Introduction to Neural Engineering: Design and Development of a BME-in-practice Course through the BME Instructional Incubator

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Abstract

The Biomedical Engineering (BME) Instructional Incubator is a department-level collaborative effort bringing together BME students (undergraduate and graduate), postdoctoral fellows, and faculty to create hands-on student learning experiences responsive to the rapidly changing field of BME. The Incubator engages participants in the instructional design process and utilizes student learning theory to develop curricula that can be implemented in one-credit, second-year BME-in-practice courses.

One such course was Introduction to Neural Engineering. This course was designed to provide students with a broad overview of neural engineering as a field. Introduction to Neural Engineering is an introductory learning experience intended for students interested in the brain, particularly the intersection of technology and the nervous system, as well as those interested in developing technical skills related to programming and computational modeling.

Introduction to Neural Engineering was developed with BME students first in mind. Through interviews with current students and a variety of BME stakeholders (e.g., medical device company representatives, graduate and medical school representatives), it was determined that

this course should provide value to students by teaching them various tradable skills relevant to work performed in a realistic setting, such as reading and interpretation of research articles, MATLAB programming, and COMSOL finite element modeling.

What sets Introduction to Neural Engineering apart from other courses in the BME curriculum at our institution is its firm grounding in constructivism and situated learning. Inquiry- and experiential learning-informed problem sets scaffold students during instructor-facilitated lab sessions to enable them to learn alongside one another. Active pedagogical practices of engagement also influence in-class activities. Ample time is allocated to provide students with locus of control opportunities, where they are able to tinker with algorithms that process neural data sets in meaningful ways. Students are able to apply knowledge obtained from lecture sessions by solving complex problems using real neural data (acquired from animals and humans), creating clinically informed models, and navigating ethical quandaries specific to neural engineering. Students are encouraged and expected to develop cooperative learning skills and attitudes through extensive group work. Course effectiveness will be assessed throughout the semester through pre- and post-course surveys, student reflections, and teaching evaluations.

As neural engineering continues to grow in scientific output, media representation, and social popularity, it becomes even more important to expose students early on to an academic path towards a career in this field. By the end of Introduction to Neural Engineering, students will be able to identify research and work opportunities available in the field as well as be comfortable performing basic experiments using fundamental neural engineering techniques. These outcomes will help students determine if they wish to pursue a curricular focus and/or career in neural engineering.

Introduction

In the Fall 2017 semester, the Biomedical Engineering (BME) Instructional Incubator was launched to bring together upper level BME undergraduates, graduate students, postdoctoral fellows, and faculty to create instructional change and develop a departmental community of practice committed to forward thinking BME education. The Incubator stemmed from the need to address department-wide calls to integrate more experiential learning opportunities offering BME students exposure to alternative postgraduate opportunities into the BME curriculum.

The Incubator was designed to create one-credit experiential learning courses for second-year BME students to expose them to BME practice and help facilitate their interdisciplinary learning. Incubator participants engaged in the instructional design process to create short courses responsive to the the current technological needs of the practicing BME community. The Incubator was informed by learning theory and addressed student learning theory and curriculum design best practices. Through the Incubator, participants actively engaged in curriculum design and learned about student learning (e.g., situated learning theory, social constructivist learning theory, pedagogical content knowledge, metacognition, active learning). As a result of the Incubator, participants experienced the curriculum design process using evidence-based best practices. Concurrently, the Incubator offered iterative design to BME curricula responsive to current workforce trends.

BME Instructional Incubator (Fall 2017)

The Incubator met two times per week (Tuesdays and Thursdays) for 15 weeks. Tuesdays were dedicated to the instructional design process, while Thursdays were dedicated to exploring student learning theory, pedagogy, and best practices. Instructional design encouraged Incubator participants to focus curriculum development on the needs of the student. While different variants of instructional design exist, there were five specific activities consistent across variations[1]: 1) analysis of the setting and learner needs; 2) design of a set of specifications for an effective, efficient, and relevant learner environment; 3) development of all learner and management materials; 4) implementation of instructional strategies; and 5) evaluation of the results and development both formatively and summatively. The Fall 2017 semester was dedicated to activities 1-3. Participants worked as a collective to analyze setting and learner needs and design specifications. Based on their own personal interests, participants self-assembled into teams of two to three students with postdoctoral fellow mentors to develop one-credit courses as well as all of the learner and management materials meeting the specifications designed in activity 2.

1) Analysis of Setting and Learner Needs

Instructional Discovery. Incubator participants analyzed setting and learner needs by conducting instructional discovery through in-depth interviews with second-year BME students, stakeholders, and faculty. Participants also conducted master class observations, where they observed other instructors teaching in the classroom to identify effective teaching strategies, use of technology, and student engagement strategies.

Learning Theory and Active Pedagogical Approaches. One goal of the Incubator was to bring about education transformation through the integration of research-based best teaching practices grounded in student learning. Incubator participants explored learning theories and active pedagogical approaches. Learning theories included cognitive (e.g., student misconceptions, mental models, idea development), metacognitive (e.g., reflective exercises), constructivist (e.g., student-led learning), social constructivist (e.g., student-student interactions), and situated (e.g., student participation, class culture) theories[2-5]. Active pedagogical approaches included collaborative and cooperative learning, problem- and project-based learning, and discourse and discussion[6-11].

2) Design of Specifications

Based on student and stakeholder interviews and classroom observations, Incubator participants identified and designed specifications for an effective, efficient, and relevant learner environment for second-year BME students.

3) Development of Learner and Management Materials

Learner and management materials were the final deliverable for the Incubator. Student teams were required to create an instructor guide as well as all of the course content (e.g., lectures, labs, reading materials, assignments). The instructor guide was intended to be an all-inclusive document that others could use to teach the course elsewhere. Incubator participants were instructed to include specific guidance on how to execute the course using evidence-based practices and how those practices were based on an understanding of student learning.

4) Implementation of Instructional Strategies

Student teams were given the opportunity to launch their course the following semester (Winter 2018). The one-credit courses were scheduled for four weeks, meeting six hours per week. Teams were responsible for executing and teaching their course, with mentorship from the postdoctoral fellow mentors and the Incubator instructor (AHS).

5) Evaluation of Results and Development

Pre- and post-course surveys and student reflection prompts were created to assess course learning objectives and iteratively improve upon the course in subsequent semesters. These materials were later administered to students enrolled in the course as well as postdoctoral fellow and faculty mentors.

Results

Twenty-three people participated in the Fall 2017 Incubator (19 students, three postdoctoral fellows, and one lecturer). Six courses in total were created. While all six student teams had a desire to launch their course, scheduling conflicts limited the initial launch to three courses, one of which was Introduction to Neural Engineering.

Student and Stakeholder Interviews

Incubator participants interviewed 23 second-year BME students and developed prototypical archetypes representative of typical second-year BME students. Based on the interviews, students have a strong interest and ability in science and mathematics. They found their first-year courses (e.g., mathematics, physics, chemistry, and biology) challenging, but manageable. Despite favoring courses that are quantitative in nature, students were able to adapt well to courses in the biological sciences, which tended to require more rote memorization.

Students' motivation for learning stemmed from their desire to benefit the health and well-being of people. They were naturally competitive and wanted to be successful in all of their courses. Students were genuinely interested in the material that they learned during their first year. However, exactly how that newfound knowledge could be applied in the context of BME remained unclear. They were excited to take actual BME courses during their second year and hoped that the courses would be more hands-on compared to their first-year courses, which mostly employed the traditional lecture approach. In the current BME curriculum, students noticed that the second-year courses listed in the sample schedule were all required. Consequently, there was little flexibility for them to add any non-required classes to their schedule unless they wanted to risk overloading themselves. Students had expressed interest in taking some non-required classes (e.g., business, entrepreneurship), but they did not want their grades in their BME courses to suffer as a result of them having less time to spend on those courses. Some of them noted that they had an issue with the breadth of required classes because they would have preferred to focus on their specific interests.

Students were aware that BMEs have a wide range of job opportunities after earning their bachelor's degree. They also knew that, in general, there were three major career paths that they could take after graduating: 1) graduate school to pursue an MS or PhD; 2) professional school to pursue an MD, DDS, or JD; or 3) industry. Students were in the process of determining their future career plans and wanted research and internship experiences to help them narrow down the possibilities. They were just starting to get to know professors in the department and their research areas. Students hoped that doing this would help them choose a concentration area (e.g., biomechanics, bioelectricity, biomaterials) that best aligned with their interests.

Twenty stakeholder interviews were conducted. Based on these interviews, technical skills looked for in BME students included analytical and quantitative problem solving, computer literacy, statistics, experimental design, root cause analysis, product development, and regulatory body requirements. Soft skills looked for in students included the ability to work collaboratively in a team environment and effectively with people at all levels in an organization, the ability to communicate complex ideas effectively and confidently (verbally and in writing), a strong record of leadership in an academic, professional, or extracurricular setting (leading through influence), and the ability to understand and relate to people. Compared to technical skills, soft skills were considered to be equally, if not more, valuable. Stakeholders strongly recommended that students emphasize interactions with others.

Regarding internships, student expectations mostly involved soft skills (e.g., professionalism, time management, problem solving). However, technical skills like MATLAB were commonly required. Some of the students interviewed noted that they still had limited MATLAB experience after their first year, despite taking a required introductory MATLAB programming class. Statistical knowledge, including software (e.g., Minitab, JMP, R), is not necessarily required, but would give students a competitive edge when applying. BME students are often viewed by stakeholders as "jacks of all trades" because they have a broad understanding of a variety of topics. The students interviewed echoed this concern. Both stakeholders and students believe that further specialization in a specific area would be beneficial.

Curriculum and Master Class Observations

At our institution, BME students usually choose a concentration area to specialize in near the end of their second year, which they will focus on for the majority of their fourth year. A common concern among the students interviewed was a lack of familiarity with what each concentration was about. Most students agreed that second-year courses exploring each concentration would address this concern and help them make a more informed choice.

Based on the current BME curriculum, it was found that the BME department did not offer any type of undergraduate-level course directly related to neural engineering. There was one graduate-level neural engineering course, which was permanently designated only last year. Fourth-year students were able to take this course with instructor approval. Regarding the bioelectrical concentration, which neural engineering falls under, it was found that students are formally exposed to topics such as electrical conduction in excitable tissue, quantitative models for nerve and muscle, biopotential mapping, and functional electrical stimulation during their fourth year only if they opted to take the department's non-required electrical biophysics course. There was no formal coordination between this electrical biophysics course and any neural engineering-related courses within or outside of the department.

Despite recent growth and development in our department's neural engineering research, an emphasis on neural engineering education lags behind that of other similar institutions. For example, one institution reviewed had a formal neural engineering concentration with multiple neural engineering-related course options for both undergraduates and graduate students.

Nineteen lecture, discussion, or lab sessions from different BME courses taught at our institution were observed to gain insight into how instructors effectively teach and engage students in the classroom. Based on the master class observations, most classes followed the traditional lecture format (i.e., the instructor talks and writes on the board). Instructors often started class with a brief review of the material covered in the previous class before moving onto the next topic. They showed evidence of lesson planning, as made evident by handwritten notes and/or explicitly stated goals for the class. When teaching, some instructors used slides, while others opted to write everything on the board. Instructors often solicited student input and encouraged critical thinking through in-class questions related to different topics throughout the class. However, not all instructors utilized active learning approaches (e.g., small-group activities).

There were a few things that instructors did that worked particularly well during class. For example, some instructors gave historical context to the material as it was introduced. Others incorporated humor related to the material into their lectures, which students seemed to appreciate. When students had questions, most instructors were willing to pause to answer their questions in full. Regarding student attention, instructors tended to lose it after about the first hour of class. However, they were usually able to regain attention through combinations of in-class questions and breaks.

Student Learning Theory-informed Design

Knowledge gained from the literature was integrated into the course design, specifically, the lectures, labs, and problem sets. For example, inquiry- and experiential learning-informed problem sets were designed to scaffold students during instructor-facilitated lab sessions to enable them to learn alongside one another. Ample time was allocated to provide students with locus of control opportunities, where they are able to tinker with algorithms that process neural data sets in meaningful ways.

Learning Objectives and Student Skills

Student interviews indicated that second-year BME students are seeking hands-on classes that offer them technical skills in the context of practical BME problem solving as well as further clarification regarding the different concentration areas. At the same time, BME stakeholders are looking for BME students who are natural problem solvers possessing experience with common engineering software tools (e.g., MATLAB) and some specialization in a specific area. As a result of these student and stakeholder needs, Introduction to Neural Engineering was developed to expose students to relevant BME skills in the context of neural engineering. The learning objectives were as follows: students will be able to: 1) interpret the neural engineering literature on a basic level; 2) organize and manipulate large neural data sets; 3) solve and troubleshoot complex neural engineering problems; and 4) translate neural engineering models to clinical applications. These learning objectives were also aligned with the most recent ABET criteria for BME (www.abet.org).

Achieving the above learning objectives would provide students with skills and knowledge desirable for a student to develop early on in their neural engineering (or BME in general) career, such as: 1) reading and interpreting research articles; 2) understanding basic neuroscience and electrophysiology; 3) applying basic signal processing techniques; 4) applying basic modeling techniques; 5) programming with MATLAB; 6) interpreting COMSOL finite element modeling and analysis; and 7) collaborating in teams.

These specific skills were chosen because they are all relevant to work performed by neural engineers in practice, whether it be in a research or industrial setting. BME stakeholders seeking BME students for research experiences or internships will likely appreciate their larger knowledge base with respect to neuroscience and electrophysiology, as well as their experience with common engineering and modeling software programs.

Course Description, Format, and Schedule

The field of neural engineering has recently garnered much popular interest courtesy of tech startups and entrepreneurs (e.g., Neuralink and Elon Musk). Many students think neural engineering is interesting, but they do not know what it is really about or how to get involved. Introduction to Neural Engineering was designed to serve as a launching point for such students.

The course provides students with a broad overview of neural engineering as a field (e.g., what it is, what it is not, what has been accomplished in the past 50 years, what is coming up in the near future). Students rapidly engage in real-world neural engineering problems and topics relevant to modern research and medicine. Topics to be covered include basic neurophysiology and neural interfacing, neural signal processing, volume conductor theory and finite element modeling, and neuroethics.

Introduction to Neural Engineering applies programming and modeling techniques to real-world problems and applications, showcases specialized content within the field, facilitates student exposure to relevant academic, medical, and industrial careers, and caters to popular interest. The course offers a specific set of experiences that align with what students want to see in their courses. Upon completion of Introduction to Neural Engineering, students should understand the different types of research and work opportunities available in the field, and be comfortable with relevant technical skills such that they will be able to determine whether or not they would like to pursue a curricular focus and/or career in neural engineering.

The course was designed for a four-week period during the Winter 2018 semester (Table 1). Each week consists of two lectures and one lab session. Each lecture focuses on a specific neural engineering topic, which students actively explore through in-class group problems (i.e., problem based learning) and discussions. Each lab builds upon the previous lectures by having students "learn by doing." Specifically, students learn how to analyze and build neural data sets and computational models describing neural function and behavior using MATLAB and COMSOL, two common engineering software tools. Perusall (www.perusall.com), a collaborative e-book reader, is also used to further engage students in understanding real-world neural engineering practice. Research articles from the neural engineering literature are assigned as readings for students through the Perusall platform to expose them to scientific writing and interpretation of figures and data in preparation for future academic and professional activity. Thought-provoking questions are provided for each reading to facilitate discussions between students and instructors that can carry over to the classroom.

Table 1: Introduction to Neural Engineering Winter 2018 Course Schedule

Date	**Class**	**Topic and Assignment**	**Assignment Due**
Thu, 1/4	Lec 1	Course overview. Overview of neuroscience, basic neurophysiology, neuroanatomy, and neural imaging and signal modalities. Overview of neural engineering as a field. How to read a scientific paper. *Reading 1 assigned*	n/a
Mon, 1/8	Lec 2	Neurons and how they communicate. Neural recording and stimulation models, implantable electronics, deep brain stimulation *Reading 2 assigned*	Reading Assignment 1 (Buzsaki 2012)
Wed, 1/10	Lec 3	GHK and HH models. Ordinary differential equations and how to solve them numerically. Matlab software.	n/a
Thu, 1/11	Lab 1	Programming in Matlab. Begin computational components of Problem Set 1 in class. Model neuron signaling behavior in Matlab. *Problem Set 1 and Reading 3 assigned*	Reading Assignment 2 (Mainen 1995)
Wed, 1/17	Lec 4	Neural signal processing. *Problem Set 2 assigned.*	Problem Set 1
Thu, 1/18	Lab 2	Begin computational components of Problem Set 2 in class. Model small neural networks and analyze real neural data sets in Matlab. *Reading 4 assigned*	Reading Assignment 3 (Irwin 2017)
Mon, 1/22	Lec 5	Volume conductors, finite element modeling in COMSOL. *Problem Set 3 assigned*	Problem Set 2
Wed, 1/24	Lec 6	History and future of neural engineering in research and medicine.	n/a
Thu, 1/25	Lab 3	Finite element modeling in COMSOL. Begin Problem Set 3 in class. Simple model. *Reading 5 assigned*	Reading Assignment 4 (Malaga 2015)
Mon, 1/29	Lec 7	Patient-specific tissue activation modeling in deep brain stimulation. *Problem Set 4 assigned*	Problem Set 3
Wed, 1/31	Lec 8	UM Neural Engineering professor visit, discussion, and Q&A panel. Neuroethics.	n/a
Thu, 2/1	Lab 4	Course wrap-up. Begin Problem Set 4 in class. Model deep brain stimulation probe and electrical activity during stimulation. More complex model.	Reading Assignment 5 (McIntyre 2013)
Tue, 2/6	n/a	n/a	Problem Set 4, Group Reflection, Course Evaluation

Lectures were designed to emphasize the students' active exploration of neural engineering as a field through in-class problem solving sessions and discussions. For example, during Lecture 8, neural engineering faculty participated in a panel so students could learn about different areas of neural engineering research, as well as discuss various ethical considerations regarding the use of emerging neural engineering technology.

Labs were designed to familiarize students with common engineering and modeling software programs (e.g., MATLAB, COMSOL) by having them use these programs to build and interact with data sets and computational models describing neural function and behavior. For example, Lab 4 involved the development of a patient-specific tissue activation model for deep brain stimulation applications (e.g., treatment of Parkinson disease). In this lab, students were walked through the process of creating three-dimensional finite element models incorporating patient-specific anatomy, tissue electrical properties, and stimulation parameters, which they used to estimate the amount of brain tissue affected by stimulation (Figure 1).

A) B)

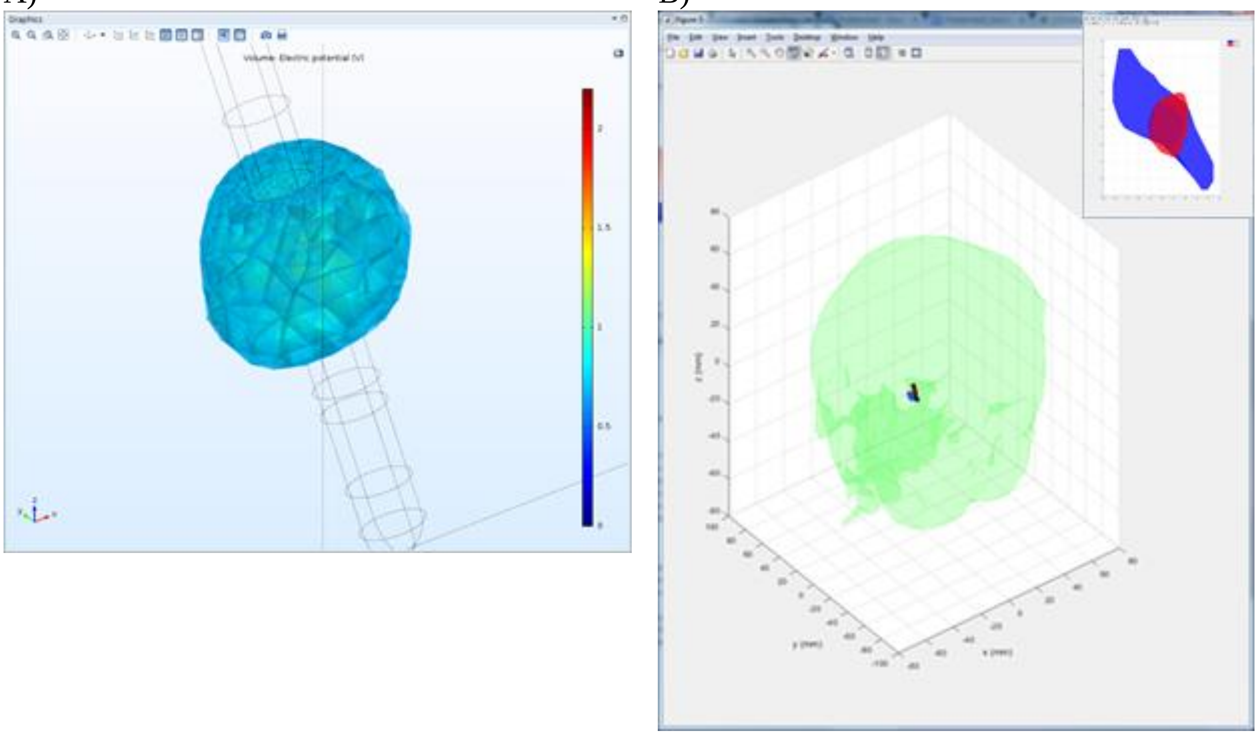
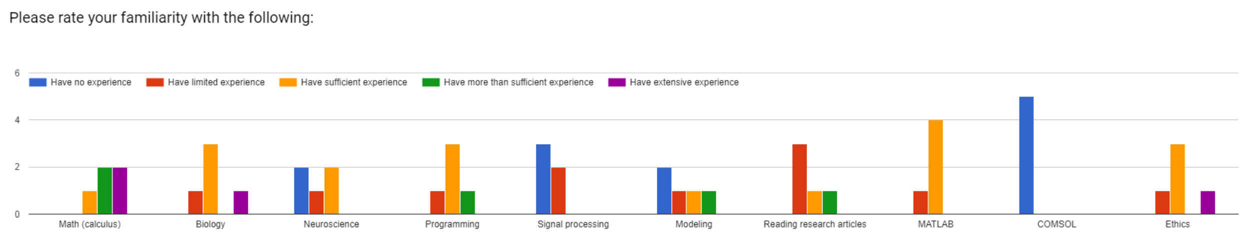


Figure 1: Lab 4 - Patient-specific tissue activation modeling in deep brain stimulation (DBS). A) COMSOL plot of the volume of tissue activated (shown in blue) by DBS. A wireframe rendering of the DBS lead is also shown. B) MATLAB plot of the volume of tissue activated (shown in red) by DBS. Anatomical models of the head and subthalamic nucleus (the DBS target) are also shown in green and blue, respectively, as well as the DBS electrodes (shown as black squares).

Pre- and Post-course Surveys

During the writing of this manuscript, the first offering of Introduction to Neural Engineering was completed. From an initial poll, the number of undergraduates interested in enrolling in the course was 19. However, course scheduling conflicts precluded all of them from enrolling in this first offering. Ultimately, five students officially enrolled in the course (three second-year and two first-year). Upon enrollment, pre-course surveys were administered to assess what students were hoping to gain from the course and their familiarity with different topics to be covered in the course (e.g., basic neuroscience, MATLAB programming, reading research articles) (Figure 2A). A common motivating factor among the students for enrolling in the course was a genuine interest in learning about what neural engineering entails (e.g., "The topic sounded extremely interesting and I figured that I could gain some hands-on experience on what BMEs do in industry," "I'm interested in the topics offered and I want to learn about them before I normally would in my education."). All students mentioned that they hoped the course would help them narrow down their academic options in some manner (e.g., "It will possibly help me decide what concentration to choose and what I would like to pursue with my degree," "It will help me determine what major I pursue (BME or something else, possibly comp sci) and introduce me to a topic that I may pursue further if I find it interesting and fun.").

A)



B)

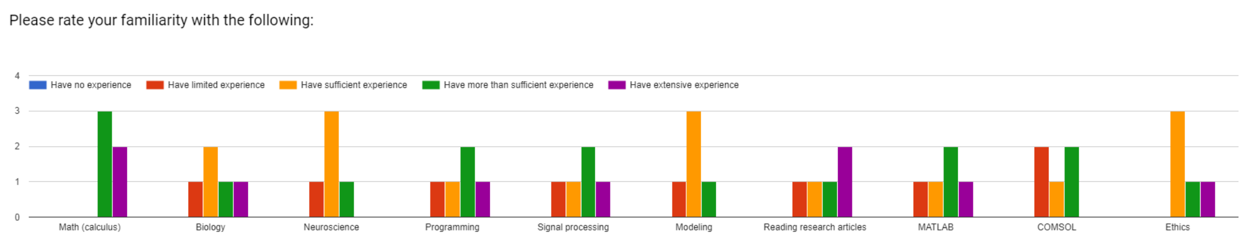


Figure 2: Student familiarity with different topics covered in Introduction to Neural Engineering at the A) start and B) end of the course.

At the end of the course, post-course surveys were administered to assess if the students' expectations for the course were met and what they gained from the course. All students reported that their expectations were met. For example, one student remarked that:

> "I think I my expectations were met because I learned a lot more about MATLAB, which I did not have much exposure to outside of Engineering 101 and Calc IV, which took in fall semester of freshman year. I think COMSOL was a delightful experience because I felt like I was actually doing engineering stuffs that I would never be able to do in other classes. I also like that I got to know a lot of biomedical engineering faculty and graduate students, who gave me useful advice throughout the course,"

while others commented that:

> "I believe that I gained a comprehensive introduction to the field of neural engineering. After completing the course, I can confidently say that I have conducted some cutting edge computational modeling, and that's pretty cool. I was also able to get a glimpse of what BMEs do after graduation through the BME faculty panel. Through them, I was able to learn about the other cutting edge research that is occurring in the world of neural engineering,"

and

> "My expectations were far exceeded. The class was engaging and I got a great introductory experience to COMSOL."

Regarding what the students gained from the course, most of them reported gaining skills in using MATLAB and COMSOL as well as a better understanding of neural engineering as a field (e.g., "The ability to interpret graphs in research papers, solid MATLAB, and basic COMSOL skills. I also learned a lot about the career path for neural engineering," "A much broader understanding of neural engineering and neural engineering techniques; basic understanding and comfort using COMSOL to model specific physics; and more comfort using MATLAB in general as well as specifically to filter and analyze data," and "An idea of what possible BME career paths are within the field of neural engineering."). One student specifically noted that:

> "I definitely will need a lot of MATLAB in the future so this class really helps me to get faster writing my code, plotting, and looking for things I don't know about. I also think COMSOL is a helpful tool to solve finite element analysis. As I am thinking of it, I still feel it was surreal that I got to know this cool application and practice it in my sophomore year. I hope to have more practice with it in the future. I think with better MATLAB and COMSOL skills, I can be more assured that I am actually understanding things and able to intern at research labs or in industry."

At the end of the course, the same skills survey administered at the start of the course was given to assess how the students' familiarity with the different topics covered in the course changed (Figure 2B).

Conclusions

Introduction to Neural Engineering is a new one-credit experiential learning course for second-year BME students designed and developed by participants of the BME Instructional Incubator. This course was created using engineering design principles, as informed by evidence-based instructional practices and student learning principles, and is part of a recent departmental initiative focused on creating meaningful and engaging student learning experiences in BME education to address the dynamic landscape of BME practice.

A combination of student and stakeholder interviews, curricula assessments, and classroom observations allowed Incubator participants to identify critical skills and best instructional approaches for effective student engagement to incorporate into the course. Course content, exercises, and assignments were also influenced by these different sources of information. Preliminary results from pre-and post-course surveys administered to the enrolled students indicated that all of them gained a variety of tradable skills relevant to work performed in a realistic setting as well as a better understanding of neural engineering as a field and the opportunities within it. Students also commented on how engaging the course was and how it stood apart from all of the other courses that they had taken up to this point in their education.

Before the launch of this course, BME undergraduates were not exposed to neural engineering until relatively late into their academic career. Early exposure to neural engineering topics in the second year will help students prepare for future courses within the bioelectrical concentration and potentially reveal new career paths. The principal aim of Introduction to Neural Engineering is to add quality content to the current BME curriculum as well as promote the BME program to undergraduates by providing unique course content that highlights the growing departmental research in neural engineering through engaged learning.

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