

“Interdisciplinary education”, “R&D”, and “Contamination”: Comparing the Stressors of Biomedical Engineering Doctoral Students to Other Engineering Fields

Abstract

Purpose

Doctoral students experience high rates of mental health distress and dropout; however, the mental health and wellness of engineering doctoral students is understudied. Studies of student persistence, wellness, and success often aggregate fields together, such as by studying all engineering students. Thus, little work has considered the experiences of biomedical engineering (BME) doctoral students, despite differences between doctoral BME research, course content, and career expectations compared with other engineering disciplines. In this qualitative interview case study, we explore stressors present in the BME graduate experience that are unique from engineering students in other disciplines.

Methods

We analyzed a longitudinal interview study of doctoral engineering students across four timepoints within a single academic year, consisting of a subsample ($n=6$) of doctoral students in a BME discipline, among a larger sample of engineering doctoral students ($N=55$). BME students in the sample experienced some themes generated from a larger thematic analysis differently compared with other engineering disciplines. These differences are presented and discussed, grounded in a model of workplace stress.

Results

BME participants working in labs with biological samples expressed a lack of control over the timing and availability of materials for their research projects. BME participants also had more

industry-focused career plans and described more commonly coming to BME graduate studies from other fields (e.g., another engineering major) and struggling with the scope and content of their introductory coursework. A common throughline for the stressors was the impact of the interdisciplinary nature of BME programs, to a greater extent compared with other engineering student experiences in our sample.

Conclusions

We motivate changes for researchers, instructors, and policymakers which specifically target BME students and emphasize the importance of considering studies at various unit levels (university department level vs college level vs full institution) when considering interventions targeting student stress and wellness.

Keywords: longitudinal research, qualitative research, graduate students, mental health and wellness, retention

Introduction

Engineering doctoral students in the United States suffer from high rates of mental health distress and high dropout rates (Evans et al., 2018; Lipson et al., 2019), contextual to broader mental health crises (Evans et al., 2018; Flatt, 2013) in higher education. While the national dropout rates for doctoral engineering are not as high as those for some other disciplines, a concerning rate of as many as 30% of engineering doctoral students do not complete their programs (Cassuto, 2015; Lott et al., 2009-2010). This rate of departure may also be underreported in engineering, as “mastering out” (Maher et al., 2020), a phenomenon where students depart PhD studies early with Master’s degrees, may be considered graduation data by some institutions (Zerbe et al., 2022b). Mastering out may be more common in engineering disciplines, where Master’s degrees can open doors for high-paying government or industry employment, offering an opportunity for program exit. Further, engineering students at all levels are less likely to seek help for mental health issues (Lipson et al., 2016), leading to prolonged negative experiences. While these issues exist, studies of graduate student mental health are rare in engineering (Bork & Mondisa, 2022) and are especially rare in engineering sub-disciplines.

Stress is an important factor in both the mental health and wellness of students and also in student persistence. Experiences of stress have been reported to contribute to symptoms of depression (Bekkouche et al., 2021; Levecque et al., 2017) and anxiety (Hunter & Devine, 2016; Mackie & Bates, 2019; Pyhältö et al., 2012) for graduate students. Doctoral students have described high stress environments as causing “simmering pressure” which leads to mental health struggles and increased intention to depart PhD programs (Berdanier et al., 2020; Bekkouche et al., 2020).

This study is part of a larger program of research in which the authors have sought to uncover the nature and effects of different stressors, or sources of stress, experienced by doctoral students (Authors, 2022; Authors, 2023). Existing studies of engineering student stress and persistence across engineering disciplines often encourage and suggest interventions or practices for students, advisors, and universities (ex. Korsten et al., 2021; Zerbe et al., 2022a). However, different approaches to intervening on behalf of students may be warranted in different degree programs.

To highlight differences between engineering disciplines, BME is a compelling field, as the doctoral work of BME shares some traits in common with engineering and some with life sciences, yet BME is commonly aggregated with engineering disciplines. The authors were unaware of studies which specifically explore the mental health of biomedical engineering (BME) students. However, while studying the results of a large, longitudinal, qualitative study of doctoral engineering student stress, we noticed that some stressors and experiences, particularly regarding lab and research work, introductory classes, and career intentions manifested differently for our BME participants. Further, implications we would suggest for BME students differed in some ways from how we would suggest policies for all engineering graduate disciplines, motivating work which considers the experiences of individual fields as cases among broader disciplines.

This study asks the research question: *How do BME doctoral students' experiences and stressors differ from the experiences of other engineering doctoral students?* In addition to presenting differences between BME student experiences of major themes of stressors, we suggest how to tailor interventions to target these different stressors and motivate future studies within individual fields.

Theoretical Framework

The guiding theoretical framework for this work is the Job-Hindrances-Control-Support (JHCS) model (Dawson et al., 2015), a model of stress in workplaces. Originally formulated as a combination of a sense of control and support in workplaces to offset the stress of job demands (Karasek, 1979), revisions to the model have included more perceptual elements such as to what degree job demands are perceived as stressors (Li et al., 2020; Podsakoff et al., 2007). The JHCS model postulates that the perception of **demands** in the workplace as **hindrances** increase stress, which can be reduced through **supports** (e.g., resources, people) in the workplace, and increased *or* decreased by perceptions of **control** or a lack thereof. We argue that the **demands** of graduate school, particularly in research, can be likened to a conventional job, and introducing **supports** or perceptual changes to students to improve how **hindrances** are experienced can improve working conditions and thereby lower stress. Throughout the results, we will refer to elements of the JHCS model in bold; examples and definitions of important terms in the model are summarized in Table 1.

Table 1: Summary of the JHCS Model

JHCS Term	Definition	BME Doctoral Student Examples
Job Demands	Tasks or requirements needed to complete a job	Preparing cell cultures, training an undergraduate student, completing required classes and milestones
Hindrances	Job demands which are perceived as stressful or limiting ability to succeed, raising stress levels	Working with a difficult colleague, hours required in lab over weekends, a high stakes exam
Challenges	Job demands which are perceived as less stressful and as opportunities for growth and advancement	Authorship on a paper, taking a class about an interesting topic
Appraisal	How a worker perceives an aspect of their job (e.g., to consider a demand a hindrance or challenge)	A student with anxiety about speaking sees attending a conference as a hindrance ; a student without those concerns sees the same conference as a challenge

Supports	Resources (including people) in jobs that reduce stress levels	A helpful friend in the research group, vacation time, a training manual, university counseling services
Control	The sense of power or ability the worker has over the existence or management of job demands	(In/)Ability to set working hours, unanticipated cell death (low control), a research fellowship (high control over one's own funding source)

Method

This project is part of a large, mixed methods program of research on doctoral student mental health and persistence in engineering which asks the overarching research question *What is the nature and what are the effects of stressors for doctoral engineering students?* The qualitative case study presented in this paper comprises four longitudinal interviews with six BME students conducted during a single academic year; these students' responses are compared to responses from other students in engineering disciplines in the larger study.

Positionality

The project team consisted of the authors: two faculty investigators and a postdoctoral fellow, who was a doctoral student during the data collection and analysis. The authors were supported by three additional individuals: a Master's student and two undergraduate student research assistants. Among the six investigators, four identify as women; two identify as men. Four investigators identify as straight; two identify with LGBT+ identities. One investigator identifies as Asian-American; five identify as White. One investigator has been diagnosed with a mental illness.

Among the project team, expertise with social science research varied by a range of over 20 years, from undergraduate student investigators conducting their first educational research project to the project's PI, who had 24 years of educational research experience. Four team members had experience as engineering students and/or researchers, with experience in

engineering physics, civil engineering, and BME. Five team members had experiences as social sciences students and/or researchers, with experience in counseling psychology, educational psychology, engineering education, and sociology. This combination of experiences allowed the team to bring mixed perspectives, broadening the scope of research design (Secules et al., 2021). Before the analysis stage of research, the team compiled individual positionality statements to consider during analysis. The first author had experiences with significant stressors and mental health distress and had elected to drop out of a science PhD program prior to the study. This leveraged his experience to empathize with participants, and using that understanding, he conducted all interviews and correspondence, sharing his own experiences occasionally to add mutualism to his relationship with participants. The team concluded that having performed all 212 interviews with one researcher was important for building rapport with participants during the longitudinal study (Farrall et al., 2014). Throughout the formulation, collection, analysis, and writeup of the study, we followed quality considerations for qualitative engineering education research (Walther et al., 2017) and reflected on the research progress in weekly meetings.

Study Context

The study was conducted at a large, Midwestern research-intensive university. Data were collected during the 2021-2022 academic year, during the COVID-19 pandemic. In that year, the focal institution enrolled approximately 2,400 doctoral engineering students. Approximately 54% of these graduate students are international students and 22% identify as women. The institution offers doctoral degrees in 12 engineering departments, with enrollment varying considerably by department (about 50-100 PhD students in most small programs and 400-500 PhD students in the largest programs). Of those students, approximately 120 were in a BME

program¹. Therefore, our sample of six students slightly overrepresents BME at the institution. Among the focal university's engineering disciplines is a Department of Bioengineering, which includes BME topics such as computational bioengineering, cell-based research, and biomedical technology. Students in this program take approximately six years to complete PhD work, complete a comprehensive qualifying examination near their second year, and a dissertation proposal defense typically 1-2 years before defending their thesis. Students typically receive research assistantship funding, but sometimes complete teaching assistantships, which are not required.

Participants and Procedures

Participants in the broader study were six PhD students in a BME discipline and 49 other adult PhD engineering students at the focal institution. Participants of our broader study were intentionally stratified to be representative of the site institution by race, identifying (could select multiple options) as 47% White, 36% Asian/Pacific Islander, 13% Hispanic, 9% Indian subcontinental, 4% Arab/Middle Eastern, 4% Black, and 2% American Native; gender, identifying as women (42%), men (56%), and nonbinary (3%). In the full sample, four participants mastered out by the end of the academic year, and four completed their PhDs during or after the academic year. Additionally, one of the six BME PhD students was considering departure at the end of the study. The BME students were part of the full stratification approach but were not themselves stratified to be representative of the BME department, as a qualitative case, they oversample students who identified as women and students who were in the middle-stage of their PhDs, between qualifying examinations and preliminary dissertation proposal defenses. Only quotes collected from the six BME participants in the broader study are

¹ At the focal institution, this program is named "Bioengineering" and has a program of research and study considered to be synonymous to BME.

presented. Trends between our BME participant case and the full study are presented. Students in the full study were stratified by aggregated department size.²

The 6 students in the BME discipline case include one student preparing their dissertation, one first year student, and four students between their qualifying comprehensive examinations and dissertation proposals; these participants worked with computational research, biomaterials, or cell-based research; including two international students, one student who identifies with a racial group minoritized in engineering, five students who identify as women, and one who identifies as a man. Some of the participants completed undergraduate degrees in bioengineering or BME; others completed undergraduate degrees in other STEM disciplines (exact disciplines would be potentially identifying and are not included). To protect anonymity given the small department size, specific research areas are not tied to participants and specific years in program are not provided. These participants are referred to by the following pseudonyms in this study, and these pseudonyms are only directly tied to gender: the participants were Veena, a woman; Karina, a woman; Jan, a man; Laura, a woman; Sue, a woman; and Natasha, a woman.

Interviews

All interviews were conducted on Zoom with audio recording only. Consent information was restated at the beginning of each interview. Participants were offered \$40 gift cards for participating in the initial hour-long interview in October 2021 and \$10 gift cards for participating in each subsequent 15-min follow-up interview, in the subsequent December,

² Large departments (22 participants) at the focal institution by number of students are mechanical engineering, electrical engineering, and computer science; medium departments (20 participants) are materials science and engineering, physics, and civil and environmental engineering; and small departments (13 participants, including six BME participants) are agricultural and biological engineering, aerospace engineering, bioengineering, industrial and systems engineering, and nuclear, plasma, and radiological engineering.

February, and April. The semi-structured interview protocol for the initial interviews in October 2021 included questions about housing and access to food and other quality of life needs, self-assessments of class and research performance, top-rated student sources of stress, experiences with microaggressions, intention to remain in the same PhD program, and strategies for coping with stress (refer to [redacted repository link] for the full protocol and follow-up interviews). Initial interviews were conducted for an average of 45.0 minutes. The semi-structured design of interviews intended to elicit feedback on the **appraisals** of stressors (as more/less severe, or **hindrances/challenges**), the degree of **control** felt over stressors, and **supports** (e.g., coping strategies, advising relationship) used by students.

Follow-up interviews were designed to inquire about program progress, stressors, coping, emergent themes, and the effects of COVID-19 on stress. Follow-up interviews were conducted for an average of 13.1, 11.4, and 19.8 minutes.

Data Analysis

Qualitative interview data were analyzed using thematic analysis (Braun & Clarke, 2006). First, the full team collaborated to create codebooks grouped by overarching themes such as classes or advisor relationships. These themes were grouped by categories of stressors, and these categories were determined by a review of the literature involving graduate stressors. After coding, segments of captured text related to stressors were analyzed using the JHCS framework as a lens, namely where evidence of **appraisals**, a sense of or lack of **control**, and descriptions of **support** occurring were explicit. Team members with relevant experiences drafted codebook sections, e.g., themes regarding graduate student research and classes were developed by a graduate student team member. See [link redacted for review] for code names and overarching themes, definitions for the code, a usage guide for each code, and one to two example quotations.

One author coded 100% of interviews, 100% of which were re-coded by a combination of the other authors. All coding was done in Atlas.ti (Version 9.1.7). Discrepancies between coders were reviewed by the coders until agreement was reached (O'Connor & Joffe, 2020). We treated the BME participants as a qualitative case study, and compared their stressors to the non-BME, but still doctoral engineering students in the same institution. Qualitative case studies are characterized by small sample sizes and limited timepoints, focusing on narrowly banded experiences (Creswell & Creswell, 2017). In this study, we specifically investigated how the experiences of BME students at one institution, as a group comprising this qualitative case, differed from engineering students in other disciplines at the same institution. We anticipate that BME departments at other institutions, treated as an additional qualitative case, may comprise students experiencing stressors similar to those discussed in the findings below (Creswell & Creswell, 2017, p. 202-3).

Findings

Eleven themes related to doctoral student stressors were generated in the full study (Authors, 2023a, in review), containing over a hundred different codes representing sub-stressors related to each theme. The eleven themes, or categories of stressors from the full study were the advising relationship, classes, lab and research work, COVID-19-related stressors, teaching assistant stressors, microaggression-related stressors, work-life balance stressors, self-related stressors (i.e., career direction, impostor syndrome, perfectionism), campus life and finance stressors, milestone-related stressors, and a miscellaneous category including topics like sudden expenses or illness, current world events, family/friend/partner stressors, and social comparisons (e.g., evaluating performance vs other students). In this qualitative case study, however, we only

report sub-stressors within themes that BME participants experienced differently compared with other doctoral engineering students. For example, in some major themes, such as advisor relationships, the subsample of BME students experienced the same variations in quality of advising relationships – including aspects such as mentoring style, receiving direct training and feedback, and policies for working hours and vacation – as did the full engineering sample. Similarly, topics such as teaching assistantships and milestone preparation were described similarly by BME students and in other engineering fields. In this study, we re-analyzed the coded information associated with our BME participants’ transcripts to see what major stressors were experienced differently by BME students compared with other engineering students at the same institution.

In this paper, we focus on stressors that were different between BME students and other engineers at the institution studied. However, we do not present stressors that were a consequence of a specific BME policy at the focal institution. In the interviews, we learned that some stressors described by BME participants were caused by policies specific to the focal institution or its specific departments. For example, BME students in the institution we sampled are not required to be teaching assistants at any point during their studies, while other departments in the larger study required a semester or more of teaching. For BME students and other engineers who did not have policies related to being a teaching assistant, teaching roles were perceived as higher hindrances and teaching commitments were more frequently described as stressful, which we believe is due to teaching being not required by the specific program. In our presentation of these results, our goal is to describe findings which are potentially transferrable to other engineering and BME programs, thus only themes representing stressors that we would expect to exist and be experienced differently between BME students and other

engineers across most BME programs are presented. We present three major areas in which BME doctoral student experiences differed from other engineers' experiences at the institution sampled: in research and lab work, in introductory graduate coursework, and in career goal setting and expectations. While each theme includes a few sub-stressors, a fourth theme of interdisciplinarity in BME research cuts across the three themes, affecting some research, career, and class stressors.

Research and Lab Differences

The broadest area in which we noticed differences between our BME participants and other doctoral engineering students was in research and lab work, which included topics such as funding sources, interdisciplinarity, working hours and **control** over experiments, and supply chain issues.

Working hours in BME labs were the most severely discussed stressors in our qualitative case, and the cause for long hours differed from other working hour stressors in the larger study across engineering disciplines. For many participants in the full study who described stressors due to long hours, the working hours were required by demands of advisors or finishing a PhD within a shorter-than-average period (e.g., a shorter PhD due to financial plans). However, given the nature of research with biological samples, BME participants who worked in laboratory settings described long working hours and inflexible working conditions due to the nature of work with biological materials (e.g., delays due to growing cell cultures).

Laura, a late-stage PhD student described working forty-hour weeks with three-to-six hours of weekend work, which she described as less work than she had done in her first few years. Laura described the number of hours she spent in her lab as a stressor, saying it became “difficult to find time for my friends or for my partner,” and consequently “within the past few

years, I've tried to purposefully take more time, especially on the weekends to see everyone."

Laura described the how departure of labmates due to dropping out led to her working alone on projects due to a lack of **support**, creating conflict between her personal and research life, for she could not **control** needing to be in her lab for a large portion of time in order to finish her degree. She elaborated further, saying "There have been times that I get really busy in lab, and I feel like that takes a toll on my personal life. So, there's stress from that." Overall, Laura perceived her working hours as a **hindrance** stressor which decreased the quality of her working life.

Similarly, Laura and Veena described intensive working hours, including nine-hour weekdays, occasional evening work, and a "need to go in almost every weekend." Laura described that her working hours inhibited her ability to access **supports**:

I do find a hard time balancing stuff and, like, finding time to do things. I feel like because lab work takes so much of my time, I think I don't have a time to go back and like hit the gym or pursue a hobby. And that I need to save everything for the weekend. And even in the weekend, I feel like I feel guilty for not working, or not reading up on or prepping for the upcoming week.

The **demands** of Laura's BME work caused lengthy working hours which lowered Laura's ability to spend other time on **supports** such as hobbies. While this phenomenon is not exclusive to BME, for these working hours and biological lab work stressors, **control** over biological resources for research was a unique source of stress for participants. Laura described an issue with cell contamination which took over a month of her time. Veena also described the pace of her research as a stressor. She described biological research as a **hindrance** stressor which interfered with her publishing her first paper:

Because the field that I work in is, like, biological, it's quite slow. And it's dependent on so many other things. And like, I don't know. Like, I feel like I've learned a lot. I really – right now, I have an understanding of how things work.

But there hasn't really been a very measurable impact or like a measurable outcome so far.

Here, Veena describes the reality of biological research as slow work, where progress is difficult to measure. Veena described this as a major stressor, especially to make sure she was presenting progress to her advisor consistently during weekly meetings.

Natasha also described this slow progress as a stressor; she shared that receiving training to set up the microbiological environments she wished to study took a long time, making her feel “not productive” and conflicting with her first-year courses. By contrast, students in other engineering disciplines may also have **demands** for rapid progress or long working hours (i.e., that are set by an advisor), however they may have more **control** over the materials and equipment used for their research and the time it takes to use those. Indeed, BME participants such as Jan whose research did not involve biological materials described healthier balances and improved working hours, as computational research afforded them the **control** to use hybrid modalities and make progress easier.

Other consequences of slow biological work that participants described included the length of experiment progress impeding travel (Veena said, “Because we are an experimental lab, I don’t think it’s feasible for us to take long vacations.”) and increased workloads due to other PhD students departing labs, which was described by Natasha, who took on the work of another student who mastered out of her lab (a loss of a **support** in JHCS terms). To a lesser extent, “slowness” of biological research also appeared for participants, like Laura and Natasha, who had experience as teaching assistants, because experimental failure, contamination, and long times to set up laboratory experiments for classes were all potential causes of time loss. In general, the nature of BME lab work was perceived as a **hindrance** with low **control** over how

long sample preparation, testing, and maturation could take, exacerbated in the case of lacking **support**.

External research funding and ethics issues were discussed by several participants, though were less consequential overall. These topics were primarily discussed by Jan and Laura. Their research aligned with medicine or with biological samples, thus they had job **demands** for receiving additional training and learning (e.g., to accurately fill out forms and document research responsibly). They needed to receive permission to research human or biological subjects or get clinical research approvals, unique from many other engineering disciplines. These **demands** existed in addition to other **job demands** in common with research in other engineering disciplines, such as learning equipment and programming skills, training labmates or undergraduate mentees, writing and publishing, working hours, and keeping up with research progress.

The combination of these ethics considerations and the previous biological materials impacts on lab work suggests that BME doctoral students have additional biological research **demands** and skills required compared to other engineers; these **demands** can increase the stakes and consequences of BME research and also reduce student **control** as approval processes take time and may limit the types of experiments and trials which can be done.

Interdisciplinarity in research was frequently discussed by all of our BME participants. Participants frequently discussed collaborating with other campus units, including the focal university's college of medicine, biology and chemistry departments, and other engineering groups. Jan described this as a specific part of the focal institution's BME culture as "interdisciplinary education" and said, "[The program] does that, probably more than any other engineering program on campus. They're kind of in a lot of different topics." Jan described a few

stressors emerging from **demands** related to interdisciplinarity. These included requirements to learn and interact with more types of campus units than the average student, each with its own set of policies and procedures. Occasionally, politics could make their way into these issues; Jan described his most stressful situation of the first follow-up interview as securing his graduate appointments, which were split between departments. He described that “everybody was starting to jockey around for sort of control,” implying that **control** over his funding sources was decreased.

These issues recurred during the final follow-up interview, when differences between funding policies for summer research for the two units which hired him again caused Jan challenges in navigating his appointments. Later, Jan encountered stress again when struggling to adopt health insurance from his appointments. In each of these situations, Jan’s sense of **control** had decreased due to complications from his interdisciplinary appointment across university units, a situation which was unique among the participants we sampled in the full study. Other participants discussed issues such as lower stipend rates in BME compared to other departments. Thus, some participants chose to strategically select appointments outside of BME to maximize earnings. We note that some of these stressors related to specific university appointment and funding policies, which may limit the transferability of Jan’s experiences. However, we expect that (1) differences in funding based on departments, and learning multiple units’ policies may be experiences that other students in multidisciplinary situations would encounter and (2) that based on our findings, BME students more frequently are involved in interdisciplinary research and coursework compared to non-BME engineers.

For Laura, interdisciplinary work led to different challenges, for she was the only member of her lab doing biological work. Laura described how a lack of **support hindered** her research experience:

I wish my project were more collaborative. I see the other people in my cohort that are either -- well, mostly in labs are more collaborative within the lab and it seems like they are able to make more progress on papers and finishing projects, because they have multiple people working on that project; whereas for mine, it's only me that does the biology side of it.

When interdisciplinary work was described in the full study, many non-BME participants described the potential to collaborate with other engineers, across institutions or labs, or with industry partners with enthusiasm for social or networking potential. Laura, however, suggested collaboration as potentially isolating for individuals whose role in the collaboration is a unique skillset. Natasha, whose advisor was outside of her BME department, made similar descriptions in her initial interview, sharing that the schedules of graduate assistants in her lab conflicted with hers, which made receiving training challenging. Natasha also described having challenges socializing with BME students and forming a community, in part because her research was external to her department. Ultimately, Natasha felt that her research experience was isolating and uncollaborative. She said:

It's just been odd that it's been entirely just kind of on my own. And there's no one to like, be there and like, yeah, you seem to be like generally doing okay, or there's even just kind of... when I'm working, it all feels relatively solitary. Like, classes are honestly where I've gotten the most collaboration rather than research and I expected that to be flipped.

While Natasha expected her interdisciplinary work to be a collaborative and **supportive** environment, instead she described feeling like an outsider and was unsure about who could appraise that she was making satisfactory research progress. Natasha did work to **control** this stressor; in her first follow-up interview, she described a process of “actively getting to know”

her labmates and designing social events but she did not feel like she yet had the quality of social relationships she wanted. In terms of the JHCS model, the lack of **support** through other researchers or mentors familiar with her interdisciplinary situation and needs contributed here to an experience of greater stress.

Sue also experienced issues with interdisciplinarity in two instances involving expertise in research communities, first when experiencing skepticism at a conference from someone in an adjacent field, and second when receiving reviews on a paper involving both experimentation and computational modeling where reviewers appeared to only have computational expertise. In both cases, Sue described her research as being poorly understood because of its interdisciplinarity, leading to poor communication. Like Sue, Karina, Jan, and Veena each described attending multiple conferences per year across multiple fields, however the only conference-related stressors described by these participants consisted of writing conference submissions, anxiety about presentations, and acquiring funding for travel – similar to experiences of other engineers. Yet, it may be inferred that less interdisciplinary fields may have fewer conference-related **demands** (e.g., only one annual conference), especially for students who perceive funding challenges as serious **hindrances**.

Several participants described unique issues related to the COVID-19 pandemic. Jan, for example, experienced more challenge with his interdisciplinary research because of the lack of in-person interactions and scheduling challenges among his team spanning different units. Laura's previously described issue with cell contamination took longer because of supply chain shortages. Karina, who was preparing her defense during her last interview, shared that the most stressful part of her spring semester was, "COVID shipping delays," which impacted supplies such as reagents from being delivered and tightened the timeline of her final experiments. While

Sue was among the least stressed participants in the entire sample of students, she described serious stress involved with supply chain issues and shared in her initial interview that, “Almost anything and everything has been backordered at some point at this time,” and that some materials had been delayed by as long as a year. While these issues were more prevalent for BME students in our sample compared with other engineers, our BME participants also experienced COVID-related stressors in common with other engineers, including challenges adjusting to online coursework, visa and travel issues – especially for international BME participants, reduced advisor availability, social isolation, and confusion over shifting university and national policies. A complimentary work by the authors further unpacks the role of COVID-stressors across engineering disciplines (Authors, in press, 2023b).

Coursework Differences

Participants described stressors due to the **demands** of coursework, which included stressors due to course content and the level of preparation participants had for their graduate-level curriculum.

Aligned with previous themes related to interdisciplinarity, BME participants more often took courses in other disciplines compared to other engineers in our sample. Across our six participants, they described taking external coursework in math, computer science, chemical engineering, civil and environmental engineering, and biology, in addition to research methods and training courses for research on human subjects, as previously discussed. Frequently, advisors suggested participants choose classes outside of their departments, a **demand** which was much more prevalent with our BME participants. These **demands** could cause stress when the topics of challenging classes were unfamiliar – unfamiliarity with computing and mathematics in graduate-level course topics was described as a stressor by both Laura and

Veena. Veena, whose undergraduate work was not math-intensive, described the math in her first-year courses as her biggest stressor related to classes.

Interdisciplinarity also created stressors in terms of the variety of content being covered in BME coursework, which attempted to balance broad research interests spanning (per participant descriptions): computational methods, biomaterials, medicine and applications, cell engineering, research ethics, and genetics and genetic engineering. Sue, who did not have much trouble with coursework, expressed frustration instead at the variety of topics in her required BME coursework. She said:

I feel like graduate-level courses [in my program] are so open ended. It just...I don't know, you cannot go deep into anything. So, I don't know, it becomes a little hand-wavy for me. But I get it's hard because you're getting a very diverse group of people [in terms of research].

Similarly, Karina described multiple times across interviews that her classes had not been particularly useful towards her research. She described her class-taking as more “checking boxes” than being useful or “related to what I had to do.” Natasha, an early-stage³ student, also expressed this; she said that her classes were “not in my field” and not “something I was excited to take.” Natasha did not blame her department or instructors for this; she felt like her own instructors were not catering to their own subfields, but rather that the students had “a divided first background in terms of our academic background in the past” and that the research interests of her classmates were too “wide” to “cater to everyone.”

While these class stressors may exist for any student whose doctoral degree is in a different field from their bachelor's or Master's degree, these stressors were more common for BME students in our sample, and we expect these would exist for students in any

³ By early-stage, we mean a participant who had not yet completed comprehensive qualifying exams. This obfuscation of year in program is introduced to protect participant anonymity.

interdisciplinary field like BME. The lack of interest in course content (e.g., due to breadth or depth) leads to an **appraisal of demands**: where the classes may present stressors due to difficulty, such as by taking classes in an unfamiliar field, a lack of interest makes it less likely that students perceive classes as **challenges** that present opportunities and rather as **hindrances** to simply “get through” or “check boxes” with.

Career Expectation Differences

In the initial interview and final follow-up interview, some participants discussed their future career plans; our BME participants’ perceptions of industry positions differed from other engineering participants’ plans and opinions. Compared with many other engineering fields, our BME participants more frequently intended to take industry or government positions. Our BME participants also had more prior industry experience: three participants came to their BME doctoral studies from prior industry positions and three of the participants started their programs directly from their undergraduate programs, a higher ratio compared to any other engineering field in our sample. While not inherently a stressor, this finding suggests that career resource needs for BME PhD students may differ from STEM PhD fields with more student expectations for academic-focused career tracks. Navigating career path intentions was not described by all students, however, this was a major stressor experienced by Natasha, an early-stage BME student. The value of industry roles was also described by Veena, who was between her qualifying exam and dissertation proposal defense during the study.

Participants were also asked to describe the value of roles of the various paid positions graduate students could have, such as internships, research and teaching assistantships, and fellowships. While most participants in the full sample did not rate internships as very prestigious, no BME participant suggested a lack of value to internships for doctoral student

workers. By contrast, some other engineering participants considered internships to be “worthless” or a sign of unserious pursuit of academic jobs. Natasha and Veena, instead, considered that internships could be more prestigious than research roles, especially if the internships were “very lucrative” (Natasha). This aligned with Veena’s stated career intentions, as she planned on working in industry. However, Veena described minor experiences of stress regarding these choices, measured against her advisors’ high opinions of research work. Veena described worrying about her advisor “not wanting” her to take her desired career path. Additionally, while Karina and Jan did not describe stressors related to career paths, they both had prior industry experience and Jan used this experience to contextualize differences between industry and academia during his interviews. In our sample, BME participants were more likely to have had or be anticipating industry careers and placed additional value on industry roles in their training and may be more relevant to the experiences of BME students compared with other engineering doctoral students.

Stressors related to navigating career paths were commonly discussed in Natasha’s case and were discussed as major stressors in all four of Natasha’s interviews. We present a summary of her experiences grounded in the JHCS model:

In her first interview, Natasha suggested that she had considered mastering out of her program but was concerned about the impact on her future career: “[in this discipline,] you're not competitive to be able to do R&D in academia or industry or any kind of like supportive sense unless you have a PhD.” Natasha perceived a PhD as an initial **demand** of the types of careers she was interested in. Natasha, as described in the other sections, experienced major stressors in her classes, research, and community. These stressors were major **hindrances** to completing her PhD, and she struggled with a lack of **support** from other students. Natasha described additional

stressors, not reported here, related to her advising relationship, which constitute a further lack of **support**. Natasha debated her desire to complete a PhD throughout the study and ultimately decided to wait out another year before deciding.

In terms of the JHCS model, Natasha's process of choosing whether to stay or depart from her PhD was a process of a job **appraisal**: were the **demands** of a PhD, which she perceived as required to her desired career, **challenges** to overcome along her career trajectory or **hindrances** which caused too much stress to make the process worth it. Natasha was explicit about undergoing this **appraisal** process during her first follow-up interview:

[My] short term goal is just learn a lot more about what I could do with a PhD. [...] Then figure out exactly what I could do with the degree I'm currently pursuing. Because right now, because of the uncertainty, I don't know, I don't feel fully convinced that this is right for me.

This process led Natasha to take a research-focused internship instead of a research assistantship in the summer, particularly because Natasha wanted to experience a job like the ones she considered at the start of her program, which she described in her second follow-up interview. In that interview, Natasha had also spoken with her advisor about her struggles and requested more **support**. By having that conversation and making a plan, Natasha described being less stressed about her career during that interview. We believe that this stress decreased because Natasha's conversation with her advisor and choice of internship over assistantship provided her with additional **control** over her career stressors.

By the final follow-up interview, Natasha had decided on "giving it some more time; seeing how things span out. But honestly, I'm kind of leaning towards leaving and transferring." Natasha described possibly, if she still maintained the same career goals after the year, taking a Master's degree and going to a different institution where she might find a PI in her same department.

While this theme was reported less often than research or course issues, the role of perceptions of BME careers played a direct impact on Natasha's retention and future plans, while interdisciplinary research, described in Natasha's quotes in previous sections, had created major stressors in research, community, and classes. Perceptions such as Natasha's have the potential to be significant to BME students' experience and persistence, as shown in this qualitative case.

Discussion

Engineering-wide interventions to support the research stressors graduate students may not target the specific stressors which emerge from the nature of BME doctoral experiences, namely as more interdisciplinary, broad research experiences with prominent industry interests among students. We argue that social and career support interventions are specifically needed to address some BME stressors. We provide several suggestions for research and lab stressors, class-taking stressors, and career path stressors. We also provide advice for researchers of graduate education in BME and across engineering disciplines. We anticipate that BME departments at other institutions, treated as additional qualitative cases, may comprise students experiencing stressors similar to those discussed in our findings (Creswell & Creswell, 2018, p. 202). We provide our coding scheme and interview online so that this work may be readily replicated or similar work can be conducted: (link redacted for review).

The longitudinal, qualitative design of this study provided the authors with several advantages: rapport with participants was well-established and familiarity with the participants led to comfortable disclosure of stressors throughout the latter interviews and an ongoing 'narrative' of stressors and successes described between interviews. The longitudinal design allowed us to capture the experiences of more stressors. Some stressors exhibit seasonal changes

(such as exam-related stress, or GRFP submissions for early-stage students), and were only discussed during some interviews, or to a greater extent during some interviews. While this was more prevalent for stressors that will be presented in the full study compared to the BME-specific qualitative case, the increase in COVID-19 case reporting during the wave of pandemic cases associated with the omicron variant occurred during the study, leading to some of the research delays described by participants. Repeated instances of stressors allowed for clearer context regarding the prevalence and severity of stressors, deepening our understanding of how the stressors are experienced.

The claim that discipline-level interventions might better address student needs is far from novel, even in BME graduate education research. White and colleagues (2022) found that when designing a first-year support mentoring program for engineering students, breaking the program down by major was required, given “substantial differences” between departmental policies and subcultures (p. 197). Thus, we offer the following suggestions for BME advisors and programs:

For Reducing Stress from Doctoral Student Research

Multiple participants conducting biological research felt stress at research timelines, particularly when ascertaining if satisfactory research progress was being made. Doctoral advisors can provide encouragement and feedback while slower experiments occur and can normalize the experience of slow progress by sharing their own experiences, feelings, and coping strategies with their doctoral mentees. BME department staff and leadership can provide and/or promote resources for student working habits, wellness, time management, socialization, community needs, and in other stress-reducing areas. We recommend that departments send resources at points later in semesters, when students’ need for support may be greater, and

sending emails with targeted subject lines, rather than including resources in larger newsletters or updates. Advisors and instructors can communicate reasonable timelines for research and recall the large number of **demands** (e.g., classes, teaching assistant work, milestone preparation) that graduate students, especially in early stages, are managing.

While the impacts of COVID-19 have slowed at the time of writing, external disruptions to research supplies are possible given economic trends and the possibility of future supply disruptions. Future large-scale unanticipated incidents (e.g., pandemic, extended government shutdown, loss of research funding) are unlikely but possible and may more readily impact biological researchers (e.g., qPCR reagents or PPE become hard to purchase during a pandemic's surge). Additionally, smaller-scale incidents may occur (e.g., contamination, extended power outages during a storm, or a natural disaster damaging sensitive materials). Advisors and dissertation committee members should consider the implications of these incidents on graduation timelines and requirements. In these events, and in coordination with department heads and other appropriate administrators, they should proactively make adjustments to the expectations for graduation of BME students and communicate plans and reassurances to students early on to avoid creating uncertainty or anxiety. Administrators can consider what types of emergency support and provisions can be provided for labs and communities undergoing unexpected disruptions or hardship and communicate these with departments, who can share plans with students. Additionally, department staff and leadership can monitor news for potential supply chain issues and provide warnings or mitigations for researchers.

For Reducing Stress from BME Courses

The focal institution of this study required a set of introductory BME courses; all incoming PhD students take the same set of classes. Our participants suggested that a more

flexible curriculum would be appreciated. Advisors can give insight into which courses best reflect skills and knowledge that are salient to their lab's research, perhaps by maintaining lists of recommended courses, including ones outside of BME departments. These types of lists can also be provided within departments, especially ones with resources for specific content sub-areas (e.g., working groups, communities of practice, graduate minors). A major issue raised by participants was the breadth, instead of depth, of course content. Drawing from examples from undergraduate engineering education may be helpful here, as curricula and courses may be designed to favor "T-shaped" engineering may help orient students and construct expertise (e.g., in Babatope et al., 2020). Instructors of courses with a "survey" or "overview" design can more readily access student interests through independent projects or by including "journal club"-style lessons (Golde, 2007). These classes can also stress participation, attendance, and assignments over examinations or projects to reduce class-related stressors and increase the likelihood of **challenge appraisals** over **hindrance appraisals**.

For Improving Career Planning and Expectations

Our BME participants had a greater focus on past industry experiences and focused more in their interviews on career intentions compared to our larger sample. BME departments can support student career development in a few ways. Short surveys of incoming graduate students' career goals and exit interviews can give departments a feel for what interests their students hold; invited guest speakers, career fairs, industry partners, advertisements for internships and jobs, and course content can be adapted or shared to match these interests. Natasha articulated uncertainty over job requirements and about what the PhD experience would be like. Resources at the undergraduate level can make what sorts of positions are made possible by earning a PhD, versus a Master's or bachelor's degree, clearer, and graduate student speakers at undergraduate

orientations or introductory classes can provide descriptions of student life that might better set expectations for graduate school. However, these resources at early levels should consider helping students explore options, rather than to become siloed into tracks or specialization early on. For later stage students who have had the opportunity to explore options and are interested in graduate studies, undergraduate mentoring programs for students interested in graduate research may help students prepare their career intentions by experiencing research and learning about graduate life from a graduate student mentor (Fallon, 2023).

Limitations

Several limitations to this project warrant discussion. First, participants self-selected to participate in study of stress, suggesting a potential for bias towards higher stress participants. While this effect was partially addressed by financial remuneration for study participation and the purposive sampling of participants to represent the focal institution's engineering PhD student population, any potential self-selection biases supported recruitment of the student population which is most in need of this work. A partial limitation to the transferability of this sample is the small size of the case: we interviewed a limited number of BME students at a single institution. The students in the full study were intentionally stratified by many metrics, consequently students in individual programs did not represent all experiences. Our qualitative case sample was primarily composed of women, and students between their qualifying exams and doctoral defenses. We may not have captured unique stressors experienced by first-year students or students finalizing their dissertations in BME. Our sample did not include students discussing stressors in all BME lab settings; for example, we did not hear descriptions of many stressors experienced outside of wet lab research. We do not claim to have captured the full set of stressors unique to BME students. However, we do find that exploring this subsample as a

qualitative case has provided evidence that policymaking and programming with the intent of reducing stress while aggregating stressors across engineering disciplines may miss key programmatic stressors. Additional limitations include the specific university environment (e.g., policies, cultural and socioeconomic local conditions, local politics) and the effects of this environment on stressors such as finances and microaggressions.

Conclusions

The **job demands** of BME students differ in some important ways from those of engineering students in other disciplines, leading to unique stressors and challenges BME students experience. Our participants described unique stressors in their research work, in classes, and in their perceptions of industry work which impacted their satisfaction and retention. Many of these stressors emerged from the nature of biological lab work and from interdisciplinary research groups and course content. Future research on doctoral student stress and persistence that aggregates by field should critically consider whether, and in what ways, phenomena observed occur across all subdisciplines observed, and how accurate generalized implications are to all participants. Further work closely exploring the experiences of BME students – and experiences in other engineering fields – is warranted. Based on our experience closely exploring this subsample, we expect that stressors unique to many engineering disciplines, individual departments, and local contexts exist. Understanding discipline-specific stressors will be important to improving graduate student experiences.

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