients.

As we developed the course, we became very aware of how the term *project-based learning* (PjBL) was typically used and that it held a decidedly different meaning than problem-based learning (PBL), which often includes project-based learning within its framework. Both are, like spatial intelligence, complex: they provide a focus for intellectual inquiry; they eschew a tidy problem statement or any predetermined outcome; they encourage application of knowledge rather than rote learning; they rely on student action and critical thinking; functioning in teams; they encourage hands-on work; and they facilitate learning guided by faculty serving as mentors or guides [14-22].

From the start, we deployed PjBL purposefully, incorporating faculty clients who provided the projects for student teams. Our reasoning and research lead us to believe that having a concrete deliverable was a powerful tool for student engagement at a deep learning level. As such, we purposefully included client meetings and assessment as 2.5% and 5% of the final grade, respectively. We understood well that, while PBL may have some expected or predictable outcomes, PjBLs have no such comforts. Client interaction can bring new and fresh constraints, freedoms, or regulating factors on a team's project. The instructor often will not be able to anticipate a client simply saying "I don't like this team's approach at all," or "Can you do this all again, but this time aim for an audience of 8th graders?" In a sense, the instructors deploying PjBL have to be as agile (or more so) than the student teams working with the client. As PjBL work often does not have a pre-determined outcome or deliverable, clients can (and did) frame the deliverable with their teams variously. Projects were contingent on the client's specific need, and the projects were "real" and "authentic" because the deliverables/artifacts were going to be put into immediate use for biomedical engineering research purposes, in our case. The deliverables were to be a technical report (for academic assessment), a formal presentation where all clients and other stakeholders were present (assessed by clients and instructors alike), and the delivery of the client's requested artifact (poster, demo model, visual, etc.). The artifact needed to meet the specific stated needs of the client (which may differ from the expectations of the instructors) while also meeting the requirements of the academic unit.

We believed that this project-based course design would not only teach students SV skills, but empower them to apply these skills in real engineering contexts, thus enhancing and deepening their knowledge of spatial visualization. Furthermore, we believed that such early application of spatial visualization skills would provide relevant practice for engineering students for future school and engineering work. In addition, immediate examination of the process of applying spatial visualization skills to engineering project work would enable us to understand if and how SV skills specifically and spatial intelligence more generally enhances success in engineering.

In order to study students' development or what "success" might actually entail, we employed two research methodologies. The first was an action research methodology, intentionally creating a new course design that went beyond drill-and-demonstrate. We wanted to deploy active-learning with a project-based pedagogy. We adhered to the standard approach for such action research, i.e., plan, act, observe, and reflect, collecting both quantitative and qualitative in nature. Inputs included PSVT pre- and post-test results, in-class instructor observations, journals, expert feedback on project results, student progress reports, project evaluations, and e-portfolios. We then used our second research methodology, "grounded theory" to code and analyze the data. Combining these two methodologies enabled us to track and learn about students' acquisition of SV skills, the development of spatial intelligence, their application of those skills, and their ability to critically evaluate their own and others' use of spatial intelligence.

2 RESULTS

2.1 Students showed enhanced spatial visualization knowledge after ENGAGE lectures

As noted above, the PSVT was twice administered. Students showed overall improvement after attending the prescribed six one-hour lectures. The mean score increased by 13% in the post-test as compared to the pre-test mean score of 75% (student's t-test, $p<0.05$). Furthermore, the spread in scores decreased, from a range of 35-100% on the pre-test to a range of 53-100% on the post-test, with 26 out of 31 students scoring higher on the post-test than the pre-test, two students with no change, and three students with a 1-question reduction in score.

2.2 Phase 1 of SV Project-Based Learning: Bridging the gap between SV skills and the engineering project

In partnership with Cornell Biomedical Engineering faculty, the graduate student instructors designed four eight-week projects that would deploy student SV skills in a meaningful engineering context. Each faculty "client" provided a set of images and/or data from his or her laboratory's research where a visualization was needed. Clients framed the basics: the information to be communicated via the visual, the target audience, and the nature of the final product (2-D, 3-D, animated, or unspecified). Here, we will present one client project, "Nuclear Squeeze," to show the stages of student team work

"Nuclear Squeeze" was completed for Dr. Jan Lammerding, whose lab studies the mechanical properties of cell nuclei and how those properties are modified in diseased cells. . The Lammerding lab uses high-resolution confocal microscopy, a custom-nanofabricated cellular-level "obstacle course," and fluorescently labeled cells to take images of single cells passing through a constriction, which allows them to observe and quantify the forces that cause a cell's nucleus to deform. Dr.

Lammerding requested a visual of the three-dimensional cell moving and changing shape over time, as it progressed through the obstacle course. The visual must explain to a layperson the movement of the cell and to answer one question, “Does the cell’s nucleus change in *volume* as it moves through the obstacle course?”

Nuclear Squeeze project teams were given a set of two-dimensional, multi-channel confocal microscopy images of the cell in the obstacle course with three distinct components: images of the cell body (green), images of the cell nucleus (blue), and images of the obstacle course (gray) (Figure 1A). The images were taken in “stacks” that could be compiled to create a 3-D picture of the cell (Figure 1B). These stacks were collected at regular intervals to create a full data set describing the 3-D cell’s movement in time (Figure 1C).

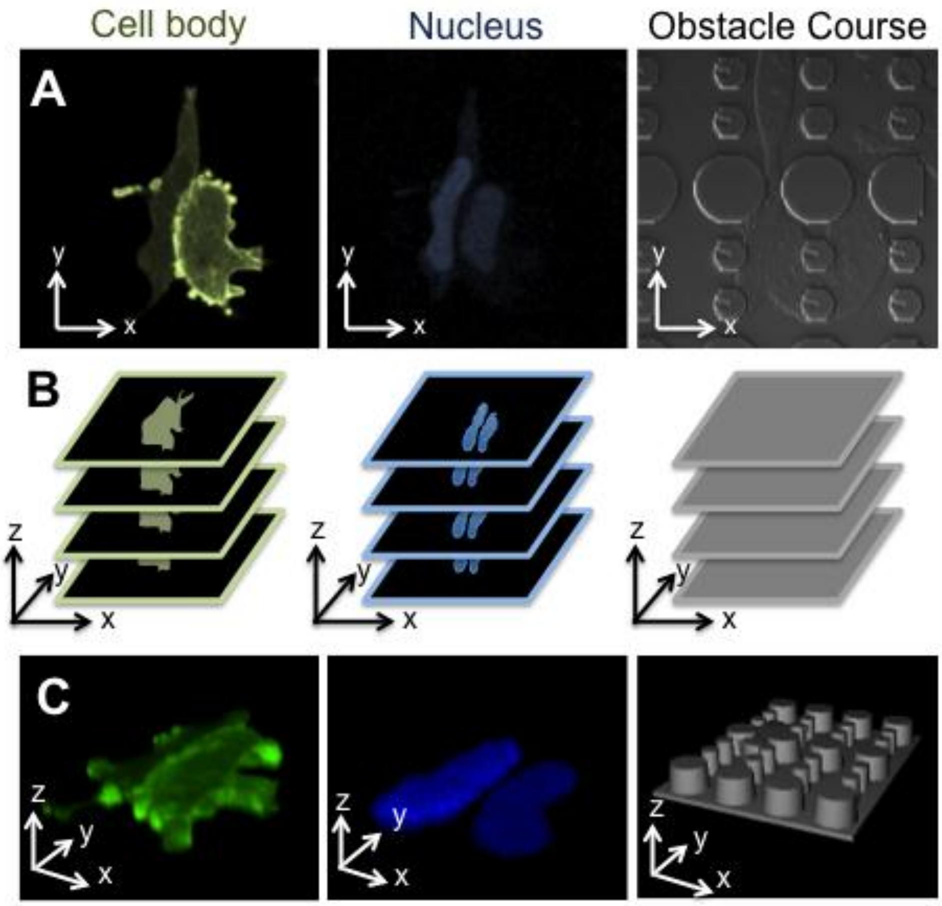

***Figure 1**. SV Project “Nuclear Squeeze” data from faculty client. A) “Top-view” confocal microscopy images were taken of cells moving through a nano-fabricated obstacle course (green: cell body, blue: cell nucleus, gray: obstacle course). B) Sets of images had to be compiled by students into vertical “stacks” of 2-D images that could be rendered into 3-D by using image analysis software. C) These are 3-D renderings of image stacks, visualizing cell body, cell nucleus, and obstacle course.*

To facilitate cognitive connections between lectures and the client project, instructors created a worksheet for each project that connected students’ SV skills to the client requests (see Figure 2). These activities connected the SV skills learned in the course to the Nuclear Squeeze project, initiating students’ application of spatial intelligence/reasoning.

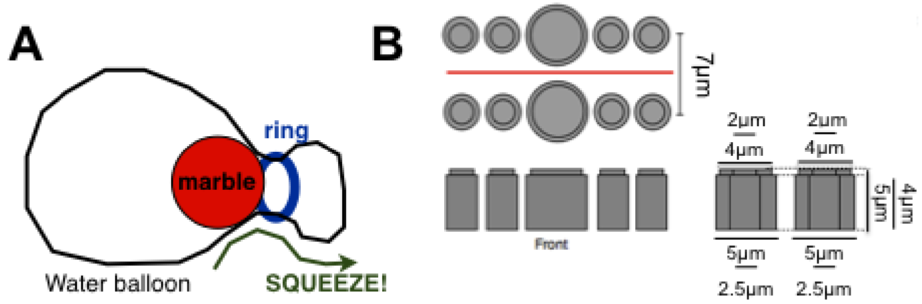

Figure 2. *Partial worksheet for the Nuclear Squeeze project, designed by instructors to bridge the gap between SV lectures and projects. A) Analogy of cell moving through an obstacle course to a water balloon with a marble inside being passed through a ring. B) Orthographic projections of the "obstacle course" used by the Lammerding lab to apply forces to cells. Students had to create isometric drawings of the system and identify axes of symmetry.*

An early launch in the fifth week of the course included teams receiving their client's request and preparing for an initial client meeting Teams created lists of three clarifying and/or extending questions for clients. During this client meeting, students and clients alike gained their footing:

> -- Student: *What do you think you could get out of looking at this in 3D?*
> -- Client: *Let me turn that back to you...Do you gain much by looking at this data in 3-D? Or do you not really gain much by doing this in 3-D versus using the best plane in 2-D?*

Such interactions reveal the hesitancy of students to claim SV proficiencies. Still, they lacked the confidence to deploy their SV skills in a real-world context. Thus, clients played an important role in maintaining the status of the students as SV consultants, by encouraging the students to act as SV experts.

2.3 Phase 2 of SV Project-Based Learning: Students iteratively apply SV knowledge to complete project tasks

Student teams progressed through three general stages of project work (Figure 4), as documented inside their e-portfolios and teacher interactions. First, students strove to understand the data set given to them by their client. Second, students iteratively applied SV skills and technology to develop an appropriate visual. Third, students revealed that visual to their clients and others.

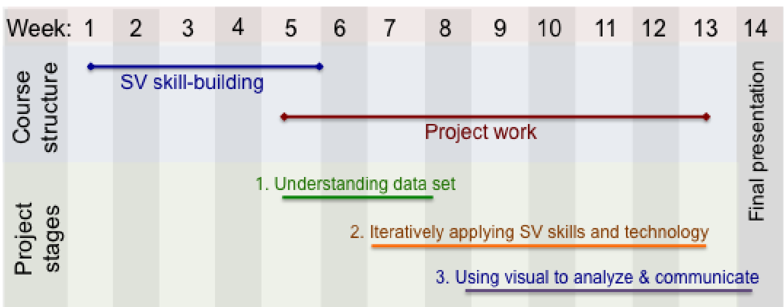

Figure 4. *Skill-building and project-based structure of the course over 14 weeks of instruction (upper). Project work proceeded in three overlapping stages (lower).*

In Stage One, students attempted to grasp the client's data and to create a thorough understanding of the problem at hand. This stage was characterized by student e-portfolio entries such as these:

> -- *[I] Was unfamiliar with the structure of a cell, so I researched info online.*
> -- *By attending the client meeting, now I know what the main goal of the project is as well as a more concrete idea of what to do. [sic]*

Stage Two could happen only once they understood the context of their data set. Then, they iteratively applied SV skills to begin creating visuals. The instructors encouraged and mentored the use of technology, including MATLAB®, ImageJ®, SolidWorks®, and PowerPoint®. Students then connected SV lecture content to real-world applications. For example, students described challenges they overcame in using SV within the image processing software, ImageJ:

-- Had problems with orthogontal [sic] *views in ImageJ. Solved it by changing resolution of image.*
-- Played with imageJ and figured out how to do an animated 3d gif. Also made orthographic images of our data. [sic]

Armed with their developing language and skills, students easily manipulated SV technologies to create 3-D models, 2-D representations, cutting planes, and isometric views of the concepts integral to their client's project. For instance, it was only after the Nuclear Squeeze team had created an isometric view of the images that students began to truly understand the challenge of quantifying a 3-D quantity such as *volume* from a set of 2-D images. Such understanding arose from the authentic SV interaction.

In Stage Three, analysis and communication, students cycled between visual creation, visual analysis, and visual communication, with clarity as the goal. For example, the Nuclear Squeeze students created a beautiful isometric 3-D rendering of the cell moving through the obstacle course over time. However, they found that the isometric view of the whole cell was not sufficient in answering their client's question: "Does the nucleus change in volume over time?" The team revised the visual to answer the question, eventually deciding to employ multiple orthographic views. They wrote:

-- [We] Calculated an estimated volume of cell based on pixel area of top and side view pictures… Figuring out how to find pixel area of irregular shape in photoshop. Found out through online researching. (emphasis added)

Finally, this group used a subset of their different visuals to communicate details of the data set, their approach, and their conclusion. Students made a 3-D CAD of the cell within the obstacle course to facilitate their own understanding and to print a hand-held replica of the obstacle course for their final presentation (Figure 5A). They also used multiple image-rendering functionalities within ImageJ to visualize and assess the data set, including a surface plot of the cell's shape (Figure 5B). Furthermore, the students presented the orthographic views (top and side) of the cell at different time points of its migration through the obstacle course to communicate to their audience how they calculated change in nuclear volume (Figure 5C).

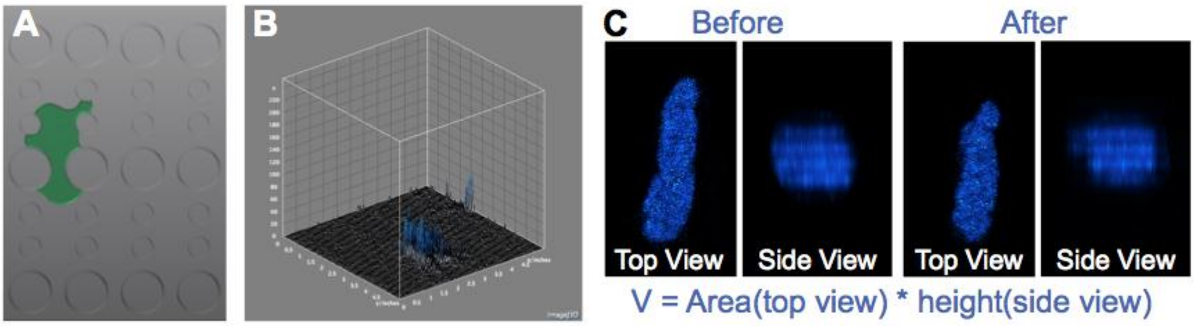

***Figure 4**. Visuals created by students working on the Nuclear Squeeze project. A) CAD drawings of the cell (green) within the obstacle course (gray). B) Surface plot of the cell nucleus (blue). C) Orthographic projections of the cell nucleus viewed from the top and side, with volume calculations.*

2.4 Phase 3 of SV Project-Based Learning: Students act as SV experts, examining and critiquing use of SV in the final projects

Throughout the project, students were able to use their mastery of SV to critically evaluate their own use of visuals in representing and evaluating an engineering concept, documenting progress in e-portfolios.

-- Tried to observe a change in the nucleus by overlaying 3 channels of images, but realized it was too cluttered.
-- [The challenge is] deciding which software would be best suited to our desired task and whether our approach to using the software will be viable throughout all stages of the project. The way to solve this is to keep experimenting.

Their demonstrated insight into the effectiveness of different visualization strategies points to translation of SV skills learned in lecture to the ability to create, interpret, assess, evaluate, and improve visuals of their own creation in real-world engineering contexts.

The course culminated with a formal presentation for peers, instructors, and faculty clients. At the same, students evaluated their peers' projects, specifically for SV prowess (Figure 6). Students identified use of simulations" as praise-worthy SV, indicating that the videos or animations used by their peers facilitated understanding. Students also praised "scaling" to zoom in or out on a feature and the use of vectors to indicate direction, among others. The ability of students to not only use, but to identify and critique the use of these complex strategies in others, is evidence of their ability to deploy SV skills successfully and act as subject matter experts in the use of SV in real-world engineering contexts.

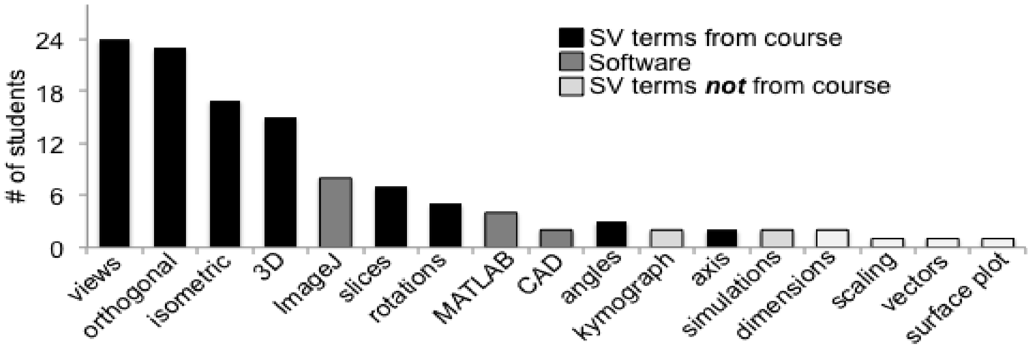

Figure 6. *Frequency of student use of different terms in peer evaluation of SV projects. Note the range of terms not specifically taught but gained*

3 DISCUSSION AND CONCLUSIONS

This spatial visualization course went beyond drill-and-demonstrate methods. Faced with complex research-based data sets, they deployed knowledge of SV to understand the data, examine it, manipulate it and communicate it. Students not only gained basic spatial skills, but they were then able to use those skills successfully and authentically. Unlike many first-year courses, this course did not simply assume students were novices, but instead afforded them with an opportunity to become early experts.

Faculty clients were at the core of the course's success, critically examining and assessing students' ability. An innovation in this course is the direct interaction between first-year students and with high-level engineering researchers (all too rare). This course enabled and encouraged first-year students to work directly with faculty and the community of practice. Faculty provided feedback throughout the course and students gained confidence in their abilities to understand and in turn, engage in intellectual dialogues about current research projects. As a result, students were exposed to engineering beyond the usual first-year mathematics and science courses, and this exposure deepened their interest in engineering, as students sought to learn more and communicated frequently with their faculty clients.

Using e-portfolios, students were encouraged to self-reflect on their progress and challenges throughout the duration of the course. This generative knowledge began to build a mastery of spatial techniques, thus enhancing spatial intelligence. Indeed we might argue that in a preliminary way the above results represent important empirical evidence concerning what spatial intelligence actually involves. Through the acquisition of generative knowledge, students were not only able to understand the data presented to them, but were able to manipulate it, synthesize information and critically examine their use of learned skills in communicating the data. E-portfolio provided instructors with a direct lens to not only examine student progress and challenges, but to also understand the process by which students acquired generative knowledge in the course.

Unlike typical first-year classes, this course empowered spatial mastery through the use of several innovative methods. First, this course went beyond the usual drill-and-demonstrate method by implementing the application of visual skills in current engineering projects. Furthermore, students were not only assumed to be proficient at SV, but they were treated as experienced consultants in their interactions with current engineering faculty clients. Engagement with faculty in discussions about current research built student confidence and deepened the knowledge of engineering and its applications. Throughout the course, students were also able to acquire generative knowledge through self-reflection and the use of E-portfolios, further building a mastery of spatial skills and enhanced spatial intelligence.

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