Empowering Early Mastery of Spatial Visualization Skills in Underrepresented Minority Engineering Students

Olufunmilayo O. Adebayo
Biomedical Engineering, College of Engineering
Cornell University
Ithaca, NY, USA
ooa22@cornell.edu

Emily J. Farrar
Biomedical Engineering, College of Engineering
Cornell University
Ithaca, NY, USA
ejh88@cornell.edu

Traci Nathans-Kelly, Ph.D.
Engineering Communications Program, College of Engineering
Cornell University
Ithaca, NY, USA
nathans-kelly@cornell.edu

Rick Evans, Ph.D.
Engineering Communications Program, College of Engineering
Cornell University
Ithaca, NY, USA
rae27@cornell.edu

Tyi Lindsey McCray, Ph.D.
Diversity Programs in Engineering, College of Engineering
Cornell University
Ithaca, NY, USA
tlm52@cornell.edu

Abstract— Students entering university-level engineering programs must be adept at spatial visualization and reasoning. The Cornell University Engineering Success (CUES) program used the NSF ENGAGE curriculum to introduce spatial visualization basics through an innovative project-based course to a select group of first year students. Students in the course were chosen to participate based on multiple background characteristics that place them at risk and may hinder their persistence in engineering. Course results were strong, with an overall 13% improvement in tested skills. Additionally, our teaching team believed that skills application in authentic spatial visualization projects would provide deeper learning. Student teams worked with biomedical researchers who asked for professional-level visualizations. We employed an action research methodology (observations, instructor journals, expert responses, and e-portfolios), tracking their acquisition of spatial concepts, representations and critical stances. Our hope was to give students a competitive edge, taking advanced visualization techniques and professional skills into future projects.

Keywords— spatial visualization, spatial intelligence, project-based learning, underrepresented minority students, engineering, first-year students.

I. 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. We strive to increase the retention and graduation rate of students underrepresented in higher education, often referred to as underrepresented minority students (URM), and students who are the first in their family to attend college or first generation college students (FGC). More specifically, our goal in the implementation of a grant from the National Science Foundation (NSF) and the Science, Technology, Engineering, and Mathematics Talent Expansion Program (STEP) (award: DUE #1317501) is, by the end of a five year period, to increase the overall graduation rate of URM and FGC students from 66% to 84%. The latter is the overall graduation rate of the engineering student body at Cornell. We recognize that while the overall graduation rate from Cornell Engineering is far above the United States national average (63%), progress could still be made by closing the gap between the graduation rates of URM and
FGC students and those more traditional students. Three interventions are outlined in our grant implementation, including: a tutoring program, a summer math institute and a spatial-visualization course. In this paper, we focus on the third of those interventions of creating, effecting and researching a course to improve the spatial visualization (SV) skills of URM and FGC engineering students at Cornell.

As the range of definitions for “spatial visualization” is wide and varied, we feel compelled to define it here for our purposes. Perhaps the simplest definition is “the ability to mentally manipulate, rotate, twist, or invert pictorially presented stimuli” [1]. However, that simplest of definitions soon becomes more complicated when Voyer et al., [2] redefine it as “the ability to manipulate complex spatial information when several stages are needed to produce the correct solution.” The first definition represents spatial visualization as a kind of mental exercise; the second as a response to a particular problem or project.

Our understanding gets further complicated when we consider the relation of SV skills to “spatial ability” or “representing, transforming, generating and recalling symbolic, nonlinguistic information” [3], and their 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 that can mean different things are often used interchangeably. For the purposes of this paper, we would like to define SV skills more generally as spatial intelligence, a term that we allow to contain 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 you towards mastery. Lieu and Sorby note that “you need to do a variety of tasks to develop your spatial intelligence, just as developing linguistic intelligence requires you to read, write, and listen” [5].

There exists a preponderance of evidence for three understandings in relation to the development of SV skills. First, there are at least some group differences, most specifically related to gender, and then only to particular kinds of SV skills, e.g., 3D mental rotations. The strongest explanation for these differences is dissimilar socialization processes [3-5]. Second, it is possible to reduce or even eliminate these differences through direct instruction [6-9]. 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. Currently, there is little empirical evidence, and even worse, no investigation relating to how students actually use or apply their newly-won SV skills in response to authentic engineering projects or to solve real engineering problems. In other words, while there may be some suggestive correlations that SV skills vary according to socialization, that these variances can be reduced or eliminated, and that such reductions or eliminations can lead to success; 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 URM and FGC students SV skills. While our primary aim was to improve the SV skills of those students, hoping as we suggested above to increase their overall graduation rate; we were equally (actually more) interested in developing their spatial intelligence as well as investigating exactly what that spatial intelligence really means in response to authentic engineering projects or in solving real engineering problems.

II. COURSE DESCRIPTION AND RESEARCH METHODOLOGIES

The cohort of students involved in this first iteration of our SV course, entitled Spatial Visualization/Thinking for Engineers, were pre-registered based on their invitation to and voluntary enrollment in the Robert L. Ryan Scholars Program. Ryan Scholars are entering first-year students (median age: 18) selected based on their demonstrated potential for success in engineering, as determined by Cornell admission, but also based on the existence of a variety of risk factors that have been shown to make persistence in engineering more difficult. 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 preregistered 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. In order to coordinate with the NSF ENGAGE curriculum [13], we designed the first six lectures to instill mastery of 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 students’ ability to perform spatial visualization tasks. The pre-test was administered prior to the beginning of the course. Students then attended the six one-hour lectures, with homework assignments to provide practice and further enhancement of SV skills. The post-test was administered immediately following these lectures. The second part of the course consisted of project work, in which
students were placed in teams. Each student team had a client from Cornell biomedical engineering faculty. Prior to the course and in partnership with the instructors, the clients each developed a visualization request that would employ and extend students’ SV skills. The clients’ requests were designed to challenge the students’ ability to understand, manipulate, and communicate complex SV concepts by requiring them to create clear and accurate visuals from cutting-edge engineering research data, provided by the clients. At the course conclusion, student teams were required to present their visuals in a formal, professional setting, in which the visuals they developed were evaluated by their peers, the instructors, and the 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 outside clients and stakeholders who provided the projects for student teams. Our reasoning and our research led 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 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 in which we quite intentionally created a new design for an SV course, one that instead of relying simply on drill and demonstration to improve SV skills was more focused on active-learning and a project-based pedagogy. We adhered to the standard approach for such action research, i.e., plan, act, observe, and reflect. The data that we collected were both quantitative and qualitative in nature. For example, we used PSVT pre- and post-test results and in-class instructor observations and journals, respectively. However, we also devised ways to generate other, also valuable kinds of data: expert feedback on project results, student progress reports and project evaluations. We even required each of the student teams to create and use an e-portfolio to document their project’s progress, challenges, and goals during each of week of the semester. We then used our second research methodology, “grounded theory” to code and analyze the data. By combining these two methodologies, we feel that we were able to track, and indeed, to learn about students’ acquisition of SV skills and presumably spatial intelligence, their application of those skills and their ability to critically evaluate their own and others’ use of spatial intelligence.

III. RESULTS & DISCUSSION

A. Students showed enhanced spatial visualization knowledge after SV lectures.

Students showed overall improvement in SV test results after attending the six one-hour lectures designed to improve SV skills. 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) (Fig. 1A). 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, 2 students with no change, and 3 students with a 1-question reduction in score. In general, high scorers on the pre-test also scored highly on the post-test, and low scorers on the pre-test generally showed the largest improvement in test score (Fig. 1B).
An initial activity identified a primary practical SV weakness: students did not know how to create visuals (in this case, a 2D drawing) to communicate complex features of a 3D object (Fig. 2). This activity required students to draw a given 3D object, exchange drawings with a peer, and then reconstruct the object drawn by their peer. During the activity, instructors observed students attempting to create a drawing of these features in a number of ways. Some students used labeled “front, back, side” views. Some drew isometric sketches of their object, but failed to capture details that were “hidden” from the perspective they chose (Fig. 2, arrows). Still others used shading, annotations, or distortions (dashed boxes) in their drawing to communicate complex surfaces or details that would be hidden using standard isometric views. The students then exchanged their “visual” with a peer. Uniformly, the students declared themselves unable to recreate the object sketched by their peer’s drawing, revealing to both instructors and the students the need for clear, understandable ways of creating visuals in order to have success in this simple “engineering”

This activity was later compared to student performance in their final project and their ability to create a visual, representing a complex engineering concept, in a manner that could be understood by others. Based on expert feedback from biomedical researchers as well as peer evaluations, each student group was able to successfully create a spatial visual that explained their engineering topic in an understandable way. The student group shown in Fig. 3 transformed 2-D images into a 3-D visual that also communicated change over time (Fig. 3, purple to orange boxes) and successfully interpreted the meaning of their visual within the context of biomedical engineering (Fig. 3, orange to red boxes).

![Fig. 1. Student improvement on PSVT after 6 weeks of SV course](image1.png)

![Fig. 2. Week 1 activity to reveal and evaluate student use of SV](image2.png)
Furthermore, we gathered evidence of SV mastery by asking students to identify SV use in the final project presentations by their peers. Each student was required to observe the project presentations given by their peers (eight presentations total) and to record what he or she felt demonstrated “use of SV” in each presentation. Student responses were compared to instructors’ evaluations of the presentations and judged to be accurate observations of SV, though often described in variable language. The most common student response was *views*, which encompassed student identification of a number of SV ideas, including *3D views*, *multiple views*, and *front/side/back views*. Students also frequently used *orthogonal*, *isometric*, and *3D* to describe SV use in their peers’ presentations. Seven students identified use of *cutting planes* in the presentations, which were also referred to as *slices* or *sections*. The ability of students to accurately identify explicit uses of SV in the presentations of their peers is evidence of their enhanced knowledge of SV skills and language.

Two things struck us as particularly interesting about students’ evaluations of their peers presentations: identification of technology as SV use and identification of SV using language *not taught by instructors*. First, many students identified use of different software programs as a SV technique. Throughout the course, we taught students how to use several software programs to create “visuals” for their faculty clients. These included ImageJ®, an open source image processing platform developed by the NIH, MATLAB®, developed by MathWorks and licensed by Cornell University, and SolidworksTM®, also licensed by Cornell University. Up to eight students identified use of these programs as explicit use of SV, suggesting that students could “read” their peers’ presentations, evaluate what software was used, and identify that software use as inherently a SV technique. This reveals a fascinating “behind the scenes” look at what qualified as “SV” in the minds of our students. Secondly, students also used words that were not explicitly defined as “SV” within the course to describe SV use in their peers’ presentations. These vocabulary items included *kymograph, image stacks, angles, volume calculations, depth, vector geometry, interpolation, simulation, surface plot, multiple dimensions, and scaling*. These words were observed by instructors to arise from work on the SV projects, including dialogue with faculty clients, discussion with instructors, teamwork with peers, and the inherent challenge of their project that extended their application and understanding of SV.

### B. Students applied SV knowledge in an engineering context, iteratively.

While the direct mastery of the spatial visualization knowledge was quite evident in the test scores and student language, the use and application of said knowledge in an engineering context proved more difficult to interpret. Using analysis of student progress reports and instructor journals, we were able to examine the evolution of student SV knowledge throughout the course. First, we observed that students needed to be able to mentally visualize their project’s problem statement before they could begin the process of visual creation. This mental visualization arose either through previous familiarity with the topic, or through analogy with a familiar reference. For example, one student team was tasked with creating a visual of a cell and its nucleus moving through an “obstacle course”. These students used the analogy of a marble (nucleus) within a balloon (the cell) being squeezed through a ring (obstacle course) as an initial mental visualization of the problem (Fig. 4). This group was able to quickly begin applying SV skills to their creation of a visual for their client.

As a counter-example, a separate team of students was asked to create a visual of microglia cells migrating in the brain. These students struggled to find an analogy to this that they could understand, due to lack of background information on the topic and the difficulty of understanding the images provided to them by their client. Progress in this team was slow and they were unable to articulate how they could use SV skills in this context. Eventually, the instructors were able to identify this “road-block” and assist the team in developing an understanding of the microglia in the brain (Fig. 5). After
the students understood the nature of microglia and their role in the human brain, they were immediately able to apply SV skills such as isometric views, cutting planes, and rotations in pursuing their goal of creating a visual that effectively captured microglia movement for their client.

For all student project teams, achieving a solid mental visualization of their given concept preceded their ability to begin meaningful work in visual creation for their projects. Once they understood the context of their visualization project, only then were they able to use assistive visual tools such as MATLAB®, ImageJ®, and SolidWorks® to begin creating their representative visuals. Students were able to use these tools appropriately and in a meaningful way, due to their recent knowledge of spatial visualization. Armed with the language and knowledge of SV terms, students easily manipulated visual tools to create 3D models, 2D representations, frames, cutting planes of objects and isometric views of various objects integral to their engineering concept. This knowledge allowed the students to not only manipulate visual tools, but actually to begin to interpret, examine and further their understanding of their engineering concept. For instance, it was only after the students studying microglia migration had created an isometric view of their data, that they began to truly understand migration of these cells, learning that they needed to account for the shape and density of certain microglia.

Essentially, SV skills not only allowed students to utilize visual tools more appropriately, but also facilitated further understanding of complex engineering concepts. A deeper understanding of these engineering concepts then empowered students to create more appropriate spatial visuals to represent their given topic. This iterative process thus enabled students to not only gain a deeper understanding of engineering concepts through SV knowledge, but also strengthened their use and ultimate creation of appropriate, meaningful visuals to explain these concepts. Furthermore, this cycle empowered students with a level of mastery to then critically analyze their own and others’ visual representations of the engineering concepts.

C. Students gained a level of mastery to critique their own and others’ use of SV.

Throughout the duration of the project, students were able to use their mastery of SV to critically evaluate their use of visuals in explaining their engineering concept. From “trying to decide which software would be best to accomplish [the] task” to discovering that a set of data was missing some images, students were able to expertly debate which visual was most appropriate for their goal of easily explaining their concept to others. For instance, one groups, tasked with the challenge of visually representing the concept of brain machines, started with visual simulations in MATLAB®, before ultimately deciding to simplify the visual by creating a
Students were asked to identify strengths and weaknesses in the final project presentations given by their peers. Interestingly, students often identified higher-order SV uses that were not included in the original ENGAGE curriculum as strengths. For example, one student identified “Good step-wise process” in reference to a team’s use of visuals that captured different points in time to communicate the nature of a complex 3D concept. This was expressed by a different student as, “Nice visual of putting together the images from 2D different times.” This extension of SV skills from multiple dimensions in space to include the time component shows how the project stimulates contextualization of SV reasoning. The ability to create and read visuals that incorporate multiple dimensions across time is an important component of engineering course work and an unexpected benefit of the SV projects.

Students perceived contextualization as critical to the efficacy of the visual presented by each team. Having worked on their own projects to capture and communicate a complex engineering idea by careful combination of SV skills with scientific data, they were highly critical of how well their peers achieved this aim. Students praised projects that were “easy to follow” with “good data backup.” The students could “read” the visuals created by their peers and decide, as experts, whether or not that visual was effective in communicating its technical message. Criticisms most often focused not on the clarity or technical strategy of the visuals used, but on how those visuals were explained within the context of the project.

Students reacted very negatively to presentations that failed to accurately or effectively contextualize their visuals. Criticisms of contextualization included, “They should have given info first and then shown the visual,” and “A little more background to help understand relevance.” The students critically evaluated not just the technical aspects of a visual, but how well it communicated a complex, contextualized engineering concept. It is evident that students attained a level of mastery that enabled them to not only analyze their own use of visuals throughout their project, but also to further inform their understanding of their engineering concepts. Deeper understanding of said concepts then allowed students to delve into examining their use of SV skills, empowering them with the mastery to critically analyze theirs and other’s choices of SV techniques. The use of a project-based course, not only enhanced SV skills but more importantly, enabled mastery of such skills by deepening the practice of SV application within engineering contexts. Students will inevitably be faced with many visuals throughout their engineering careers, and the use and knowledge of SV will be extremely important. This course empowered students with SV tools and challenged them to practice the ways in which they can use those tools to interpret and analyze visuals to aid in their understanding of engineering concepts. The expectation is that the enhanced spatial knowledge gained in this course will be helpful to students in their future educational careers; however examination of this hypothesis should be the subject of future investigations.

IV. CONCLUSIONS

Like other studies, student post-test results and use of language demonstrated evidence of improved SV skills by direct instruction [6-9]. However, the novelty of this project-based course lies in the understanding of how students used SV skills within engineering applications and its implications for success and retention in engineering programs. While there is little doubt about the relevance of SV in engineering contexts, the way in which students applied such skills within their projects reflects a more complicated link than previously hypothesized. Before the process of SV application could begin, students had to first understand or mentally visualize their given engineering concept. This process is extremely important to note, as students are unable to use SV appropriately without first visually grasping the engineering concept. The engineering concept after being “thrown on the mind’s screen” can only then be “observed and manipulated by the mind’s eye” [23]. The process of “observation and manipulation” here can specifically be described as students applying SV knowledge within the context of their projects. Such a process was iterative, as students used their SV skills to not simply create their visuals but also to further inform their understanding of their engineering concepts. Deeper understanding of said concepts then allowed students to delve into examining their use of SV skills, empowering them with the mastery to critically analyze theirs and other’s choices of SV techniques. The use of a project-based course, not only enhanced SV skills but more importantly, enabled mastery of such skills by deepening the practice of SV application within engineering contexts. Students will inevitably be faced with many visuals throughout their engineering careers, and the use and knowledge of SV will be extremely important. This course empowered students with SV tools and challenged them to practice the ways in which they can use those tools to interpret and analyze visuals to aid in their understanding of engineering concepts. The expectation is that the enhanced spatial knowledge gained in this course will be helpful to students in their future educational careers; however examination of this hypothesis should be the subject of future investigations.

ACKNOWLEDGMENT

Our team thanks NSF and it continued support through its ENGAGE programs. As well, we thank Cornell University and the Office of Diversity Programs in Engineering.

REFERENCES


