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Article

Investigating Students' Learning Experiences in a Neural Engineering Integrated STEM High School Curriculum

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Abstract: STEM integration has become a national and international priority, but our understanding of student learning experiences in integrated STEM courses, especially those that integrate life sciences and engineering design, is limited. Our team has designed a new high school curriculum unit that focuses on neural engineering, an emerging interdisciplinary field that brings together neuroscience, technology, and engineering. Through the implementation of the unit in a high school engineering design course, we asked how incorporating life sciences into an engineering course supported student learning and what challenges were experienced by the students and their teacher. To address these questions, we conducted an exploratory case study consisting of a student focus group, an interview with the teacher, and analysis of student journals. Our analysis suggests that students were highly engaged by the authentic and collaborative engineering design process, helping solidify their self-efficacy and interest in engineering design. We also identified some challenges, such as students' lower interest in life sciences compared to engineering design and the teacher lacking a life sciences background. These preliminary findings suggest that neural engineering can provide an effective context to the integration of life sciences and engineering design but more scaffolding and teacher support is needed for full integration.

Keywords: integrated STEM curriculum; neural engineering; integrated life sciences and engineering unit; learning experiences; learning challenges

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1. Introduction

The problems facing science and society nowadays, from global warming to vaccine development, require the integration of knowledge and skills across science, technology, engineering, and math (STEM) disciplines [1]. However, the long-established compartmentalization of disciplinary knowledge and skills in K-12 and higher education does not reflect the inherent interconnectedness of real-world STEM research [2]. On this basis, integrated STEM education has become a national and international priority in the last decade [3,4].

The shift towards a more integrated conceptualization of STEM requires new approaches where learning is contextualized in real-world issues to promote scientific and technological literacy [5–7]. Even though there is still lack of consensus surrounding how integrated STEM should be conceptualized and put into practice [8–10], there seems to be agreement on four main characteristics of integrated STEM education: (1) presence of at least two disciplines; (2) inclusion of authentic real-world problems; (3) fostering 21st century skills (e.g., critical thinking, communication, collaboration); and (4) promoting student awareness of STEM careers [3,9–12]. Other common characteristics include integration of (1) learner-centered pedagogies [13,14]; (2) engineering design [12,15]; and (3) authentic STEM practices [16,17].

Despite the growing body of research on the characteristics of integrated STEM, the literature is still lacking a detailed operationalization that can guide the design, implementation, and evaluation of integrated STEM in K-12 contexts [12,18] and additional research is needed to understand students' learning experiences and outcomes in integrated STEM courses, specifically in courses that integrate science and engineering [9,12].

2. Literature Review

Research on learning outcomes in integrated STEM education has not yet yielded a consistent picture, as outcomes seem to vary based on the type of integration (e.g., which disciplines are integrated) and the context (e.g., in-school vs. out-of-school programs) [1,19]. For example, in their meta-analysis of 28 empirical studies, Becker and Park [20] examined the effect of the integrative approaches among STEM subjects, in which they calculated the effect size (ES) as the difference between the experimental and control group. While the integration of all four STEM disciplines was associated with a large effect size ($ES = 0.8$), the integration of mathematics and engineering was represented by a very small effect size ($ES = 0.2$) [20]. Some studies reported that integrated STEM activities lead to better mathematics and science learning outcomes compared to non-integrated instruction [21], but other studies suggested no difference [22,23]. Despite the effect of integrated STEM on learning being mixed, there is evidence that integrated STEM activities can facilitate the development of students' interest in STEM and STEM careers [24–26]. It is believed that integrated STEM is more student-centered and can provide more relevant and interesting learning experiences for students [27,28] through which students' interest in STEM careers and STEM learning can be fostered [29]. However, most of this research was conducted in out-of-school, rather than in-school settings.

Within the integrated STEM education literature, there is a gap in our understanding of how engineering design and life sciences can be effectively integrated [18] (see Section 2.2). Roehrig and colleagues recognize that biomedical engineering has the potential to bridge this gap [18]. However, the level of knowledge and skills needed in biomedical engineering courses might exceed the K-12 level. Additionally, these courses typically require technologies that are not commonly found and used in K-12 classrooms [30]. Here, we illuminate a possible pathway for the integration of life sciences and engineering through neural engineering.

Neural engineering is an emerging interdisciplinary field that blends together neuroscience, engineering, and technology. It aims to design technological solutions to improve the life quality of people with neurological conditions, such as stroke, spinal cord injury, and traumatic brain injury, which are estimated to affect roughly one in six of the world's population [31]. Thus, directly or indirectly, many students are likely exposed to or affected by neurological disorders, indicating the problem's personal relevance and societal needs for these technological solutions [32].

In the last decade, there have been exciting breakthroughs in neural engineering technology, such as the development of brain-machine interfaces. For example, using this technology, patients with paralysis can now control robotic arms simply by thinking about moving their own arm [32]. With low-cost tools, such as Arduino and bioamplifiers [33], students can be introduced to neural engineering technology and engage in engineering design that is closely integrated with the life sciences.

2.1. Theoretical Framework

Our work is grounded in social constructivism, the process of constructing knowledge through social interactions [34–36]. When learners work together in small groups, they engage in distributed cognition: they spread the learning task across individuals and can build on various knowledge bases and ideas and expand their working memory capacity as a group [37]. Small group work allows learners to clarify and organize their ideas, elaborate on what they have learned, be exposed to other views, discover inconsistencies in their own thinking, and develop their reasoning and argumentation skills [38]. Through this process learners can also develop a more sophisticated view of the nature of knowledge, realizing that knowledge is likely to evolve over time [39]. In line with the social constructivist view, prior research suggests that small group learning in STEM is associated with positive learning outcomes, motivation, persistence, and engagement [40,41].

Social constructivist theory views learning as a product of the interaction between a person, an activity, and a particular setting [42]. Thus, individuals within a group may construct different meanings based on their sociocultural background [43]. For example, since male and female students are socialized into the school culture in different ways, they may engage in small group learning differently. Indeed, inequitable participation in group learning is a major concern based on research findings that female students tend to participate less than their male peers in group work [44].

Small group learning has a central role in integrated STEM education [18]. STEM disciplines, such as science and engineering, have distinct social languages, norms, and disciplinary cultures. Group learning activities can help students navigate through disciplines and develop solutions that build on various views of the same problem [45]. To be effective, group learning activities should require divergent rather than convergent thinking. In other words, group activities should encourage students to negotiate different views and reach a consensus. These types of activities can support students' social interactions and provide them with opportunities to engage in meaningful conversations [46].

2.2. Gap in the Literature, Research Goals and Questions

While the integration of mathematics and science has a century-long history [47–49], there is limited work on the integration of engineering and science [4]. Engineering design is considered to be a critical component of integrated STEM education [15,50–53], but it is more easily integrated with some science disciplines, such as physical science, than others [30,54]. Specifically, prior studies suggest that students rarely engage in engineering design in life science courses [18] and that teachers find it challenging to make meaningful connections between life sciences and engineering [37]. For example, a recent analysis of fifty practitioner-designed integrated STEM units concluded that "curricula based in the earth and life sciences generally lacked conceptual integration between the science content and the EDC [Engineering Design Challenge]" (Roehrig et al., 2021, p. 1) [18]. Relatedly, engineering activities developed by physical science teachers tend to be more engaging and motivating compared to those developed by life sciences teachers. This finding calls for additional research on the barriers in the integration of life sciences and engineering [30]. From an equity/access perspective, it is critical to address this gap since nearly all U.S. high school graduates complete a biology course (97%), which is not the case for earth science (47%) and physics (40%) [55]. Therefore, integrating engineering design in life science courses would provide greater access to engineering to students who might otherwise not have this exposure. We aim to contribute to the literature by surfacing the benefits and challenges associated with an integrated STEM unit that incorporates life science and engineering design.

In this study, we designed and piloted a new neural engineering integrated STEM curriculum unit and examined how it shaped the experiences of students and their teacher. Specifically, we sought to understand the learning opportunities and challenges experienced by students and their teacher when life sciences content is integrated within an engineering design course. This study reflects the first of several planned iterations of the neural engineering integrated STEM curriculum unit. We strive to learn from each implementation so that the module may be optimized, and to ensure congruence between the intended, enacted, and experienced curriculum. In this way, our study reflects a recommendation put forth by the Committee on Integrated STEM Education [1] to ground the design of integrated STEM interventions on an iterative model of improvement.

Our research questions were:

Research Question 1: How does incorporating life sciences into an engineering course support student learning?

Research Question 2: What are some challenges that students and their teacher experience in an integrated life sciences and engineering unit?

Addressing these questions could help improve the integration of life sciences and engineering education in future curriculum design efforts. This will help realize the vision to incorporate engineering design in all science classes, a national policy initiative codified in the Next Generation Science Standards (NGSS) [4].

3. Methods

3.1. Context and Participants

This exploratory case study [56,57] focused on students' learning experiences, and, as well as their teacher's enacted experiences and challenges associated with a new neural engineering integrated STEM unit. The case for this study is the pilot implementation of the neural engineering unit in Spring 2022. The unit was implemented over a period of 6 weeks in a mixed-grade, elective engineering design course taught at a private, all-girls high school in the Northeastern United States. This specific school was selected for two reasons: (1) our university had an established relationship with the school; and (2) the school already had a pre-existing engineering design course and the teacher of this course (Ms. Peck) expressed interest in co-designing the unit with our team. This school was selected to be the focus of this case study because the other teacher who was involved in the co-design process teaches at a public school, where additional ethical review was required at the district level and this was not attainable at the time. Therefore, this sample of participants was primarily a convenience sample. All study protocols were reviewed and approved by our institutional ethics board. At the beginning of the unit implementation, the students were informed about the unit and the research. Assent and consent procedures were completed with each participant before taking part in the research.

Study participants included the teacher implementing the integrated STEM curriculum unit and students in the class. The teacher, Ms. Peck, was a white female with 28 years of teaching experience. Ms. Peck was an engineering design and technology teacher and was part of the curriculum design team. Participants of this study consisted of high school students ($n = 15$), five of which were excluded as either they or their parents did not provide consent for their data to be used in the study. The participants for the focus group ($n = 4$) were selected randomly using the RAND function in Excel. The average age of student participants was 16.1 ($SD = 1.10$). A breakdown of participant demographics is provided below (see Table 1).

Table 1. Study participants and demographics (participants included in the focus group are listed first).

Pseudonym	Age	Race/Ethnicity	Primary Language	Included in Focus Group	# of Journals Completed
Valeria	16	Hispanic/Latinx	English	Yes	6
Gabriela	15	Hispanic/Latinx	Spanish	Yes	6
Courtney	16	White	English	Yes	7
Emily	15	White	English	Yes	9
Lindsey	16	White	English	No	7
Emma	18	American Indian or Alaskan Native, White	English	No	6
Allison	16	White	English	No	7
Morgan	16	White	English	No	8
Arianna	18	White	English	No	10
Zoey	15	Prefer not to say	English	No	6

3.2. Neural Engineering Curriculum Unit

The unit was designed and developed by an interdisciplinary group of stakeholders, including science and engineering teachers and researchers from engineering, neuroscience, learning sciences, and instructional technology fields (eight co-designers in total) in biweekly synchronous sessions. The neural engineering unit is congruent with NGSS high school life science performance expectation 1–2: "Develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms" [58]. This performance expectation includes the practice of developing and using models, as well as the cross-cutting concept of systems and system models. In addition, the practice of using mathematics and computational thinking supports and informs students' engagement in engineering design. In this module, students also engage in activities that work toward the NGSS high school engineering performance expectation 1–4: "Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem" [59].

The unit centers around the real-life case of a teenage amputee named Tilly who uses bionic arms [60]. This case is introduced in the first lesson and throughout the unit students design and develop a robotic gripper that could help Tilly and other individuals with neurological conditions. The interdisciplinary group used the storyline instructional model, which uses students' questions to guide collaborative sensemaking about phenomena, as a vehicle to design a coherent sequence of activities [61]. Tilly's story was particularly selected by the teacher, Ms. Peck, as she wanted a case with which her students could resonate.

The unit is divided into two modules: motor control and sensory feedback (see Appendix A for the storyline overview). In the first module, students' efforts are oriented towards exploring how different body systems interact to support limb movement, as well as how these interactions can be obstructed by neurological conditions. This module culminates with students' collection and analysis of electromyography (EMG) signals associated with their own muscle movements. The EMG signals are then used to control a simple robotic gripper (see below).

In the second module, students explore the limitations of the robotic gripper and ways to improve its performance. Specifically, students learn about the significance of tactile feedback in the refinement of limb movement and revise their initial grippers so that their sense of touch can be emulated. This is achieved by the addition of pressure sensors that can detect when the gripper makes contact with an object. The second module culminates with a design challenge: first to enable the device to pick up a fragile object without damaging it; and second to modify the device in order to help people with specific neurological conditions.

The Robotic Gripper

Through the unit, students use a low-cost robotic gripper kit, developed by Backyard Brains, which consists of EMG electrodes, a bioamplifier, and an Arduino microcontroller (Figure 1). This kit allows students to open and close a robot gripper with their own muscle movement [33]. Due to the relatively short duration of the unit (see Appendix A Storyline Overview), students do not program the Arduino microcontroller themselves but rather use an existing Arduino program.

Figure 1. The gripper bundle with the muscle SpikerShield [62].

3.3. Data Collection

3.3.1. Demographics Survey

All student participants completed a demographic survey prior to the start of the instructional unit. The demographic survey included questions that asked students to self-report information about themselves (i.e., age, grade, gender, race, ethnicity, primary language spoken at home, disability status). Race and ethnicity questions with multiple categories selected by the research team as well as options for a write-in or prefer not to answer. Students were also given categories for disability status based on the primary eligibility categories listed in the Individuals with Disabilities Act. The student demographic survey was administered via Qualtrics.

To reduce stereotype threat, demographic data was collected after all of the other pre-test data had been collected. Moreover, enough time was scheduled between the collection of student demographic data and the next round of student data collection for stereotype threat effects to be minimized. Lastly, care was taken to ensure stereotype threat-activating cues do not occur in the classroom [63].

3.3.2. K-W-L Journals

K-W-L is a literacy strategy that encourages active learning by prompting students to organize their readings in graphic forms [64]. The K stands for knowledge and prompts students to share what they know about the topic. The W stands for Wonder and prompts students to share what they further wonder about the topic and what they want to learn in the question forms. Finally, L stands for Learn and prompts students to reflect on what they learned that helps them better understand the topic. Students were provided with a K-W-L journal template in both digital and paper formats and asked to fill the journal individually after each lesson. The prompts for each step were as follows:

- Knowledge: What do you already know about this topic?
- Wonder: What do you wonder about this topic? (Describe in question format)
- Learn: What did you recently learn that may help you better understand the topic?

The study team collected students' K-W-L journals from all the lessons of the curriculum unit and converted them into digital format (pdf). Nine students consistently completed the journal.

3.3.3. Student Focus Group

The study team conducted a semi-structured focus group with four (n = 4) students after the unit was finished. We randomly selected four students out of the 10 who granted consent to participate in this study. The focus group was used to capture qualitative information on students' experience of the neural engineering design process. For example, we asked students to reflect on the aspects of the unit that they found most challenging, interesting, or relevant. The student focus group was conducted in-person. The focus group was recorded through an audio recorder and transcribed for later analysis.

3.3.4. Teacher Interview

The study team conducted one interview with the participating teacher following the full enactment of the neural engineering program. Interview questions probed the participant on her experiences teaching with the materials, including how she prepared for class; what she found challenging; what successes, challenges, or otherwise notable things she observed about her students' learning; and where she felt there is room for improvement in the materials' design. The interview was conducted through Zoom and was audio recorded and transcribed for later analysis.

3.4. Data Analysis

We conducted a thematic analysis to analyze the student focus group, K-W-L journals, and the teacher interview, following Saldaña's [56] two-cycle coding to thematize the data, starting with an initial coding strategy. Here, the focus was to discern learning experiences/outcomes and challenges that were reported to be associated with the proposed integrated STEM curriculum unit. Then, we conducted focused coding to determine what initial codes made the most analytical sense based on our research questions and established literature on integrated STEM.

Several complementary strategies were used to maintain methodological integrity during data analysis. We analyzed multiple data sources from the key actors (students and the teacher) involved in the implementation of the curriculum unit for data triangulation [65]. The thematic analysis was carried out by two research members independently to ensure investigator triangulation [65]. Then, through multiple debriefings with the research team, we converged our findings and evidence [57]. During this process, any discrepancies between the two coders were discussed and resolved [56,66], and we aligned our findings with what is documented in the literature to finalize the categories and the codes [58].

3.5. Researcher Reflexivity

Here, we briefly present how our experiences and expertise influenced data collection and analysis (personal reflectivity) and how our methodological decisions were made and what their rationales were (methodological reflexivity) [67].

Due to the interpretative qualitative nature of the study, our expertise and experiences necessarily inform data collection and analysis [68]. Three researchers actively participated in the data collection phase. One of them attended the class activities and served as a technology mentor for students and teachers. The second one attended one class session to support technology and science-related activities. The third one visited the class to implement the consent forms, demographic survey, student focus group, and teacher interview.

The third researcher conducted the student focus group and teacher interview mainly for two reasons. One was that as she did not participate in the class activities, she was an 'outsider,' and this status would help eliminate any perception or assumption formed through personal experiences with the students and the teacher, which might have impacted the nature of the open-ended inquiries during the interviews [69]. However, her outsider status might have also impacted the depth of the follow-up prompts as she did not share or first-hand observe the experiences of the students and the teacher. The other reason is her training and expertise in research methods as she is a Ph.D. student in research methods, measurement, and evaluation.

Four researchers participated in the data analysis phase, with the two who participated in the class activities being the primary coders of the data. One had a learning design and technology training and research background and extensive experience in qualitative inquiries and analysis. The other researcher had a neuroscience training and research background and experience in quantitative inquiries and analysis. The third and fourth researchers that participated in the debriefings to converge the findings had a curriculum design and evaluation background, extensive knowledge of the integrated STEM literature, and educational technology background and expertise in qualitative evaluative studies, in respective order. Through independent coding of the data by two researchers and multiple debriefings within a team of researchers with diverse expertise and experiences, we aimed to minimize any limitations in how we approached data analysis [57,65]. Having a diverse group of researchers in the data analysis was fruitful as everybody brought their perspective to the table, prompting us to consider and discuss multiple aspects of our curriculum unit as posed by our participants.

Two methodological decisions we made for the study are worth mentioning here. One was that we limited our data sources to a student group, a teacher interview, and students' K-W-L journals because we wanted to (1) examine both student and teacher perceptions of the learning experiences during the unit implementation, (2) triangulate the findings across these data sources, and (3) identify anecdotal evidence for the dynamics between our curriculum unit and the learning experiences without making any inferences as the other data resources (e.g., student artifacts) would require interpretation to draw conclusions, and our dataset was too small to make any inferences.

The second noteworthy methodological decision was that we implemented an inductive data analysis approach. There are theoretical frameworks outlining different aspects of integrated STEM curricula [18]; yet, we did not implement them in the first phase but instead used the literature to align our codes and categories in the subsequent phases of the data analysis. Two reasons shaped this methodological decision. One was that our dataset could be too small for a deductive approach, and the second was that implementation of life sciences into engineering curriculum is a less investigated form of integrated STEM [30], and thus, different aspects and dynamics might be in play. Therefore, we wanted to follow an open-ended approach to investigate students' learning experiences in our integrated STEM unit.

4. Results

This study aimed to develop an in-depth understanding of students' learning experiences with a new integrated STEM unit that our team has designed and developed. We followed an inductive analytical approach and focused our data analysis on the student focus group, teacher interview, and the students' K-W-L journals.

4.1. RQ1: How Does Incorporating Life Sciences into an Engineering Course Support Student Learning?

Our first research question focused on identifying ways in which student learning benefited from the integration of life sciences and engineering. The thematic analysis of the student focus group, teacher interview, and students' K-W-L journals yielded four main categories of codes: engineering design and problem-solving, working with technology, small group work, and STEM careers.

4.1.1. Engineering Design and Problem-Solving

This category focused on the nature of the engineering design activities and did not specifically address the inclusion of life sciences content. Four primary codes were associated with this category: (1) trial and error, (2) creative problem solving, (3) authentic engineering design, and (4) self-efficacy.

(1) Trial and error and (2) Creative problem solving. As described earlier (see Methods), throughout the unit students worked with a DIY neuroprosthetic (i.e., an EMG-controlled gripper) and developed ideas for technological solutions that could help people with neurological disorders. Working with these tools and optimizing their design required trial and error and creative problem-solving. In the focus group, students described how they explored different engineering solutions through multiple trial and error cycles. Students also reported being inspired to develop creative ("out of the box") solutions. For example, Courtney described their approach as follows:

> *"I think like forming like common sense and logic, if this doesn't work, and if we do it this way then this will happen, so like knowing that, knowing that when something else does not work, coming up with a solution where you can try in another way to get to the solution that you want...And that's kind of how we went about it, and then how like our imagination kind of led into it with our like logic and common-sense thinking."*

Valeria resonated with Courtney's description and further argued that this cycle inspired her and her classmates to develop creative solutions for the problems they encountered, "*I really get to think outside the box and come up with my own solutions.*" The students seemed to enjoy exploring different engineering solutions and identifying solutions to problems. This sentiment was expressed both by the students and their teacher:

> *"I'm definitely more inspired to think outside the box. Seeing like other people come up with these like really cool solutions. It kind of like makes me like wanna have more ideas."*
>
> (Courtney)

> *"Even the day that the one group was having trouble with the wires and they were frustrated, it wasn't, 'I don't wanna look at this again,' it was just, 'It didn't work, why didn't it work? I wanted it to work,' type of thing."*
>
> (Ms. Peck)

(3) Authentic engineering design. Throughout the unit, students were presented with real-life challenges and asked to design engineering solutions to address these challenges. For example, in Lesson 2.4, students developed ideas for technological solutions that could help real people with neurological conditions. This prompted the use of *authentic engineering design* practices, such as user-centered design and need analysis:

> *"...we also need to be practical about it, and it's just like, will it hurt her, how will it affect her ... Like how much does it cost to do it? And then do we have the enough technology..."*
>
> (Emily, student focus group)

> *"Tilly [one of the cases] has a hard time picking up fake eyelashes. How can we make this better for her? We can add extra joints and make her fingers more human-like."*
>
> (Emily, K-W-L journals)

(4) Self-efficacy. Finally, students reported that engaging in these activities boosted their self-efficacy in engineering design and problem-solving. For example, Gabriela stated, "*...in engineering, there's no wrong way, you can keep building on what you have, and it's definitely made me more confident because I'm like, 'Okay, I can do this. I like this. This is what I wanna do'*." Similarly, Emily posed, "*It makes you confident because it makes you acknowledge everything that you learned and apply it. It's just like, its like, 'Oh, I had that in me.' It like, makes you more confident like to work with a team and like bring your own thoughts in*."

4.1.2. Working with Technology

Two primary codes were associated with this category: (1) embodied interactions with technology, and (2) real-world value of neural engineering technology.

(1) Embodied interactions with technology. The student focus group, teacher interview, and K-W-L journals suggested that students' *embodied interactions* with the provided technology fostered engagement and meaningful connections to students' day-to-day lives. Specifically, measuring students' own muscle activity and touch sensitivity created an engaging and meaningful learning experience. For example, Emily reflected on how her interactions with muscle sensors translated to her daily activities by saying, "*I like muscle movement a lot more like when I'm at the gym, like I actually think about the muscles when I'm moving...*" Similarly, Ms. Peck commented, "*I think one of their favorite day was when they were using the calipers and just touching different parts of their body. And then they got to go into the simulation. They loved that day...That took them longer because they were so interested in what the computer was saying to them...*" In another comment, Ms. Peck noted how students' embodied interactions with the technological tools boosted their interest, "*They have never worked with anything robotics. Well, at least not in my class, maybe in physics. So I think just working with the mechanic arm and seeing how we progressed from the EMG and the motions in their hands, they were really interested.*"

(2) Real-world value of neural engineering technology. The data also suggests that the unit helped students develop awareness and appreciation of the *real-world value* of neural engineering technology. For example, referring to a video they watched about a teenager using a bionic arm to do her daily activities, Valeria commented, "*This is something that like actually affects people every single day. It's really important.*" Then, she connected the teenager's story with her experiences with the muscle sensors and said, "*...the electrodes kind of blew my mind. I didn't know ... and that's what they used for the bionic arm.*"

4.1.3. Small Group Work

Building on our theoretical framework and the central role small group learning plays in integrated STEM education [18], we were interested in how students engaged in group work throughout the unit. Two main codes emerged from the data: (1) distribution of roles and (2) perception of collaborative work.

(1) Distribution of roles. Throughout the unit, students worked in groups of 3–4 and *distributed roles* within their groups based on personal interests and strengths. For example, the students in the focus group shared that in their groups some members were responsible for setting up the hardware and others focused on coding. As the students reported, such role distribution improved group performance and resembled real-life engineer/scientist teams, with each member bringing their expertise to the project. This is exemplified in Valeria's comments:

> *"…for like our group, we were kinda split, somebody was doing the technology part of that, somebody was putting everything together. I think it was just like, it brought out our strengths, what we liked and what we could figure out ourselves and brought it to the team … They're no sole person [in teams of engineers]. Like you would expect them to figure them out, everything out themselves. But no, it's a whole group of team … working behind a project. So … there may be like the model person that you think did all the work, but it's like, everybody focuses on one little thing and that adds up."*

(2) Perception of collaborative work. Students reported that their *perception of collaborative work* was positively impacted by their experiences in the unit. For example, comparing her earlier collaborative experiences with those during the curriculum unit, Courtney stated, "*Cause like I don't usually like working in groups. Cause it's like, it's my idea and I will be so frustrated. But like engineering, I like it because we can all, we can bounce off other ideas.*" Similarly, Emily stated that "*…for me, I always thought I would be better working independently in something but like, when I was working in a team, I thought like that was better cause like they thought of something that I could never have thought of...*"

4.1.4. STEM Careers

Since the unit was implemented in an elective engineering design course, students already had interest in engineering:

> *"They're [the students] interested in science, and they're interested in engineering in particular for some reason, so that's why they took this course, and so they're very interested in the design process and learning about different parts of engineering"*
>
> (Ms. Peck)

Yet, engaging in the integrated STEM unit further solidified students' interest in engineering as a career option. For example, Courtney pointed out that,

> *"I've wanted to be an engineer for like as long as I can remember. And so actually getting to work with it, it makes me like, realize that this is what I want to do so."*

4.2. RQ2: What Are Some Challenges That Students and Teachers Experience in an Integrated Life Sciences and Engineering Unit?

The thematic analysis of the student focus group, teacher interview, and students' K-W-L journals yielded two main categories of codes related to challenges experienced by students and their teacher: technology integration and content integration.

4.2.1. Technology Integration

The students and their teacher raised two main issues associated with this category: (1) limited coding experience and (2) technical challenges with the robotic gripper.

(1) Limited coding experience. Due to the short duration of the unit, students were provided with the Arduino code used to control the robotic gripper rather than develop it or modify it themselves. This was perceived by the teacher as a missed opportunity:

"...My class never got around to working with the code at all. I don't even know if they realized they could have gone in and work with the computer code ... that's one thing I think that was a little bit lacking, some of them, probably could have gotten into that computer code and tweaked a few things made it work better." Ms. Peck explained that due to her lack of experience and confidence in Arduino programming, she did not encourage students to explore the Arduino program: *"...I had never worked with any of the Arduino or any of that before, I didn't have a grounding to help the girls ... "* She then further reflected on how this impacted her approach, *"I wasn't comfortable with the code so it's not something I actually encourage them to do..."*

In the student focus group, students also reported that not all members in their groups interacted with the Arduino microcontroller. For example, Emily pointed out that, *"We never even took a look at the coding part at all, it was just like Ali* [a team member], *so it's just like...I didn't know anything about it. Whenever we were told to do something, we just give it to Ali because she had done it at first and she know how to do it ... "* Then, she further suggested, *"...so I think I would have liked to split up maybe a little bit more into the parts each, so that we could all...See how it's working directly."*

(2) Technical challenges with the robotic gripper. The second issue associated with technology integration was technical challenges associated with the operation of the robotic gripper. These technical difficulties created frustration but also offered opportunities for students to learn about the engineering design process. For example, Valeria reported that, *"Trying to pick up certain items I think was my group's main goal and to able to hold them, and it was pretty hard because our specific claw* [gripper] *was pretty frustrating."* Courtney shared that, *"...it* [gripper] *was really hard to get it to stay with one motion or to stop spasming a lot. And then once we figured it out that it wasn't us really actually doing anything wrong, we kinda had to learn to adapt and to work with it to make it work eventually."*

4.2.2. Content Integration

Three main codes were associated with this category: (1) lower student interest in biology, (2) limited understanding of biology content, and (3) teacher lacking a biology background.

(1) Lower student interest in biology. As noted earlier, the course was an elective engineering design course, and the students were notably more interested in engineering design while reporting *less interest in biology*. For example, Ms. Peck noted, *"...they were engineering students... Biology...the diseases, they could care less about that ... that was probably the least effective."* The students in the focus group explained their lower interest in biology in different ways. For example, Valeria shared that, *"I definitely like engineering better and I'm more confident in engineering. Because it's more ... I really get to think outside the box and come up with my own solutions. Then there's already a solution set and I'm not like trying to find that answer. That answer is already there. I can actually come up with my own." Emily added that in engineering "we gotta do things in teams solve things out rather than just like sitting at a desk reading this..."*. Courtney emphasized the real-life impact of engineering: *"It's not like tests and quizzes, it's projects, which like actually make a difference..."* (Courtney).

(2) Limited understanding of biology content. Students' lower interest in biology content translated to more focus on engineering-design activities and fewer efforts to understand the life sciences background. As mentioned by Ms. Peck, *"most of them had no interest in that type of background. They were very interested in playing with the mechanical hands. But trying to figure out why it was working the way it was working to work with neurology of it. wasn't as interested."*

Analysis of the K-W-L journals revealed that students were curious about the scientific background, as indicated by questions that they posed in the *Wonder* section of the journal (e.g., *"How is this possible? Are there electroids in the bionic arm?"*). However, the *Know* and *Learn* sections demonstrated partial understanding of scientific concepts, such as EMG and muscle movement. For example, Emily wrote that *"robotic arms move because they sense the EMG"* (correct) but also noted that *"they know when to move because when you move that muscle, your nerves send EMGs to the arm"* (incorrect). This suggests that Emily had a practical sense that a robotic arm can be controlled by EMG activity, but she did not develop a full scientific understanding of this process.

(3) Teacher lacking a biology background. One potential explanation for these findings is that *the teacher had limited biology background*. In her interview, Ms. Peck emphasized that her not having a biology background might have limited students' engagement with biology content. For example, she posed, "*. . . one of the more challenging (aspects) for me was the fact that I don't have biology background. So sometimes I felt like I shortchange my students by not providing more information. Like when* [program staff] *came in, he was able to answer some questions that I hadn't even thought of. He brought in some aspects that didn't even occur to me to talk about.*" Ms. Peck further explained that, "*we didn't do as much drawing of the anatomy, but it's an engineering class not a bio class. So, that's something I kind of pulled out of it, which would flow much better or easier, if it was biology class or anatomy class.*"

Finally, as a solution to this challenge, Ms. Peck suggested partnering with a science teacher and co-teaching the curriculum unit with them, "*. . . if somebody who teaches biology that is free . . . and they wanted to come in, that would be something I look at doing another year to help, especially with some of the classes where they're talking about. . .*"

5. Discussion

In response to recent research calls [9,12], the primary goal of this exploratory case study was to develop an in-depth understanding of student learning experiences from both students' and their teacher's perspectives in an integrated STEM high school unit. Specifically, we explored how students experienced the integration of life sciences and engineering design via neural engineering activities. Our analysis of a student focus group, student journals, and a teacher interview suggests that students were highly engaged by the authentic and collaborative neural engineering design process. Students reported that this process increased their self-efficacy and interest in engineering, but there were also challenges associated with students' lower interest in biology and the teacher's limited biology background.

Q1. How incorporating life sciences into an engineering course supports student learning. Our data analysis yielded four main categories of codes: engineering design and problem-solving, working with technology, small group work, and STEM careers. The neural engineering unit introduced students to the real-life challenges of people with neurological conditions and engaged students in the development of technological solutions to help these individuals. In the focus group, students emphasized their appreciation for the real-world value of engineering and technology. This finding aligns with previous work, which demonstrated that authentic and real-life problems are an important and motivating component of integrated STEM curricula [12,15,70,71] that helps students develop their conceptual understanding of STEM principles [3,72] and meet the engineering design standards [4]. Further, the literature suggests that exposure to real-life engineering practices can broaden students' understanding of the discipline [73] and increase their interest in the relevant subject matter and practices [74]. Indeed, our findings suggest the neural engineering unit helped solidify students' interest in engineering practices and engineering as a career.

Our findings further suggest that challenges encountered by students in the neural engineering design process were perceived as learning opportunities and eventually led to increased confidence and self-efficacy in engineering design and problem-solving. Optimization, troubleshooting complex technologies, and meeting design criteria while staying within the determined constraints are critical principles of the engineering design process [75]. Thus, allowing students to confront failure and learn from their mistakes could support authentic engineering design practices [53,76]. However, it should be noted that our students' pre-existing interest and experience in engineering design might have contributed to these findings. Students with no prior experience in engineering design often experience fear of failure, which tends to result in avoidance behaviors, such as students avoiding equipment due to their fear of damaging it [53].

One of the unique aspects of the neural engineering unit was students' embodied interaction with technology. The experience of measuring one's own muscle activity and the use of this data to control the movement of a robotic gripper seemed to increase student engagement and foster meaningful connections between the unit and students' day-to-day lives. This finding is consistent with previous research on how hands-on and kinesthetic activities can motivate students, foster meaningful connections between science and students' lives, and improve learning outcomes [77,78].

Another element of the unit that positively impacted student learning was collaborative design in small groups. The students in the focus group reported that after the unit their perceptions of collaborative work became more positive. This is an important finding because fostering productive collaboration in classrooms can be challenging [79–81]. Several issues, such as lack of collaborative skills, varying competence levels among students, friendship, and free-riding, lead to adverse perceptions of collaboration, negatively impacting students' interest in collaborative tasks [80,82]. The positive shift in students' perceptions was promising as it could suggest that our curriculum unit cultivated collaboration, one of the core 21-century STEM skills [83].

RQ2: Challenges experienced by students and teachers in an integrated life sciences and engineering unit. Our data analysis yielded two main categories of codes related to challenges experienced by students and their teacher: technology integration and content integration. Unlike previous reports in the integrated STEM literature [84], the teacher in this case had high confidence in integrating engineering-related activities into her curriculum. However, she had no prior experience in computer programming and therefore did not encourage students to explore the program that controlled the robotic gripper. Feeling inadequate can lead to a decrease in teachers' confidence in their teaching efficacy [85,86]. This can result in divergence between curriculum expectations and how a curriculum is implemented [86–88] since students' exposure and learning are usually limited to the teacher's knowledge and comprehension [87].

Professional development (PD) can be an effective strategy to support teachers' knowledge and confidence in teaching integrated STEM curricula [76]. However, there are also instances where teachers show limited improvement in their teaching confidence even after multiple PD sessions [77,89]. In this study, the teacher's self-efficacy in Arduino programming has not significantly improved, potentially because the PD sessions were conducted virtually. Troubleshooting hardware and software remotely can be challenging, and thus, it is possible that in-person support would be more effective in increasing teachers' comfort with technology and programming. Technical glitches have been identified as a barrier to development of teachers' technology self-efficacy [90]. Given there was some malfunctioning technology in Ms. Peck's implementation, the provision of backup materials that are known to be fully functioning may also help build teachers' confidence in future iterations.

Another challenge that emerged from the data was the integration of life sciences content. Analysis of student journals suggested that students' understanding of the underlying biological phenomenon (e.g., interaction of body systems and muscle contraction) was limited. Building on prior work, our goal was to develop a fully integrated life sciences-engineering unit [12]. However, as our results and the literature suggest, school implementation might vary depending on multiple factors, such as teacher self-efficacy, confidence, previous knowledge, and students' motivation and interest [54,85,86]. Ms. Peck, as an engineering teacher, emphasized mostly the engineering design aspects of the unit rather than the biology aspects. As she also pointed out multiple times during the interview, she did not feel comfortable enough to prompt and support biology-related inquiries and did not think it would be necessary to do so in an engineering design class. This finding supports one of the acknowledged challenges of integrated STEM: often teachers do not have the discipline knowledge beyond the subjects they teach [86], and they struggle or may not be willing to learn subject matter knowledge needed to teach STEM in a more integrated way [91]. Teachers in the United States have less non-instructional time in their weekly schedules to learn, prepare, and collaborate than teachers in most nations [92]. This may limit or obstruct teachers' ability to learn disciplines for which they have no or little prior background.

A noteworthy solution proposed by Ms. Peck and the literature was establishing collaboration among teachers with different expertise [93]. Ms. Peck expressed that her school encouraged collaborations among teachers to co-design and possibly co-teach classes. Even though it was not the case in our study, teaming up with a teacher with a biology background might alleviate some of the issues reported with regard to biology content integration. However, the school in this case was a private school, and we acknowledge that teacher collaborations might be quite challenging in under-resourced public schools [90]. In addition, given biology is a broad field of study (e.g., marine science, molecular and cell biology, ecology), it is possible that some high school biology teachers may not have completed an anatomy and physiology course or may be new to teaching the neuromuscular system. For these reasons, we plan to include more educative materials in lesson guides to efficiently support teachers' learning, as well as assessments of teachers' knowledge in future iterations.

Another reason noted by the teacher for the focus on engineering design at the expense of biology content was students' lower interest in biology. However, student journals suggest that this may not be the case as students were seemingly very curious about the biology background. The teacher's perception of student interest might have played a role in the way she implemented the unit by giving less space for scientific discussions around biology content [85,86], and this ultimately might have impacted students' interest in biology content [94].

This study was conducted at a girls-only school, which raises the topic of potential gender differences in STEM education. There is evidence that integrated STEM activities can positively influence students' interest in STEM [95] and some researchers have recognized that the features of integrated STEM may be leveraged to positively influence girls' perceptions about science and engineering [96–98]. In this case, the integration of biology (a STEM discipline that girls tend to find relatively interesting to pursue) and engineering design (a STEM discipline that girls might perceive as relatively less interesting) could lead to greater interest of girls in engineering [99,100]. Since this study did not specifically address gender, future research is needed for further clarify this issue.

6. Limitations and Future Research

Our goal was to provide preliminary insights into how the integration of life sciences and engineering might shape students' learning experiences. However, this pilot study was constrained to one high school course, taught at a private school by an experienced teacher. Thus, our findings do not represent the range of students' and teachers' experiences in integrated STEM courses. Furthermore, the course in question was an elective engineering course, and thus our findings are susceptible to self-selection bias. This course was taught at an all-girls school, and, therefore, our findings might not be generalizable to mixed gender classrooms. Future studies should expand these findings to other types of STEM courses taught across a range of schools with diverse samples of students. These studies could better address questions such as how teachers' background and expertise impact the implementation of integration STEM curricula and what kind of scaffolding and teacher support is needed to achieve more profound integration of life sciences and engineering.

In conclusion, this study showcased how life sciences can be incorporated into an engineering design course via neural engineering design activities. Our preliminary findings suggest that the authenticity and real-life relevance of the design activities increased student engagement, interest, and self-efficacy in engineering. However, students' lower interest in life sciences compared to engineering and the teacher lacking life sciences background made it more challenging to achieve full integration of the two disciplines.

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Appendix A Storyline Overview

Appendix A.1 Learning Objectives

Green = Life Sciences
Blue = Engineering Design
Orange = Computational Thinking

(1) Students will investigate a sensory-motor impairment (e.g., loss of limb/nerve damage/spinal cord injury) and argue with evidence the impacts of the impairment on people.
(2) Students will develop, revise and apply a model to explain how the interaction between body systems is affected by the disorder that they selected.
(3) Students will use computation to acquire, digitize, and analyze biological signals to inform the design of a biomedical device (human–machine interface/neuroprosthetics).
(4) Students will design and evaluate engineering solutions that can help improve the lives of patients with sensory-motor impairments (i.e., a human–machine interface).

Appendix A.2 Storyline Overview

Anchoring Phenomenon: At only 15 months old, Tilly Lockey, contracted Group B meningococcal septicaemia, with doctors giving her zero chance of survival. Amazingly Tilly survived but had to have both her hands amputated at the wrist. For years she used basic silicon arms that had only an open or close grip. However, in 2018 she became the first child in the UK to have bionic arms when she received a pair of high-tech, 3D printed arms that give her a much fuller range of movement. Yet, bionic arms still have a long way to go before they achieve the full range of motion, control, and sensitivity of 'biological' limbs.

Lesson	Driving Questions	Key Activities	Implementation—Class Sessions (1 h 10 m)
Module 1: Motor Control			
1.1	How do bionic arms work?	• Introduction of the anchoring phenomenon (Tilly: the teen with the bionic arms) • Generating questions that will be investigated as the module unfolds.	1

1.2	How do different body systems contribute to limb movement and what could go wrong?	• Reaction time measurement. • Constructing a model of body systems that are involved in voluntary movement. • Investigating how neurological conditions could impact limb movement.	2
1.3	How can we identify and measure the activity of muscles?	• Exploration of muscle electrical activity (EMG)	1
1.4	How can EMG signals be used to control a robotic gripper?	• Design challenge #1: EMG-controlled gripper	2
Module 2: Sensory Feedback			
2.1	How does sensory information impact movement?	• Measuring reaction time with gloves	1
2.2	How does the nervous system process tactile information and what could go wrong?	• Homunculus mapping • Constructing a model of body systems that are involved in touch perception. • Investigating how neurological conditions could impact touch perception.	1
2.3	How can bionic arms sense objects?	• Design challenge #2: Can you grab an egg with a robotic arm without cracking it?	2
2.4	Putting it all together: How can technology help people regain motor control and sense of touch?	• Problem definition • Design challenge #3: design a human–machine interface. • Students share their designs.	1

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