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Skill Development of Engineering and Physical Science Doctoral Students: Understanding the Role of Advisor, Faculty, and Peer Interactions

Abdulrahman Alsharif, Virginia Polytechnic Institute and State University

Abdulrahman Alsharif is a research assistant for the Engineering Education Department and a PhD candidate at Virginia Tech.

Dr. Maya Denton, University of Oklahoma

Maya Denton is an Assistant Professor of Engineering Pathways in the Gallogly College of Engineering at the University of Oklahoma. She received her B.S. in Chemical Engineering from Purdue University, and her M.S. in Environmental Engineering and PhD in STEM Education from the University of Texas at Austin.

Dr. David B. Knight, Virginia Polytechnic Institute and State University

David Knight is a Professor in the Department of Engineering Education at Virginia Tech and also serves as Special Assistant to the Dean for Strategic Plan Implementation in the College of Engineering. His research tends to be at the macro-scale, focused on a systems-level perspective of how engineering education can become more effective, efficient, and inclusive, and considers the intersection between policy and organizational contexts. Knight currently serves as the co-Editor-in-Chief of the Journal of Engineering Education.

Dr. Maura Borrego, University of Texas at Austin

Maura Borrego is Director of the Center for Engineering Education and Professor of Mechanical Engineering and STEM Education at the University of Texas at Austin. Dr. Borrego is Senior Associaate Editor for Journal of Women and Minorities in Science and E

Dr. Andrew Katz, Virginia Polytechnic Institute and State University

Andrew Katz is an assistant professor in the Department of Engineering Education at Virginia Tech. He leads the Improving Decisions in Engineering Education Agents and Systems (IDEEAS) Lab.

Skill Development of Engineering and Physical Science Doctoral Students: Understanding the Role of Advisor, Faculty, and Peer Interactions

Our research paper examines the role of climate (e.g., interactions with others) in the skill development of engineering and physical science doctoral students. Skill development in graduate school often occurs related to students' primary funding mechanism, in which they might interact with a research group or teaching team. Advisors also play a pivotal role in the engineering doctoral student experience; however, less is known about how positive mentoring influences skill development for engineering doctoral students. We investigated the following research questions:

1) How, if at all, do interactions with advisor(s), faculty, and peers predict skill development (associated with primary funding mechanism) for engineering and physical science doctoral students?
2) Specifically, how do such interactions predict skill development (associated with primary funding mechanism) for the following career-related skills: a) research, b) teamwork and project management, c) peer training and mentoring, and d) communication?

We administered the Graduate Student Funding Survey to engineering and physical science doctoral programs in the United States, with focused sampling of institutions that produce a high number of doctorates and that have highly ranked programs. We developed the survey, including survey items on demographics, funding mechanism, skill development, and climate (i.e., interactions with others). Data collection occurred in Fall 2019 (n = 615). We did not restrict respondents based on year of study or citizenship status. Following data collection, we conducted an exploratory factor analysis (EFA) on the interaction survey items, resulting in three climate factors: 1) Advising climate (9 items), 2) Faculty and staff climate (4 items), and 3) Peer climate (4 items). In our findings, we report descriptive statistics for field of study, gender, race/ethnicity, and citizenship status. We ran stepwise logistic regression models for each skill development variable (research, teamwork and project management, peer training and mentoring, and communication), for four regression models in total. Independent variables for the models included demographics, funding mechanism, and the climate factors. We found that advising climate was statistically significant for all four career-related skills, faculty and staff climate for peer training and mentoring skills only, and peer climate for both peer training and mentoring and communication skills. All statistically significant climate variables positively predicted skill development. Our findings highlight the importance of climate within engineering doctoral programs, quantifying how a positive climate promotes development of career-related skills. Future work should examine the specific actions that contribute to a positive climate and provide further guidance on how graduate programs can adopt such practices at their institutions.

Introduction

Preparing a competent and inventive scientific workforce is important to America's economic development; in order to stay competitive, the country needs a steady supply of qualified scientists and engineers [1]. However, the workforce needs scientists with research skills and the capacity to break new theoretical ground [2]. Therefore, the purpose of graduate education is to help students become scholars and researchers, not just highly certified workers [3]. To accomplish this goal, many STEM graduate students in the United States receive funding support during their doctoral studies through several forms of funding, such as fellowships, research assistantships, and teaching assistantships [4, 5]. However, little is known about graduate students' skill development related to their funding mechanism(s); it is anticipated that skills would grow as a result of graduate-level training or socializing [6].

Prior research has focused on the exploration of doctoral student funding and its relation to student development in terms of graduation timeline, job outcomes, student agency, and professional productivity [7-11]. A few studies explain graduate student interactions with advisors, peers, and faculty as a form of socialization [12, 13]. Another study explored the role of the research group in regard to interactions with advisor(s) and peers, communication, and mentorship in the context of learning and the development of professional skills [7]. Crede and Borrego [7] state: "Regardless of disciplinary differences, the role of the advisor and effects of peers have been shown to be of critical importance to student success in graduate school" (p. 101). However, the relationship between interactions with advisor(s), faculty and staff, and peers during graduate school and the skill development associated with doctoral student funding has rarely been studied.

Our previous research found that the development of career-related skills (e.g., research, teamwork and project management, peer training and mentoring, and communication) associated with primary funding mechanism for STEM doctoral students were predicted by type of funding mechanism [9]. We build on our prior work to examine the role of climate (interactions with others) in skill development, with a focus on engineering and the physical sciences. Our research questions are as follows:

1) How, if at all, do interactions with advisor(s), faculty, and peers predict skill development (associated with primary funding mechanism) for engineering and physical science doctoral students?
2) Specifically, how do such interactions predict skill development (associated with primary funding mechanism) for the following career-related skills: a) research, b) teamwork and project management, c) peer training and mentoring, and d) communication?

Literature Review

Graduate students' professional development is linked to their satisfaction with their advisors [14]. Themes related to advisor satisfaction found in Schlosser, et al. [14] include frequent meetings, meeting availability, educational and career guidance, addressing students as colleagues, fostering professional involvement, and showing interest in students' research. Advisor guidance in career trajectory and encouragement for professional involvement are important aspects of the overall career development for students [14]. Recent research shows that a complex interaction of several layers of graduate school cultures, networks, and structures shapes graduate students' experiences, and this interaction is a key factor in developing professional skills [15]. The supervisory connection advisors form with graduate students, along with peer learning that occurs outside of advisors' presence, are critical components of students' development in graduate school and particularly in research groups [7]. The interactions of these two factors (e.g., advisors and peers) play a crucial role in a student's performance in research environments [7].

Graduate students are often engaged in faculty-led laboratories (or research groups) and collaborative teams as students develop both their teaching and research skills [7, 16, 17]. Depending on the size of the research group, faculty advisors' roles and interactions might vary (e.g., large-size, mid-size, or sub-size) [7]. Crede and Borrego found that there were substantial differences in the perceived roles and interactions between faculty and graduate students across different sized labs [7]. In particular, large-sized groups appeared to be run more like small businesses (i.e., advisors requesting information on deliverables, following up on specific parts of the project, and ensuring that everything proceeds according to plan), whereas small-sized groups had stronger student-advisor relationships. Moreover, faculty advisers who perceive greater levels of expertise may offer more important or challenging assignments to graduate students, accelerating their skill development and scholarly productivity [6].

Borrego, et al. [8] research investigated STEM graduate students' agency in relation to degree progression and career preparedness. They found that students with supportive advisers, adequate funds, and an interest in industrial positions sought out short-term summer internships to learn more about the industry and develop their skills, but students were unable to explain how their funding type prepared them for the industry. Summer internships can help students advance their professional development and prepare them for industry, and advisors can assist students in exploring career development options that suit their individual needs and abilities. However, it should be noted that these papers investigated different aspects of advising, faculty, and peer interactions at the graduate level. They are a collective effort to improve our overall understanding of the topic and cannot inform our understanding of the career-related skill development of STEM doctoral students' in relation to their interactions with advisors, faculty, and peers.

Methods

Researchers on our team developed the Graduate Student Funding Survey, which we used to survey STEM doctoral programs in the United States. Following data cleaning, we focused on predicting skill development (associated with primary funding mechanism) through stepwise logistic regression models. We build on our prior work that predicted skill development through primary funding mechanism for a larger sample (all of STEM, rather than engineering and physical sciences only) and did not include the climate variables in their models [9]. In this analysis, we focus largely on the findings related to the climate variables and context specific to engineering.

Data Collection

We administered the Graduate Student Funding Survey to STEM doctoral programs in the United States, with focused sampling of institutions that produce a high number of doctorates and have highly ranked programs. In addition, we prioritized institutions that offered doctoral programs in multiple STEM disciplines (our target disciplines included biological sciences, chemical engineering, chemistry, civil engineering, electrical engineering, math/statistics, mechanical engineering, and physics). We collected data in Fall 2019, working with university officials and departmental leaders at 35 institutions to help us administer the survey. Our prior work contains additional information about survey development [9]. The Graduate Student Funding Survey had survey items on demographics, funding mechanism, skill development associated with primary funding mechanism, and climate (e.g., interactions with others), which we use in our analysis. The survey questions about climate focused on advisors (10 items), faculty and staff (4 items), and peers (4 items).

Participants

In total, 1162 doctoral students responded to the Graduate Student Funding Survey. We removed respondents if they did not fully respond to certain questions needed for our analysis. The initial dataset included respondents in engineering, the physical sciences, and the life sciences. When we ran the exploratory factor analysis for the climate variables (see Variables section and Results), the life sciences grouped the climate variables differently when compared to engineering and the physical sciences. Unlike the other fields, the life sciences loaded *faculty climate* and *peer climate* as one factor. We excluded life sciences from our analysis due to the differing results and because of our focus on engineering. With the cleaned dataset and removal of life sciences respondents, we included 615 respondents in our final dataset. We show descriptive statistics for the final dataset below (see Table 1).

Table 1. Descriptive statistics of respondents (n=615)

	N (%)
Field of study	
Engineering	433 (70%)
Physical sciences	182 (30%)
Gender	
Man	352 (57%)
Woman	255 (42%)
Genderqueer/gender non-conforming	5 (0%)
Decline to state	3 (0%)
Citizenship	
U.S. citizen	382 (63%)
Non-U.S. citizen	233 (37%)
Race/ethnicity	
White	325 (53%)
Black	19 (3%)
Hispanic	55 (9%)
Asian	196 (32%)
Other	20 (3%)

Variables

Dependent variables. We used skill development variables (associated with primary funding mechanism) as the dependent variables in our models. In our prior work, we conducted an exploratory factor analysis to create the skill development variables [9]. In the Graduate Student Funding Survey, respondents answered items following the prompt: "Describe the following aspects of your skill development associated with your current primary funding source. My current primary funding source helped me learn how to [followed by specific survey item(s)]". This exploratory factor analysis resulted in four skill development variables: *research skills*, *teamwork and project management skills*, *peer training and mentoring skills*, and *communication skills*. The four skill development variables were re-coded to be categorial variables, with 0 indicating low agreement and 1 indicating high agreement. Our prior work provides further details on the exploratory factor analysis and re-coding procedures used to create the skill development variables [9].

Independent Variables. We included independent variables for primary funding mechanism and climate. Primary funding mechanism was a categorial variable, with the categories of *research assistantship*, *external fellowship*, *internal fellowship*, and *teaching assistantship*. Internal fellowships are from the university, while external fellowships are from sources outside of the university. We used *research assistantship* as the reference group. We conducted an exploratory factor analysis (EFA) to create the climate variables (see Table 2). The EFA resulted in three climate variables: *advising climate*, *faculty climate*, and *peer climate*. The climate questions on the Graduate Student Funding Survey were measured on a Likert-type scale from 1 (strongly disagree) to 5 (strongly agree). The three climate variables were then re-coded to be categorical variables, with 0 indicating low agreement and 1 indicating high agreement (i.e., score of 4 or higher). One item from the survey questions about advisor climate did not load on the corresponding factor.

Table 2. Exploratory factor analysis for climate variables (n=615)

Question	Factor	Item	Loadings	Cronbach's Alpha
Please indicate your level of agreement with the following statements about your current dissertation advisor(s):	Advising climate	Prioritizes my dissertation progress.	0.66	0.85
		Facilitates interaction with other faculty or staff.	0.62	
		Respects my career intentions.	0.78	
		Respects my identities.	0.74	
		Treats me fairly.	0.87	
		Treats me as well as other students.	0.83	
		Consider my personal abilities, talents, and interests when advising me.	0.81	
		Is interested in collaborating with me on research.	0.75	
		Helps me network with other researchers and scholars.	0.7	
Please use the scale below to indicate level of agreement with the following statements about faculty and staff on campus:	Faculty and staff climate	My interactions with faculty and staff on campus are mostly positive	0.73	0.86
		My career intentions are respected by faculty and staff in my department.	0.8	
		My identities are respected by faculty and staff in my department.	0.93	
		I am treated as well as other students by faculty and staff in my department.	0.76	
Pease use the scale below to indicate level of agreement with the following statements about your peers:	Peer climate	My interactions with peers are mostly positive.	0.8	0.88
		My career intentions are respected by peers.	0.65	
		My identities are respected by peers	0.75	
		I am treated as well as other students by peers.	1.01	

Control Variables. We included control variables for demographics (gender, race/ethnicity, and citizenship status), field of study, and year in program. Gender was a categorial variable, with the categories of *man*, *woman*, *decline to state*, and *genderqueer/gender non-conforming*. We used *man* as the reference group. Race/ethnicity was also a categorial variable, with the categories of *White*, *Black, Asian*, *Hispanic*, and *Other* (including American

Indian/Alaska Native, Native Hawaiian/Pacific Islander, and multi-racial respondents). We used *White* as the reference group. Citizenship status was a categorical variable, with the categories of *U.S. citizen* and *non-U.S. citizen*. We used *U.S. citizen* as the reference group. Field of study was a categorical variable, with the categories of *engineering* and *physical science*. We used *engineering* as the reference group. Year in program was a categorical variable, with the categories of *year 1*, *year 2*, *year 3*, *year 4*, and *year 5 or more*. We used *year 3* as the reference group.

Data Analysis

We report descriptive statistics for field of study, gender, race/ethnicity, and citizenship status for our dataset (see Table 1). In addition, we conducted an EFA to identify and construct the climate variables, using its ability to uncover pattens and relationships within the data (see Table 2). We ran stepwise logistic regression models to predict each skill development variable (research, teamwork and project management, peer training and mentoring, and communication), for four overall regression models. However, we conducted a three-step model for each skill development variable, meaning we have 12 models in total. The first step of each overall model includes only the control variables, specifically demographics (gender, race/ethnicity, and citizenship status), field of study, and year in program. The second step of each overall model adds the independent variable of primary funding mechanism, and the third step of each overall model adds the independent variables of climate (advising climate, faculty climate, and peer climate). We conducted all analysis using R Studio.

Results

Tables 3-6 display the three-step models for the stepwise logistic regressions predicting skill development (associated with primary funding mechanism) of engineering and physical science doctoral students. The dependent variables for each table are as follows: research skills (Table 3), teamwork and project management skills (Table 4), peer training and mentoring skills (Table 5), and communication skills (Table 6). We share the odds ratio for each regression coefficient, along with the standard error (displayed as odds ratio (standard error) in the tables). An odds ratio greater than one indicates a higher likelihood of skill development, while an odds ratio less than one indicates a lower likelihood of skill development (in comparison to the reference group for the variable).

Research Skills

Model 1 (control variables) explains 4.3% of the variance in research skill development through primary funding mechanism, from the Pseudo-R^2. Three variables were statistically significant predictors in Model 1: Asian (race/ethnicity variable), physical science (field of study variable), and year 1 (year in program variable). Compared to White respondents, Asian respondents were 86% more likely to report that they developed high research skills associated with their primary funding mechanism. Compared to respondents in engineering, respondents in the physical sciences were 42% less likely to report that they developed high research skills associated with their primary funding mechanism. Compared to respondents in Year 3, respondents in Year 1 were 41% less likely to report that they developed high research skills associated with their primary funding mechanism.

Model 2 (addition of independent variable of primary funding) explains 11.9% of the variance in research skill development through primary funding mechanism, from the Pseudo-R^2. Two variables were statistically significant predictors in Model 2: Asian (race/ethnicity variable) and teaching assistantship (primary funding mechanism variable). Compared to White respondents, Asian respondents were 77% more likely to report that they developed high research skills associated with their primary funding mechanism. Compared to respondents primarily funding through a research assistantship, respondents primarily funded through a teaching assistantship were 78% less likely to report that they developed high research skills associated with their primary funding mechanism.

Model 3 (addition of independent variables of climate) explains 18.5% of the variance in research skill development through primary funding mechanism, from the Pseudo-R^2. Three variables were statistically significant predictors in Model 3: Asian (race/ethnicity variable), teaching assistantship (primary funding mechanism variable), and advising climate (climate variable). Compared to White respondents, Asian respondents were 73% more likely to report that they developed high research skills associated with their primary funding mechanism. Compared to respondents primarily funding through a research assistantship, respondents primarily funded through a teaching assistantship were 77% less likely to report that they developed high research skills associated with their primary funding mechanism. Respondents who reported high advising climate (i.e., 4 or higher on a 5-point scale) were 222% more likely to report that they developed high research skills associated with their primary funding mechanism, in comparison to respondents who reported low advising climate (i.e., a rating lower than 4).

Table 3. Logistic regressions for research skill development (Models 1-3)

n=615	**Model 1**	**Model 2**	**Model 3**
Intercept	1.34 (0.28)	1.33 (0.33)	0.38^{**} (0.14)
Gender (ref.=Man)			
Decline to State	0.45 (0.56)	0.31 (0.39)	0.45 (0.61)
Genderqueer	1.46 (1.40)	1.83 (1.90)	2.07 (2.14)
Woman	0.89 (0.15)	0.81 (0.15)	0.90 (0.17)
Race/ethnicity (ref.=White)			
Asian	1.86^{**} (0.44)	1.77^{*} (0.44)	1.73^{*} (0.45)
Black	0.66 (0.33)	0.62 (0.32)	0.53 (0.28)
Hispanic	1.05 (0.32)	0.98 (0.31)	0.96 (0.31)
Other	1.92 (0.97)	1.71 (0.89)	1.51 (0.82)
Citizenship status (ref.=U.S. citizen)			
Non-U.S. citizen	0.82 (0.18)	1.08 (0.27)	1.24 (0.32)
Field of study (ref.=Engineering)			
Physical science	0.58^{**} (0.11)	0.88 (0.18)	0.87 (0.18)
Year in program (ref.=Year 3)			
Year 1	0.59^{*} (0.15)	0.65 (0.17)	0.59 (0.16)

Year 2	0.77 (0.19)	0.81 (0.21)	0.73 (0.20)
Year 4	0.77 (0.19)	0.84 (0.22)	0.80 (0.22)
Year 5 or More	0.73 (0.19)	0.86 (0.24)	0.87 (0.25)
Primary funding (ref.=Research assistantship)			
External fellowship		1.56 (0.40)	1.57 (0.42)
Internal fellowship		0.94 (0.24)	0.98 (0.26)
Teaching assistantship		0.22^{***} (0.06)	0.23^{***} (0.06)
Climate variables			
Advising climate			3.22^{***} (0.70)
Faculty climate			1.13 (0.27)
Peer climate			1.37 (0.38)
Pseudo-R^2	4.3%	11.9%	18.5%

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Teamwork and Project Management Skills

Model 4 (control variables) explains 6.4% of the variance in teamwork and project management skill development through primary funding mechanism, from the Pseudo-R^2. Three variables were statistically significant predictors in Model 4: Asian (race/ethnicity variable), non-U.S. citizen (citizenship status variable), and physical science (field of study variable). Compared to White respondents, Asian respondents were 95% more likely to report that they developed high teamwork and project management skills associated with their primary funding mechanism. Compared to U.S. citizen respondents, non-U.S. citizen respondents in were 41% less likely to report that they developed high teamwork and project management skills associated with their primary funding mechanism. Compared to respondents in engineering, respondents in the physical sciences were 46% less likely to report that they developed high teamwork and project management skills associated with their primary funding mechanism.

Model 5 (addition of independent variable of primary funding) explains 11.7% of the variance in teamwork and project management skill development through primary funding mechanism, from the Pseudo-R^2. Three variables were statistically significant predictors in Model 5: Asian (race/ethnicity variable), external fellowship, and teaching assistantship (both primary funding mechanism variables). Compared to White respondents, Asian respondents were 99% more likely to report that they developed high teamwork and project management skills associated with their primary funding mechanism. Compared to respondents primarily funding through a research assistantship, respondents primarily funded through an external fellowship or a teaching assistantship were 65% and 69% respectively less likely to report that they developed high teamwork and project management skills associated with their primary funding mechanism.

Model 6 (addition of independent variables of climate) explains 16.3% of the variance in teamwork and project management skill development through primary funding mechanism, from the Pseudo-R^2. Four variables were statistically significant predictors in Model 6: Asian (race/ethnicity variable), external fellowship and teaching assistantship (primary funding mechanism variables), and advising climate (climate variable). Compared to White respondents, Asian respondents were 99% more likely to report that they developed high teamwork and project management skills associated with their primary funding mechanism. Compared to respondents primarily funded through a research assistantship, respondents primarily funded through an external fellowship or a teaching assistantship were 67% and 66% respectively less likely to report that they developed high teamwork and project management skills associated with their primary funding mechanism. Respondents who reported high advising climate (i.e., 4 or higher on a 5-point scale) were 126% more likely to report that they developed high teamwork and project management skills associated with their primary funding mechanism, in comparison to respondents who reported low advising climate (i.e., a rating lower than 4).

Table 4. Logistic regressions for teamwork and project management skill development (Models 4-6)

n=615	**Model 4**	**Model 5**	**Model 6**
Intercept	1.15 (0.24)	1.89* (0.47)	0.53 (0.19)
Gender (ref.=Man)			
Decline to State	0.30 (0.38)	0.28 (0.36)	0.31 (0.44)
Genderqueer	0.60 (0.58)	0.91 (0.86)	1.00 (0.99)
Woman	0.87 (0.15)	0.91 (0.16)	0.98 (0.18)
Race/ethnicity (ref.=White)			
Asian	1.95** (0.47)	1.99** (0.49)	1.99** (0.51)
Black	0.55 (0.28)	0.65 (0.33)	0.56 (0.29)
Hispanic	1.26 (0.38)	1.46 (0.46)	1.43 (0.46)
Other	1.34 (0.69)	1.22 (0.65)	1.04 (0.56)
Citizenship status (ref.=U.S. citizen)			
Non-U.S. citizen	0.54*** (0.10)	1.05 (0.26)	1.16 (0.30)
Field of study (ref.=Engineering)			
Physical science	0.58** (0.11)	0.88 (0.18)	0.87 (0.18)
Year in program (ref.=Year 3)			
Year 1	1.04 (0.27)	1.01 (0.27)	0.95 (0.26)
Year 2	1.19 (0.30)	1.13 (0.29)	1.09 (0.29)
Year 4	1.04 (0.27)	1.07 (0.28)	1.03 (0.28)
Year 5 or More	1.43 (0.39)	1.39 (0.39)	1.43 (0.41)
Primary funding (ref.=Research Assistantship)			
External fellowship		0.35*** (0.09)	0.33*** (0.09)
Internal fellowship		0.67 (0.17)	0.70 (0.19)
Teaching assistantship		0.31*** (0.07)	0.34*** (0.08)
Climate			
Advising climate			2.26*** (0.47)
Faculty climate			1.33 (0.31)
Peer climate			1.69 (0.46)
Pseudo-R^2	6.4%	11.7%	16.3%

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Peer Training and Mentoring Skills

Model 7 (control variables) explains 3.1% of the variance in peer mentoring and training skill development through primary funding mechanism, from the Pseudo-R^2. One variable was a statistically significant predictor in Model 7: Black (race/ethnicity variable). Compared to White respondents, Black respondents were 73% less likely to report that they developed high peer mentoring and training skills associated with their primary funding mechanism.

Model 8 (addition of independent variable of primary funding) explains 7.5% of the variance in peer mentoring and training skill development through primary funding mechanism, from the Pseudo-R^2. Three variables were statistically significant predictors in Model 8: Black (race/ethnicity variable), physical science (field of study variable), and external fellowship (primary funding mechanism variable). Compared to White respondents, Black respondents were 70% less likely to report that they developed high peer mentoring and training skills associated with their primary funding mechanism. Compared to respondents in engineering, respondents in the physical sciences were 43% less likely to report that they developed high peer mentoring and training skills associated with their primary funding mechanism. Compared to respondents primarily funding through a research assistantship, respondents primarily funded through an external fellowship were 70% less likely to report that they developed high peer mentoring and training skills associated with their primary funding mechanism.

Model 9 (addition of independent variables of climate) explains 11.8% of the variance in peer mentoring and training skill development through primary funding mechanism, from the Pseudo-R^2. Seven variables were statistically significant predictors in Model 9: Black (race/ethnicity variable), physical science (field of study variable), external fellowship and teaching assistantship (primary funding mechanism variables), and advising climate, faculty climate, and peer climate (climate variables). Compared to White respondents, Black respondents were 76% less likely to report that they developed high peer mentoring and training skills associated with their primary funding mechanism. Compared to respondents in engineering, respondents in the physical sciences were 44% less likely to report that they developed high peer mentoring and training skills associated with their primary funding mechanism. Compared to respondents primarily funding through a research assistantship, respondents primarily funded through an external fellowship were 72% less likely and through a teaching assistantship were 59% more likely to report that they developed high peer mentoring and training skills associated with their primary funding mechanism. Respondents who reported high advising climate (i.e., 4 or higher on a 5-point scale) were 68% more likely to report that they developed high peer mentoring and training skills associated with their primary funding mechanism, in comparison to respondents who reported low advising climate (i.e., a rating lower than 4). Similarly, respondents who reported high faculty climate and peer climate were 62% and 82% respectively more likely to report high peer mentoring and training skills associated with their primary funding mechanism, in comparison to those reporting low climate scores.

Table 5. Logistic regressions for peer training and mentoring skill development (Models 7-9)

n=615	Model 7	Model 8	Model 9
Intercept	0.84 (0.18)	1.24 (0.30)	0.34^{**} (0.12)
Gender (ref.=Man)			
Decline to State	0.54 (0.68)	0.68 (0.89)	0.69 (0.95)
Genderqueer	0.80 (0.75)	0.95 (0.94)	1.06 (1.13)
Woman	1.04 (0.18)	1.14 (0.20)	1.24 (0.22)
Race/ethnicity (ref.=White)			
Asian	1.17 (0.27)	1.27 (0.30)	1.24 (0.30)
Black	0.27^{*} (0.16)	0.30^{*} (0.18)	0.24^{*} (0.15)
Hispanic	0.66 (0.20)	0.76 (0.24)	0.74 (0.24)
Other	0.83 (0.41)	0.86 (0.43)	0.76 (0.39)
Citizenship status (ref.=U.S. citizen)			
Non-U.S. citizen	1.28 (0.28)	0.91 (0.22)	0.99 (0.24)
Field of study (ref.=Engineering)			
Physical science	0.77 (0.14)	0.57^{**} (0.12)	0.56^{**} (0.12)
Year in program (ref.=Year 3)			
Year 1	1.15 (0.29)	1.02 (0.26)	0.94 (0.25)
Year 2	1.30 (0.32)	1.20 (0.31)	1.15 (0.30)
Year 4	1.35 (0.34)	1.27 (0.33)	1.23 (0.32)
Year 5 or more	1.24 (0.32)	1.02 (0.27)	1.03 (0.28)
Primary funding (ref.=Research assistantship)			
External fellowship		0.30^{***} (0.08)	0.28^{***} (0.08)
Internal fellowship		0.75 (0.19)	0.79 (0.20)
Teaching assistantship		1.38 (0.31)	1.59^{*} (0.37)
Climate			
Advising climate			1.68^{*} (0.34)
Faculty climate			1.62^{*} (0.36)
Peer climate			1.82^{*} (0.48)
Pseudo-R^2	3.1%	7.5%	11.8%

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Communication Skills

Model 10 (control variables) explains 7.7% of the variance in communication skill development through primary funding mechanism, from the Pseudo-R^2. Three variables were statistically significant predictors in Model 10: woman (gender variable), Asian (race/ethnicity variable), and physical science (field of study variable). Compared to men respondents, women respondents were 32% less likely to report that they developed high communication skills associated with their primary funding mechanism. Compared to White respondents, Asian respondents were 91% more likely to report that they developed high communication skills associated with their primary funding mechanism. Compared to respondents in engineering, respondents in the physical sciences were 42% less likely to report that they developed high communication skills associated with their primary funding mechanism.

Model 11 (addition of independent variable of primary funding) explains 11.2% of the variance in communication skill development through primary funding mechanism, from the Pseudo-R^2. Three variables were statistically significant predictors in Model 11: Asian (race/ethnicity variable), external fellowship, and teaching assistantship (both primary funding mechanism variables). Compared to White respondents, Asian respondents were 107% more likely to report that they developed high communication skills associated with their primary funding mechanism. Compared to respondents primarily funding through a research assistantship, respondents primarily funded through an external fellowship or teaching assistantship were respectively 72% and 44% less likely to report that they developed high communication skills associated with their primary funding mechanism.

Model 12 (addition of independent variables of climate) explains 15.8% of the variance in communication skill development through primary funding mechanism, from the Pseudo-R^2. Six variables were statistically significant predictors in Model 12: Asian (race/ethnicity variable), year 1 (year in program variable), external and internal fellowship (primary funding mechanism variables), and advising and peer climate (climate variables). Compared to White respondents, Asian respondents were 112% more likely to report that they developed high communication skills associated with their primary funding mechanism. Compared to respondents in year 3, respondents in year 1 were 47% less likely to report that they developed high communication skills associated with their primary funding mechanism. Compared to respondents primarily funding through a research assistantship, respondents primarily funded through an external or internal fellowship were respectively 74% and 42% less likely to report that they developed communication skills associated with their primary funding mechanism. Respondents who reported high advising climate (i.e., 4 or higher on a 5-point scale) were 55% more likely to report that they developed high communication skills associated with their primary funding mechanism, in comparison to respondents who reported low advising climate (i.e., a rating lower than 4). Similarly, respondents who reported high peer climate were 139% more likely to report high communication skills associated with their primary funding mechanism, in comparison to those reporting low peer climate scores.

Table 6. Logistic regressions for communication skill development (Models 10-12)

n=615	Model 10	Model 11	Model 12
Intercept	1.09 (0.23)	1.85* (0.46)	0.45* (0.16)
Gender (ref.=Man)			
Decline to State	0.40 (0.52)	0.46 (0.61)	0.42 (0.58)
Genderqueer	0.25 (0.29)	0.32 (0.39)	0.30 (0.41)
Woman	0.68* (0.12)	0.73 (0.13)	0.77 (0.14)
Race/ethnicity (ref.=White)			
Asian	1.91** (0.45)	2.07** (0.50)	2.12** (0.53)
Black	0.44 (0.24)	0.54 (0.30)	0.46 (0.26)
Hispanic	0.82 (0.25)	0.98 (0.31)	0.96 (0.31)
Other	1.05 (0.52)	1.05 (0.53)	0.92 (0.48)
Citizenship status (ref.=U.S. citizen)			
Non-U.S. citizen	1.07 (0.24)	0.76 (0.18)	0.82 (0.21)

Field of study (ref.=Engineering)			
Physical science	0.58** (0.11)	0.88 (0.18)	0.87 (0.18)
Year in program (ref.=Year 3)			
Year 1	0.67 (0.18)	0.59 (0.16)	0.53* (0.15)
Year 2	0.99 (0.25)	0.89 (0.23)	0.84 (0.23)
Year 4	0.96 (0.25)	0.91 (0.24)	0.86 (0.23)
Year 5 or More	1.32 (0.35)	1.11 (0.30)	1.11 (0.31)
Primary funding (ref.=Research assistantship)			
External fellowship		0.28*** (0.08)	0.26*** (0.07)
Internal fellowship		0.56* (0.14)	0.58* (0.15)
Teaching assistantship		0.82 (0.19)	0.93 (0.22)
Climate			
Advising climate			1.55* (0.32)
Faculty climate			1.57 (0.36)
Peer climate			2.39** (0.67)
Pseudo-R^2	7.7%	11.2%	15.8%

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Discussion

Summary of Results for Non-Climate Variables

Several significant variables were relatively consistent across all of the models, notably demographic variables (Asian), field of study (physical sciences), and primary funding mechanism (external fellowship and teaching assistantship). Overall, Asian respondents were more likely to report high skill development associated with their primary funding mechanism as compared to White respondents. Physical science respondents were more likely to report low skill development associated with their primary funding mechanism as compared to engineering respondents. In addition, respondents with external fellowships or teaching assistantships were less likely to report skill development associated with their primary funding mechanism as compared to respondents primarily funded through research assistantships (with the exception of teaching assistantships and peer training and mentoring skills). Our findings related to these variables generally align with the findings in our previous work [9].

Climate Variables

For the four full models (with the climate variables), research skills had the highest pseudo-R^2 (18.5%), followed by teamwork and project management skills (16.3%), communication skills (15.8%), and peer training and mentoring skills (11.8%). Advising climate was statistically significant for all four career-related skills, faculty and staff climate for peer training and mentoring skills only, and peer climate for both peer training and mentoring and communication skills. All statistically significant climate variables positively predicted skill development (associated with primary funding mechanism).

Notably, advising climate was a statistically significant predictor for all four career-related skills. Our finding aligns with the graduate engineering education literature, in that advising relationships critically impact the doctoral student experience. Prior work has found that advising relationships impact the mental health of engineering graduate students [18], their persistence and attrition [18, 19], and their engineering identity [20]. In addition, positive advisor interactions can be a form of psychosocial support for STEM graduate students, helping to ease feelings of anxiety and self-doubt [21]. Our findings connect the literature on advising climate and skill development, quantifying how a positive advising climate leads to the reporting of higher skills by engineering doctoral students. The graduate education literature highlights how faculty actions, such as allowing students to seek external assignments, providing introductions to scholars in the field, and assigning research activities, influences their skill development and socialization to the field [6, 8, 12]. Given that engineering faculty have many responsibilities in addition to advising students, they may have limited time to spend per doctoral student. It then becomes particularly important that those limited interactions are positive for students.

It is critical that doctoral students receive support from other sources in addition to their advisor, otherwise graduate school can become an isolating experience for students [18]. Doctoral students form connections with faculty/staff or peers through classes (instructors, classmates), their research groups (peers), on grant-funded research projects (including faculty and peers from other institutions), their department or college (both), student organizations (peers), and conferences and professional organizations (both). Our findings illustrate that faculty/staff climate and peer climate both predict skill development, meaning that we should consider the interactions that engineering doctoral students have outside of their advisor. A positive climate with faculty/staff and peers likely indicates that doctoral students have greater connections with other individuals, which could lead to an increased ability to ask questions of multiple people with varied experiences and backgrounds. Faculty/staff climate and peer climate were statistically significant predictors for peer mentoring and training skills. A positive faculty/staff and peer climate might indicate a more collaborative setting, where there are additional opportunities to train and mentor peers (the two items in peer training and mentoring skills). Peer climate was also a statistically significant predictor of communication skills, indicating that such an environment contributes to verbal and written communication skills and learning to facilitate difficult conversations (the three items in communication skills). In a positive peer climate, students might have a greater opportunity to receive feedback on their presentations or writing samples from peers, as well as being able to practice tough conversations and receive advice from students further along in their programs.

It is unclear why advisor climate was the only statistically significant climate variable for research skills and project management skills. Engineering graduate students often rely on peers to learn skills and other professional development, particularly in larger research groups [7]. One potential explanation is that the tone of the research group may be set by the advisor, meaning that the advisor sets expectations for interactions and actions within the group. Therefore, for the skills often developed within research groups (research, project management), advisor climate may matter more than peer climate. Actions, words, and intent all matter in shaping the climate perceived by doctoral students. The items across all three climate variables used words such as "respect", "treated", and "prioritizes". Bahnson, et al. [22] provide specific examples of how interactions with advisors, faculty/staff, and peers impacted engineering doctoral students' identity and feelings of belonging. Examples of positive interactions included providing useful feedback to students, positioning them as experts, and maintaining responsive communication. Our findings suggest that such interactions not only impact identity and sense of belonging but also contribute to the skill development of doctoral students. Future work should focus on understanding what specific interactions positively predict skill development.

Conclusion

Our findings highlight the importance of climate within engineering and physical science doctoral programs, quantifying that a positive climate promotes development of career-related skills. We build on existing literature in skill development and climate within graduate education, connecting the two topics. Advising climate predicts all four skills associated with primary funding, while faculty/staff climate predicts peer training and mentoring skills only and peer climate predicts peer training and mentoring and communication skills. Advisors should reflect on their own actions and conversations with doctoral students, considering whether they are positive interactions. In addition, advisors should evaluate the connections that doctoral students have with their peers and faculty/staff in relation to their funding assignments and what role they can take to facilitate such interactions. We recommend that future work examine what specific interactions contribute to a positive climate and provide guidance on how graduate programs in engineering can adopt such practices at their institutions.

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Appendix: Institutional Sampling of Survey Respondents

Carnegie Mellon University
Cornell University
Georgia Institute of Technology
Johns Hopkins University
Massachusetts Institute of Technology
North Carolina State University
Ohio State University
Pennsylvania State University
Purdue University
Texas A&M University
University of California Irvine
University of California San Diego
University of California Los Angeles
University of Chicago
University of Colorado Boulder
University of Florida
University of Illinois at Urbana-Champaign
University of Maryland
University of Michigan
University of Pennsylvania
University of Texas at Austin
University of Washington
University of Wisconsin-Madison
Virginia Tech
Yale University