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Exploring Engineering Graduate Students' Perceptions of Creativity in Academic and Research Environments

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Abstract

The purpose of this full research paper is to understand the creative climate of graduate-level engineering education by exploring engineering graduate students' perceptions of creativity in academic and research environments. At its core, the profession of engineering is focused on developing creative solutions to complex problems. Despite increasing calls for engineering education to engage students in curricula that foster creativity, literature shows that in actuality, students do not feel that engineering programs place a high value on fostering creativity. While several studies on creativity at the undergraduate level have attempted to address this discrepancy, there is little research at the graduate level. However, studying creativity at the graduate level is essential because creativity is required to generate new knowledge through research. This study seeks to address the gap in knowledge about graduate-level creativity through a thematic analysis of five semi-structured interviews with engineering graduate students. These interviews are part of a larger mixed-methods research project with the goal of characterizing the creative climate of graduate-level engineering education. In the interviews, we asked participants about their creative endeavors, how they define creativity, and their perceptions of creativity within engineering. We used Hunter et al.'s (2005) creative climate dimensions as a theoretical framework to assess the creative climate of graduate-level engineering education and account for academia's complex interpersonal relationships and organizational structures. Results demonstrate that many of the creative climate dimensions are absent from research group and classroom environments in graduate-level engineering education. This paper is one of the first to explore engineering graduate students' perceptions of creativity within their academic and research environments and offers implications for how graduate-level engineering education can better foster creativity.

1. Introduction and Review of Relevant Literature

Engineering is a creative act. At its core, the profession of engineering is focused on developing creative and novel solutions to complex problems [1]-[8]. In *The Engineer of 2020: Visions of Engineering in the New Century* [9], the National Academy of Engineering stresses that creativity is an essential quality of engineers that should be embraced and cultivated. Despite the increasing calls for engineering education to engage students in curriculums that foster creativity [7], [10]-[13], engineering education does not place a strong emphasis on the development of creative skills and instances of explicit creativity instruction are scarce [14]-[16].

In undergraduate engineering education, learning environments have been criticized for blocking creativity due to their rigid instruction [17], outcomes-based course structure [18], lack of acceptance of risky behavior [15], and inability to promote divergent thinking [19]. As such, Kazerounian and Foley [15] found that engineering undergraduate students perceive a lack of creativity within their education. This lack of creative support negatively impacts students' creative identities. For instance, Zappe et al. [20] found that senior undergraduate students' self-reported creative identity scores were lower than first-year students' scores. In order for students to develop creative problem-solving skills, opportunities must be provided in a supportive learning environment [16],[21], something that appears to be lacking in engineering education.

Additionally, at the undergraduate level, creative self-efficacy was negatively related to engineering undergraduate student persistence [22].

While several studies of creativity in undergraduate engineering education have been published, there is little research on creativity within graduate-level engineering education. Graduate-level engineering education is unique in its combination of academic coursework and research. Creativity is essential for graduate students to gain their degree, as students are expected to creatively generate new knowledge through their research [23],[24]. However, high pressure to produce tangible outputs quickly [25],[26], and the conservative nature of research proposals [24] can inhibit creativity within the broader research community. Just as undergraduate engineering students do not feel like creativity is valued in their education, many graduate-level STEM researchers do not feel like creativity is valued in academia [24].

We risk losing diverse talent from the field of engineering if graduate-level engineering education does not support and clearly communicate the value of creativity to graduate students. Despite efforts to increase diversity in graduate-level engineering education, enrollment is still dominated by white males [27]. A special report from the National Center for Science and Engineering Statistics [27] indicates that <30% women and <20% underrepresented racial and ethnic minorities account for total enrollment in graduate-level engineering degrees. In addition to the underrepresentation of gender, ethnic, and racial minorities, neurodiverse students (e.g., students with ADHD, autism, or dyslexia) are severely underrepresented in engineering [28]. Specifically, several researchers have hypothesized that the connection between creativity and characteristics of ADHD might explain the underrepresentation of students with ADHD in engineering programs [29],[30].

Little is known about the factors that promote and impede creativity within academic and research environments in graduate-level engineering education. The objective of this study is to understand the creative climate of graduate-level engineering education by exploring engineering graduate students' perceptions of creativity in academic and research environments. In this study, we use interviews to collect qualitative data from engineering graduate students to gain an understanding of how graduate engineering education fosters and fails to foster creativity. Emphasizing creativity in graduate-level engineering education has the potential to revitalize engineering programs and increase diversity [8],[31],[32]. Climate studies, such as this one, can help to identify climate dimensions that foster and hinder creativity, so that efforts to revitalize programs can be appropriately directed.

2. Theoretical Orientation

Creativity is commonly seen as a function of the interaction between people and their environment [33]. In climate studies, assessing people's perceptions of, or experiences in, their environments have been a predictor of creativity [34]. Within a climate, such as graduate school, multiple dimensions (e.g., autonomy, resources, positive supervisor relations) can influence creativity [35]. Hunter et al. [35] derived 14 creative climate dimensions (i.e., positive peer group, positive supervisor relations, resources, challenge, mission clarity, autonomy, positive interpersonal exchange, intellectual stimulation, top management support, reward orientation, flexibility and risk-taking, product emphasis, participation, and organizational integration) for traditional workplaces. Because engineering graduate programs are dynamic environments with complex interpersonal relationships and structural influences that exist in both academic and research settings, we modified the definitions of these dimensions to reflect research group and classroom climates. Additionally, we removed two creative climate dimensions from our codebook. First, we removed *top management support* because research advisors and professors serve as both the supervisor and top management in research and academic environments, respectively. Second, we removed *positive interpersonal exchange* due to the similarity in definitions between the *positive peer group* and *positive interpersonal exchange* dimensions. Four of the most frequently referenced dimensions in subsequent sections of this paper can be found in Table 1, and the rest of the 12 creative climate dimensions used in this study can be found in Appendix Table A1. Understanding engineering graduate students' perceptions of creativity within their academic and research environments will allow for the identification of how creativity is promoted and blocked in each environment.

Table 1. Creative Climate Dimensions Adapted from Hunter et al. (2005) for Graduate-level Engineering Research Groups and Classrooms (**see Appendix Table A1 for the other creative climate dimensions' definitions**)

Climate Dimensions	**Research Group Definition**	**Classroom Definition**
Positive Peer Group	Overall, I feel supported and intellectually stimulated by the other graduate students in my research group. Overall, my relationship with the other graduate students in my research group is characterized by trust, openness, humor, and good communication.	Overall, I feel supported and intellectually stimulated by my classmates in my graduate-level engineering classes. Overall, my relationship with my classmates in my graduate-level engineering classes is characterized by trust, openness, humor, and good communication.
Positive Supervisor Relations	My research advisor(s) is supportive of new and innovative ideas. My research advisor operates in a non-controlling manner.	Overall, my professors are supportive of new and innovative ideas in my graduate-level engineering course assignments.
Autonomy	I have autonomy and creative freedom when I conduct my research.	Overall, I have autonomy and creative freedom when I work on my graduate-level engineering course assignments.
Reward Orientation	My research advisor(s) praises and/or rewards creativity.	Overall, my professors praise and/or reward creativity with a good grade in my graduate-level engineering classes.

3. Positionality and Role of the Researchers

First author: Because I am a graduate student, an identity that I share with my participants, it is likely that participants felt comfortable sharing their honest thoughts and feelings about their graduate-level engineering education experiences with me. In order to maintain the integrity of this study and not bias participant responses, I did not share my thoughts, feelings, or individual experiences during the interview. Additionally, I only asked follow-up questions based on the information that they shared with me during the interview.

Second author: My perspectives and experiences as a past graduate student in a traditional engineering discipline, and in engineering education research, and now as a faculty member in a traditional engineering space influence the theoretical perspectives and epistemological considerations through which I understand social data, overarchingly from a psychosocial and constructivist point of view, and inform my longstanding research interest and expertise areas in investigating graduate student experiences, development, thriving, and attrition and retention. While the work in this paper is driven by the first author, my role in this research was to facilitate these perspectives on creativity and the interpretations with respect to the current body of literature in graduate engineering education.

4. Methods

This study seeks to address the gap in knowledge about creativity in graduate-level engineering programs through a thematic analysis of five semi-structured interviews with engineering graduate students. These interviews are part of a larger Institutional Review Board (IRB) - approved, nationwide mixed-methods research project to understand the creative climate of graduate-level engineering education. Quality was upheld throughout each phase of the research process from data collection to data analysis and writing [36].

4.1. Participants and Recruitment

After obtaining approval from the Pennsylvania State University IRB, we used purposeful sampling to recruit five engineering graduate students based on our pre-existing knowledge of their engineering and creative arts experiences. These participants were also selected through maximum variation sampling for race/ethnicity, gender, and number of years in graduate school [37] (**Table 2**). Using maximum variation sampling allows us to capture the experiences of participants who have marginalized identities in engineering.

Table 2. Number of participants identifying with different categories, which include the number of years in graduate school, gender, and race/ethnicity for n = 5 participants

	Number of Participants
Years in Graduate School	
1	2
2	2
5	1
Gender	
Men	3
Women	2
Race/Ethnicity	
One Selected	4
African American or Black	1
Asian	1
Hispanic or Latin American	1
White	1
Multiple Selected	1
Asian	1
Native Hawaiian or Other Pacific Islander	1
White	1

4.2. Data collection and analysis

Data was collected via semi-structured interviews conducted by the first author [38]. The interview protocol, which was validated through multiple pilot studies, was designed to explore how Hunter et al.'s [35] creative climate dimensions are or are not experienced by graduate students within their research groups and graduate-level engineering classes. Due to the semi-structured nature of the interview, the order of the questions and follow-up questions were altered based on the interviewer's perception of the directionality of the interview [38]. Participants were also asked to reflect on their journey into engineering, definition of creativity, definition of engineering, creative identity, and creative and/or performing arts experiences. Additionally, participants were asked if their advisors, lab mates, professors, and classmates view them as a creative person and if they view their advisors, lab mates, professors, and classmates as creative people. After each interview, the transcript was reviewed and any new questions that arose due to the semi-structured nature of the interviews were asked in subsequent interviews when appropriate.

Interviews were conducted on the Zoom videoconferencing platform and lasted between 40 and 150 minutes. Participants were asked to verbally provide their informed consent prior to the beginning of each interview. At the end of each interview, participants were asked to select a pseudonym. All interview audio files were transcribed using the Zoom transcription feature. During the transcription verification process, the first author removed all identifying information from the transcripts. The participants' engineering disciplines were also redacted to protect their confidentiality since including these additional identifiers significantly increases the chances of identifiability.

During the transcription verification process, memos were created to guide the coding and thematic analysis of the interview transcripts. The interview data was analyzed using emergent open and axial coding methods through a constructivist paradigm. Hunter et al.'s [35] creative climate dimensions, modified for research group and classroom climates, served as an a priori codebook (**see Appendix Table A1**). The first round of broad coding consisted of identifying the presence or absence of the creative climate dimensions. Additionally, the responses to questions concerning the participants' journey into engineering, definition of creativity, definition of engineering, creative identity, and creative and/or performing arts experiences were coded. The second round of finer coding focused on examining the relationships among the creative climate dimensions and participants' responses to the other interview questions. For instance, when a participant was describing *positive supervisor relations*, we noted the presence or absence of the other creative climate dimensions that the participant mentioned within that same quotation.

5. Limitations

This study represents the creative climate perceptions of only five graduate-level engineering students in regards to their research group and classroom environments and should not be generalized to all students. These participants were also selected based on previous knowledge of their creative backgrounds. Instead, the emergent themes shed light on how students perceive the creative climate of their graduate level engineering experiences. Additionally, redacting identifiable information, such as gendered pronouns, and separating the identity categories in Table 2 from the pseudonyms, removes aspects of the quotes that would result in an even richer description of the participants' experiences.

6. Results

We used Hunter et al.'s [35] creative climate dimensions to guide the analysis of the interview data. Specifically, we thematically analyzed the interview data using an abductive coding approach to identify contexts in which creativity is enhanced and hindered in graduate-level engineering research groups and classrooms. We present our findings in three sections. First, we focus on the five participants' (i.e., Atticus, Chopper, Felicia, Dwight, and Rain) creative personal identities and overall perceptions of creativity within graduate-level engineering education. Next, the creative climate of research groups and classrooms are presented. It should be noted that not all participants explicitly discussed aspects of each of the creative climate dimensions in research and academic environments. Furthermore, the creative climate dimensions that were explicitly mentioned across interviews provide insight into the dimensions with a strong influence over the creative climate in graduate-level engineering education.

6.1. Creative Personal Identities

Each participant was asked to define creativity in their own words. These definitions were unique to each participant with little overlap among the responses, which ranged from generating ideas, exploring different perspectives and connections with an open mind, and expressing themselves while bringing their own visions to life. Participants were also asked to define what it means to be an engineer. Unlike the creativity definitions, these responses were more similar to one another. Participants described engineers as people who leverage math and science to solve problems and create new things, which also aligns with each participant's motive for pursuing a graduate degree in engineering. This desire to create and the critical importance of creativity in graduate-level engineering education was discussed by Chopper and echoed by the other participants.

> *"Creating the research project itself is a creative endeavor… problem solving works with creativity, but also creating an experiment is where the main crux of creativity comes in." — Chopper*

The participants shared that they not only express their creativity through their research in the way that they design, conduct, and analyze data from research studies, they also express it in creative hobbies which ranged from drawing and fashion design to creative writing and fiber arts. However, despite engaging in creative hobbies, Chopper, Dwight, and Felicia initially said that they did not consider themselves to be creative people. Dwight and Chopper shared the same view as Felicia, who stated that they associate creative people with the arts.

> *"As far as when I describe people as creative, I am not like those people… it's often someone that is very into the arts… My first instinct is to link creativity with artistic, but that's not necessarily the case all the time, but that's where my mind immediately goes to." — Felicia*

However, after a series of follow-up questions, Chopper, Dwight, and Felicia remarked that they are creative people when they are conducting research. Conversely, Atticus and Rain had particularly strong creative personal identities and immediately answered yes when asked if they consider themselves a creative person. They easily spoke about their hobbies and creative approaches to research.

6.2. The Creative Climate of Research Groups

Of Hunter et al.'s (2005) creative climate dimensions, *positive supervisor relations* appear to exert the strongest influence over the creative climate within research groups. Atticus shared that their research advisor *"encourages creativity by not hand holding me too hard, and just letting me free into the open world."* Everyone except Rain, who had a very distant relationship with their research advisor, described their research advisor as a creative person and attributed their advisor's creativity to their wealth of knowledge and ability to generate ideas. However, having a creative advisor does not always mean that there are *positive supervisor relations*. Despite being a creative person, Dwight's research advisor actively shut down creativity in their research group.

> "*I would describe [my advisor] as a creative person… I feel like you can be a creative person on your own, and you can squash creativity in other people… When I have come to [my advisor] with ideas or results, or something that is like beyond exactly what we*

> *have been working on, it is oftentimes minimized… because it's so new… because it's preliminary… There's a lack of understanding of the creative process, which is just like you have to think of a new thing, or think up something unexpected, and not every time it's gonna pan out in the way that you thought it was gonna pan out… not every time it's gonna be a success... I think that part of the process is penalized a lot. Or if you're not successful on the first try, then there's not a lot of support, at least in my experience. There's not a lot of support around that, or it's like a "your fault" kind of thing…"— Dwight*

Despite lacking *positive supervisor relation*s, Dwight and Rain still had *autonomy* in their research. However, this *autonomy* was not a result of their research advisor actively trying to give them space to express their creativity, but rather because their research advisors were so uninvolved. However, having *autonomy* without *positive supervisor relations* can hinder research progress, as Rain explains.

> *"…I definitely feel like I need a guiding hand to support me in the right direction. Am I reading the right material? Am I asking the right questions? Am I connecting to the right people? Am I formulating my methods correctly? And does it then kind of flow well with my theoretical frameworks? And just getting that support makes a huge difference on how you bring your creativity to life, and how you answer the questions or not, and whether you do it successfully or not."— Rain*

The *autonomy* Rain and Dwight experienced can be attributed to the fact that they are agentic individuals who prioritize their own creative freedom. However, as Dwight explains, embarking on a creative endeavor in research without *positive supervisor relations* leads to anxiety and doubt.

> *"… [Taking a creative risk in my research] felt anxiety inducing honestly because… people want you to follow the status quo or the easiest route, or the path of least resistance, but that is not, you know, creativity… What I felt like is, I had to do it behind people's backs you know… I had to be like, okay, this is what I want to do, and I know it's gonna be okay. You have to have some level of confidence in the question that you are wanting to address… and then once I had the results that kind of were compelling enough, is when I could then bring it to people."— Dwight*

Despite having creative research advisors and being creative people themselves, no participant was confident that their research advisor sees them as a creative person. Participants shared that creativity is not regularly praised or rewarded by their research advisors, which is a lack of *reward orientation*. *Positive peer group*, *participation,* and *intellectual stimulation* were lacking among all participants. This lack of explicit creative culture within a research group leads to no one feeling particularly supported and intellectually stimulated by their lab mates. However, participants described sporadic instances of collaboration with their lab mates as energizing experiences. Felicia found seeing their lab mates demonstrate creativity to be particularly motivating.

> "*I often want to jump in I think because it's interesting… When you're in a creative space, it doesn't hurt to have somebody to, even if it's just like a mirror, to bounce things off of, and that will help a lot in your process." — Felicia*

While participants noted that they experience *challenge* and enjoy their research overall, everyone talked about working on their projects independently with little to no collaboration (*participation*) with their lab mates.

6.3. The Creative Climate of Classrooms

Upon analysis of the classroom creative climate data, it was clear that the creative climate is dependent on the type of class, assignment- and exam-based classes versus project-based classes. Assessing the creative climate for each type of class provides an insight into how class type influences the presence or absence of the creative climate dimensions.

6.3.1. Assignment- and Exam-based Classes

The majority of participants who took traditional engineering classes did not experience *positive supervisor relations*. The lack of *positive supervisor relations* resulted in a lack of *autonomy*. Participants described assignment- and exam-based classes as rigid with few, if any, opportunities to display creativity. Every participant mentioned that in these types of classes, professors are looking for one correct answer and one way of doing things. Atticus emphasized this when they said,

> *"I mean, there's only one way to do the problem, there's only one way to get the solution... there's no creativity in that, you know, there's like rules." — Atticus*

When asked if Chopper viewed their professors as creative people, they responded,

> *"No… [Professors] teach a way how to do it. You have to do it that way. There's a solution you have to follow. Sure, there's maybe like in coding stuff there's like several different approaches, but it all comes down to one answer."— Chopper*

Because professors are not encouraging students to be creative, the participants do not view their professors as creative people. A lack of *positive supervisor relations* resulted in a lack of all the other creative climate dimensions in assignment- and exam-based classrooms. Furthermore, because students are not given the opportunity to display creativity, they do not think their peers or professors see them as creative people as Atticus explains,

> *"What about my classmates… do they think I'm creative?… I think they probably don't think I'm creative… The classes that I've taken… have been very theory based… I think it's an environment where it's hard to see creativity."— Atticus*

6.3.2. Project-based Classes

In project-based classes, most participants had *positive supervisor relations*, *autonomy* and *reward orientation*. Overall, participants felt like they were able to display creativity in classes that were project-based. Felicia explained that in engineering design courses, *"creativity is necessary because there are eight right answers."* Project-based classes reward creativity through verbal praise or extra credit of an innovative feature in a project. However, Rain pointed out that *positive supervisor relations* determine the creative climate of even project-based courses.

> *"It's so rigid and structured. Even in my design courses here, there's something very specific they're looking for that kind of hinders that creativity."— Rain*

In contrast to assignment- and exam-based classes, participants viewed their project-based class professors as creative people because they were actively demonstrating creativity in class.

The combination of *positive supervisor relations* and *reward orientation* creates a climate where students feel comfortable displaying their creativity. However, even in project-based classes participants did not describe instances of *positive peer group* relationships. Even on team projects, there was not a strong bond among teammates. Also, despite the enhanced creative climate in project-based classes, students still lamented about the pressure to be creative for a grade.

7. Discussion

In this work, we explored the presence and absence of Hunter et al.'s [35] creative climate dimensions within graduate-level engineering education. This thematic analysis highlights three main points of discussion, (1) artistic creativity versus engineering creativity, (2) *positive supervisor relations* exert a strong influence over creativity within research groups and (3) the type of graduate-level engineering class, assignment- and exam-based versus project-based, exerts a strong influence over the creative climate of classrooms. Overall, there are many creative climate dimensions that participants explicitly indicated were lacking in addition to dimensions that were not highlighted often, if at all, throughout the interviews.

Artistic creativity is seen as creativity with more freedom and aesthetic beauty [24],[32], whereas engineering creativity is seen as useful and functional creativity [20]. This discrepancy is evident in the participants' definitions of creativity, which were varied and reflect the innately personal aspect of creativity. Conversely, participants' definitions of engineering were quite similar to one another and aligned with Pawley's [39] study which found that faculty members' definition of engineering includes applied science and math, solving problems, and making things. Zappe et al. [13] indicated that there is no consistent definition of creativity used within engineering education research. Perhaps if creativity was explicitly emphasized in engineering education, students would have a broader definition of engineering that aligned more with their definition of creativity.

Although participants did not think that their research advisors viewed them as creative people, participants viewed their research advisors as creative people due to their high domain expertise by correlating their research advisor's creativity with their wealth of knowledge and ability to problem solve [40]. Many participants shared that they wanted to pursue a graduate degree because they wanted to deepen their knowledge. Research advisors exert a strong influence over the creative climate within their research groups. Participants with *positive supervisor relations* enjoyed having *autonomy* in their research to explore their topic in depth (*challenge*). However, even participants that experienced *positive supervisor relations* lacked the *positive peer group* dimension. Hunter et al. [41] found that *intellectual stimulation* and *positive peer groups* had a particularly strong positive influence on the creative climate of workplaces. Based on the participants responses, they all work independently on research projects with little collaboration among their lab mates. Graduate level research can be a particularly isolating experience, but the sporadic instances of collaboration were described as motivating and energizing by participants.

The strong divide between assignment- and exam-based classes and project-based classes highlights the influence of class type on the creative climate within graduate-level engineering classrooms. The assignment- and exam-based classes emphasize technical skill development and convergent thinking by having students work towards solving problems with only one right answer [8]. These classes typically lack almost all the creative climate dimensions by impeding creative thinking and not providing students with opportunities to develop creative thinking skills [13],[19]. The participants' responses align with previous literature, which has found that the typical engineering graduate level curriculum is heavily skewed toward convergent, analytical work [8]. Based on the participants' responses, it appears that assignment- and exam-based classes shut down creativity on all levels. On the other hand, when participants described their experiences in project-based classes there was a noticeable difference in the creative climate. Oftentimes, project-based classes were characterized by the presence of *positive supervisor relations*, *reward orientation*, and *autonomy*. Instructors have the ability to foster creativity by showing their creative side, rewarding creativity, and giving students the opportunity to explore and create. Furthermore, you cannot have a creative climate if creativity is not on full display. However, even project-based classes can kill creativity by placing too high of an emphasis on grades, which aligns with Gardner's [42] stance that the "absence of evaluation seems to liberate creativity".

8. Implications

In order to fully understand how engineering graduate students perceive the creative climate of research groups and classrooms, a deep exploration of their creative self-efficacy and creative personal identity is necessary. Creative personal identity (CPI) is "the overall importance a person places on creativity in general as part of [their] self-definition" [43]. Atticus and Rain appear to have a strong CPI based on their responses, whereas Chopper, Felicia, and Dwight seem to have a weaker CPI. However, a weaker CPI can also be tied to the concept of little-c versus Big-C creativity, where little-c creativity (i.e., everyday creativity) is seen as more common than Big-C creativity (i.e., eminent creativity) [44],[45]. While Chopper, Felicia, and Dwight see themselves as creative within their research, they don't see themselves at the same level of creativity as artists. The distinction between artistic creativity and engineering creativity was also evident in the participants' responses when they described expressing creativity in their hobbies versus research.

All graduate students viewed research as a creative act because they need to creatively generate new knowledge [23],[24]. Furthermore, all participants saw themselves as people who could be creative within research, which aligns with the concept of creative self-efficacy (CSE), "the belief that one has the ability to produce creative outcomes" [46]. CSE and CPI are intertwined yet distinct constructs [47]. For instance, an increase in CPI typically leads to an increase in CSE in organizational settings [48]. Bandura [49] noted that supervisors heavily influence self-efficacy through modelling creativity and *reward orientation* [50]. However, despite demonstrating creativity through their research, participants did not think that their research advisors saw them as creative people due to a lack of *reward orientation*. Because graduate students are still developing as researchers, validation is necessary to let them know that they are on the right track [51]. Being creative is risky, and supporting creative efforts helps to increase CSE [48],[52]. Atwood & Pretz [22] similarly found this lack of *reward orientation* in undergraduate engineering education as well as a negative relationship between CSE and student persistence in engineering.

In order to retain creative talent in engineering education, creativity must be rewarded and supported. This support could not only come from research advisors, but also peers. Perhaps if research advisors facilitated more collaboration among graduate students on research projects, then the creative climate of research groups could be strengthened. Seeing peers engage in creative acts helps individuals develop their own creative reference frame and identity [52],[53]. However, the lack of a strong creative climate creates an environment where students do not feel comfortable sharing their creative identities. Engineering education should strive to create environments where creativity is on full display because engineering is a creative act.

9. Conclusion

This paper presented a thematic analysis of five engineering graduate students' perceptions of the creative climate within their research group and classroom environments. We used Hunter et al.'s [35] creative climate dimensions to assess the creative climate of research group and classroom environments. Several themes emerged from the data, specifically, the influence of *positive supervisor relations* on the creative climate of research groups, the distinction between assignment- and exam-based classes and project-based classes, and the lack of peer collaboration in research and classroom environments. Future work on this project includes a nationwide survey assessing the creative climate of research groups, classrooms, and departments and creative personal identity and creative self-efficacy of engineering graduate students. Additionally, more interviews will be conducted to better understand the creative climate and engineering graduate students' creative processes, including how students transfer skills from their creative hobbies into their lives as engineering graduate students.

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Appendix

Table A1. 12 Creative Climate Dimensions Adapted from Hunter et al. (2005) for Graduate-level Engineering Research Groups and Classrooms

Climate Dimensions	**Research Group Definition**	**Classroom Definition**
Positive Peer Group	Overall, I feel supported and intellectually stimulated by the other graduate students in my research group. Overall, my relationship with the other graduate students in my research group is characterized by trust, openness, humor, and good communication.	Overall, I feel supported and intellectually stimulated by my classmates in my graduate-level engineering classes. Overall, my relationship with my classmates in my graduate-level engineering classes is characterized by trust, openness, humor, and good communication.
Positive Supervisor Relations	My research advisor(s) is supportive of new and innovative ideas. My research advisor operates in a non-controlling manner.	Overall, my professors are supportive of new and innovative ideas in my graduate-level engineering course assignments.
Resources	My research advisor has resources to facilitate, encourage, and eventually implement creative ideas.	Overall, my professors have resources to facilitate, encourage, and eventually implement creative

		ideas in my graduate-level engineering classes.
Challenge	My research is challenging, complex, and interesting. My research is not overly taxing or excessively overwhelming.	Overall, my graduate-level engineering coursework is challenging, complex, and interesting. Overall, my graduate-level engineering coursework is not overly taxing or excessively overwhelming.
Mission Clarity	My research advisor(s) and I have clear communication regarding my research goals and expectations. My research advisor(s) and I have clear communication about goals and expectations regarding creativity.	Overall, my professors clearly communicate course goals in my graduate-level engineering classes. Overall, my professors clearly communicate goals and expectations regarding creativity in my graduate-level engineering classes.
Autonomy	I have autonomy and creative freedom when I conduct my research.	Overall, I have autonomy and creative freedom when I work on my graduate-level engineering course assignments.
Intellectual Stimulation	The debate and discussion of ideas is encouraged and supported in my research group.	Overall, the debate and discussion of ideas is encouraged and supported in my graduate-level engineering classes.
Reward Orientation	My research advisor(s) praises and/or rewards creativity.	Overall, my professors praise and/or reward creativity with a good grade in my graduate-level engineering classes.
Flexibility and Risk-Taking	My research group is willing to take risks and deal with the uncertainty associated with creativity.	Overall, my professors encourage me to take risks and deal with the uncertainty associated with creativity in my graduate-level engineering course assignments.
Product Emphasis	My research group is committed to quality as well as originality of ideas.	Overall, my professors are committed to quality as well as originality of ideas in my graduate-level engineering course assignments.
Participation	Collaboration among research group members is encouraged and supported by my research advisor(s). In my research group,	Overall, collaboration among classmates is encouraged and supported by my professors in my graduate-level engineering classes.

	communication between research group members and our research advisor(s) is clear, open, and effective.	Overall, communication between my classmates and professors is clear, open, and effective in my graduate-level engineering classes.
Organizational Integration	My research group collaborates with other research groups within my university. My research group collaborates with other research groups, companies, and/or organizations outside of my university.	Overall, my graduate-level engineering classes showcase engineering innovations from my university in lectures, homework problems, and/or projects. Overall, my graduate-level engineering classes showcase engineering innovations from other universities, companies, and/or organizations in lectures, homework problems, and/or projects.