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The Social, Cultural, and Material Contexts of Doctoral Engineering Students' Research Experiences for Professional Practice Preparation*

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Engineering educators put great faith in research experiences to prepare graduate students for professional practice, yet we know little about how the characteristics of these experiences shape them. This investigation addresses this gap by examining how different research experiences affect the professional abilities of 451 doctoral engineering students from multiple institutions. Research questions focused on the kinds of research experiences, the measured differences in experiences, and what those differences indicate about doctoral students' preparedness. It offers a Conceptual Framework that categorizes the important aspects of graduate engineering students' research experiences related to their social, cultural, and material significance to professional practice. Based on this framework, we surveyed 451 doctoral engineering students about their social, cultural, and material research experiences related to professional practice and clustered students into groups based on their responses. Students also completed the Research Experiences Instrument (REI), a measure of opportunities for students in their research experiences to practice being a professional. The combination of REI and self-report questions identified deficiencies in research settings and students' professional development improvement needs. Strategies that faculty, administrators, and students can implement to increase graduate students' opportunities for professional practice are provided.

Keywords: assessment; doctoral engineering students; professional practice; research experiences

1. Introduction

Graduate engineering students' research experiences are their formative preparation for professional practice [1–3]. These experiences provide them with opportunities to learn the nuances of becoming a researcher from advisors, peers, and internal and external collaborators [4, 5]. Yet, industry employers have indicated for decades that new graduates are not ready to put their skills into practice [2, 6, 7] and struggle to transform their education into tangible results [2, 8]. Globally, the alarm about the preparedness of graduates of engineering programs has been sounded by the European University Association [9–12], the Australian Council of Learned Academies [13], the Conference Board of Canada [14], and in the U.S., the Council of Graduate Schools and Educational Testing Service [15].

While the research experience is an established tool for preparing engineering graduate students for practice, one complication is the wide variety of experiences to which the term "research experience" applies. Factors such as the discipline, whether the research topic is theoretical or experimental, and the size and organization of the engineering lab all lead to a wide range of experiences [16]. Some students might work alone on a computer, others as part of a team sketching their latest ideas on a whiteboard, and others might be troubleshooting equipment with engineering professionals. Ethnographic studies of graduate engineering students undertaking research have identified aspects of how research groups work together based on the group size, lab organization, and faculty advisor mentorship [17], but little is known about how these different contexts prepare students for professional practice [18, 19].

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Since the National Science Foundation (NSF) began focusing on improving graduate engineering students' career preparation with Engineering Research Centers (ERCs) [8], very few studies have investigated aspects that influence how students are prepared for professional work [20, 21]. More specifically, little is understood about how students' research experiences professionally prepare them [17]. Thus, a deeper understanding of how students' research experiences prepare them for practice upon graduation needs to be gained. The purpose of this research is to investigate the types of research experiences that doctoral engineering students report are aligned with professional practice. Specifically, our research questions are:

RQ1: What are the most common types of research experiences for doctoral engineering students?

RQ2: To what extent are there significant differences in group mean scores between various contexts (i.e., social, cultural, and material) of doctoral engineering students' research experiences that indicate specific research experiences contribute more or fewer opportunities for professional practice?

RQ3: What do differences indicate about the research experiences of doctoral engineering students and their preparation for professional practice?

1.1 Positionality Statement

We approached this research with three of the four authors who started our formative years in a corporate setting before moving to academia. Our study was inspired by recognizing that many engineers (as well as those with advanced credentials) often have difficulty translating their acquired knowledge and skills to practical problems when entering the workforce. An appreciation guided us that students will have a range of experiences in different settings across their universities and institutions. We also recognize that students' research experiences include those beyond merely technical, such as professional matters (e.g., collaborating with others). As the term 'research experiences' is critical to our work, we operationalize it broadly, incorporating all students' opportunities, be those technical and/or professional encountered as part of their graduate research experiences.

2. Literature Review and Conceptual Framework

2.1 Background Literature

NSF formed ERCs in the 1980s as part of an effort to reform doctoral experiences [8]. One of the main focuses of ERCs is providing doctoral engineering students with opportunities in their research to prepare for professional practice [22]. The research experience in ERCs and similar programs typically differs from traditional basic research experiences in that they generally are more applied, require different skill sets, and involve greater interaction with government and industry sponsors [16]. ERCs were designed "to improve engineering research so that U.S. engineers will be better prepared to contribute to engineering practice" [20, p. 3]. The intent has been to produce outcomes such as fostering teamwork, new approaches to problem-solving, and better serving the needs of industry [20]. Research shows that ERCs significantly impact both the educational process and outcomes of doctoral engineering students and that their research experiences improve industry's perceptions of their level of preparation for professional practice [20, 23].

Despite such ambitions on the one hand and concerns that holders of advanced degrees are not prepared for professional work, little research has been devoted to doctoral engineering students' research experiences [17, 24]. Watson and Lyons [25] surveyed industry about what skills recent engineering Ph.D. graduates need, concluding that technical knowledge, teamwork, and communication were the most important. The few studies centered on students' research experiences have looked at specific facets of the research experiences, not the research experiences holistically, and how the experiences influenced those skills [17, 23, 24]. Other studies about doctoral engineering students, while not directly about their research experiences, such as funding impacts [26] and type of engineering research work [27], can inform the understanding of how the various contexts of students' research experiences influence their career preparation.

Many view doctoral engineering students' research experiences from the perspective of being distinctive and varied or, as remarked by Thune, a heterogeneous phenomenon [28, 29]. However, the heterogeneity of students' research experiences can be simplified by examining in what ways these experiences helped prepare them for professional work, thereby allowing the focus to be on the essential contexts related to professional practice. In our previous work, we identified and characterized the essential contexts of doctoral engineering students' research experiences related to their professional practice based on a broad review of the literature [30]. We revisit the critical elements of that characterization here, as it provides a framework that forms the foundation for our exploration of the factors that differentiate research experiences and how they shape the impact of these experiences. Thus we offer an understanding of how the different elements of research experiences relate to students' opportunities to prepare for practice as a way to offer a more robust understanding of this crucial component of training the engineering workforce that will meet the challenges of the 21st century based on the social, cultural, and material contexts of research experiences.

2.2 Theoretical Framework

A suitable theoretical framework is critical to provide a lens for measurement research [31]. In our previous study [32], we reviewed our search and choice of a framework, as we focused on those that assist in understanding what students find challenging in their shift from academia to the professional world. In line with literature showing that new Ph.D.'s struggle to apply knowledge and skills to the job [2, 33–35], we selected Dall'Alba's Ways of Being framework [18] for our research, which makes a clear distinction between the epistemological emphasis of the university setting and the ontological emphasis of the job setting. The ontological emphasis, often overlooked in academia, requires students to make the needed corrections once in the workforce to adapt to become professionals [18]. Dall'Alba explains the Ways of Being framework as it pertains to higher education: "as the development of ways of being is embedded within particular social, historical, cultural, material contexts, it is not surprising that learning is colored by context" [19, p. 111]. Dall'Alba [36] provided a practical application of this framework, characterizing the experiences of students in medical school according to their social, historical, cultural, and material contexts and how this relates to their experience in medical school that prepared them to transition to the professional, ontological settings in which they would become doctors.

We adapted the following definitions from the work of Sandberg and Dall'Alba [37] to fit the context of doctoral engineering students' research experiences. These definitions were presented in our previous literature review [30] and are critical to this current work.

Social is defined as the way in which doctoral engineering students are being with others and "taking over others ways" [37, p. 1357] of doing doctoral engineering student research.

Historical is defined as the context within which the social, cultural, and material context of the doctoral engineering student research experiences is currently taking place. Thus this context is the backdrop for understanding the social, cultural, and material present in which the research experiences we study occur.

Cultural is defined as the shared meanings that are ascribed to the doctoral engineering student research experiences that govern human action and social order.

Material is defined as the equipment used in doctoral engineering student research experiences that is "purposeful, instrumental, directed at achieving a particular end" [37, p. 1359].

2.3 Social, Cultural, and Material Contexts of the Research Experiences

Below, we synthesize the findings from our previous literature review [30], where we identified the nine contexts of the research experiences of doctoral engineering students that are essential to their professional preparation based on the social, cultural, and material significance of the research experiences.

Social: (1) Research group size, (2) group organization, and (3) work organization. Emergent from the social context of students' research experiences, the research group [38–40] and its size (i.e., the number of students on the team: small – fewer than 5, medium – 5 to 20, large – greater than 20) have been identified as a significant influencing factor in the research experience [17]. Size also influences the two other social contexts. It influences group organization, or how students work with their advisor and fellow graduate students. Students in small research groups are more likely to work in advisor-dominant groups, whereas students in medium and large research groups are more likely to work in group-focused groups [17]. It influences work organization, or how the workspace is organized. Students in small research groups are more likely to work in isolated workspaces, while students in medium and large research groups are more likely to work in shared workspaces [17]. Finally, students' work organization is influenced by the size of the research team [17] and the equipment type used. Students who work individually are more likely to work on projects involving modeling [17], whereas students who work on a team are more likely to use large, physical equipment [17, 41].

Cultural: (4) Engineering discipline. Typically, the administration of doctoral engineering research experiences is decentralized and discipline-specific [42], as each discipline (i.e., mechanical, electrical, industrial, etc.) impacts their research experiences. In addition to screening candidates and determining aspects of the curriculum, such as exam requirements, the engineering discipline typically determines the technical content of the research experience in which students participate [42].

Cultural: (5) Work type: basic or applied. Basic research experiences typically involve students working on theoretical projects lasting the duration of their time on campus, and these projects are more likely government-funded than applied experiences.

Applied research experiences involve more experimentation and are more likely to be industry-funded; they are also shorter term, and thus students who work on these projects are more likely to participate in several projects during their time on campus [16, 26, 27, 43].

Cultural: (6) Collaborators and *(7) interactions*. Dall'Alba emphasizes that students working with collaborators is essential to their professional formation and are students' "forms of practice" [19, p. 105]. Other research echoes this claim that working with collaborators is vital to professionalization [36]. The three most common types of collaborators for doctoral engineering students are government (in the U.S., NSF, or agencies such as the Department of Energy), [26], industrial companies and start-ups [26], and research centers [44]. In research centers, such as an ERC, a substantial group of students and faculty typically collaborate on research on synergistic, multidisciplinary topics, often in a shared building, and the intent of these projects is "to foster interactions and collaborations among researchers" [44, p. 900]. Interactions, then, depend on collaboration; whether students interact with their collaborators frequently, which predicts how they interact, affects the impact of their research experiences. Infrequent interactions typically occur in the form of written reports and relationships that are not very deep, and this typically occurs with government collaborators [45, 46]. Frequent interactions are more likely to involve deep relationships and to occur in person and are more likely to occur with industry collaborators [20, 45, 47].

Material: (8) Equipment and *(9) workspace*. Most doctoral engineering students employ mathematical modeling and simulation in their projects for their doctoral work at some point [48], and those skills are advanced [49]. Some students, however, use modeling simulations as their primary means in their projects for their doctoral work [50] and thus have limited access to large physical equipment. Students who have the opportunity to work with physical experiments and equipment gain troubleshooting and hands-on skills modeling projects typically do not develop [20, 29]. As noted above, equipment type also affects social contexts. Students dependent on building resources and equipment are more likely than students with few such needs to advocate for shared work areas and facilities with several similar researchers [17, 41]. Thus students working on modeling projects are more likely (or have no choice but) to be located in isolated workspaces, working alone or with just a few students [17].

Social, Cultural, and Material Summary. The Concept Map (Fig. 1) illustrates how doctoral engineering students might experience the social, cultural, and material contexts in their research experiences. It was constructed around the nine social, cultural, and material contexts in the literature: (1) social: research group size, (2) social: group organization, (3) social: work organization, (4) cultural: engineering discipline, (5) cultural: work type, (6) cultural: collaborators, (7) cultural: collaborator interactions, (8) material: equipment type, and (9) material: workspace.

3. Research Methods

3.1 Participants

The sample participants comprised 451 engineering doctoral students at one doctoral-grating PWI (*n* =

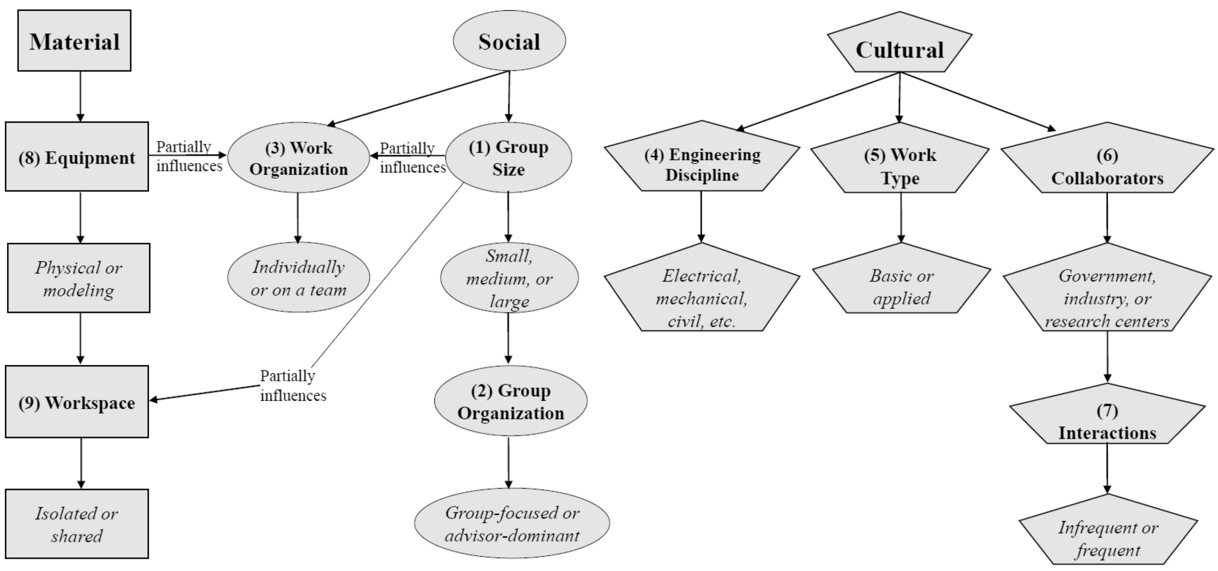

Fig. 1. Concept Map of the social, cultural, and material contexts of doctoral engineering students' research experiences.

236, 52.3%) collected in the summer of 2019 and 30 doctoral-granting universities (*n* = 215, 47.7%) collected in the fall of 2019. The entire sample included 155 women (34.4%), 294 men (65.2%), and 2 non-binary students, similar to the overall population percentages [51, 52]. Regarding students' self-reported race/ethnicity, 159 (35.3%) identified as Asian, 9 (2.0%) identified as Black/African American, 26 (5.8%) identified as Hispanic or Latino, 202 (44.8%) identified as White, 16 (3.5%) identified as a multiplicity of Black/African American, Hispanic or Latino, Native American, or Pacific Islander, 18 (4.0%) identified as a multiple of Asian, White, or Other, and 21 (4.6%) identified as Other. Of the engineering disciplines reported, 35 (7.8%) were in aeronautics and astronautics, 39 (8.6%) were in biomedical, 50 (11.1 %) were in chemical, 35 (7.8%) were in civil, 82 (18.2%) were in electrical and computer, 28 (6.2%) were engineering education, 12 (2.7%) were in environmental and ecological, 20 (4.4%) were in industrial, 32 (7.1%) were in materials, 87 (19.3%) were in mechanical, 8 (1.8%) were in nuclear, and 23 (5.0%) were in "other."

3.2 Instruments

3.2.1 Research Opportunities

We used the Research Experiences Instrument (REI) scale we developed in past research [32] to measure doctoral engineering students' opportunities in their research experiences to replicate professional practice, where professional practice is broadly defined as future employment as a researcher in academia, industry, and government. While most engineering Ph.D. recipients work in industry (NSF's 2022 survey of all doctoral recipients showed that 78.8% of engineering doctoral recipients matriculated to industry) [53], the REI measures a broad set of attributes needed for professional practice in any profession. The REI comprises 29 items, asking students how often in their Ph.D. research experience they performed various tasks similar to their future professional practice. A sample item includes "interpret data gathered from testing equipment or apparatus?". Students respond using a frequency scale from 1=never to 6=very frequently. The REI was designed to measure five factors related to doctoral students' professional development, including: *Teamwork* (i.e., students being a member of a team working on research where "students are dependent on each other to accomplish the task at hand and where working together as a team is critical due to the complexity of the system or mission goals" [30, p. 15]), *Collaboration* (i.e., students "exhibit[ing] professional actions and behaviors by working with practicing engineers who are the students' main collaborators in their research work" [30, p. 15]), *Networking* (i.e., students "exhibit[ing] professional actions and behaviors by working with practicing engineers related to their wider research experiences" [30, p. 16]), *Modeling* (i.e., students "utiliz[ing] computational thinking, methods, and techniques that practicing engineers use to solve research problems" [30, p. 16]), and *Experimentation* (i.e., students being "exposed to research experiences that involve experiments that require students to engage with complex physical experiments" [30, p. 16]), and an overall *Opportunity* score (i.e., students' total opportunities in their research for professional practice). Each factor score is calculated by averaging the score of the individual items for that factor, and the overall *Opportunity* score is calculated by summing all the factor scores [54].

We reported validity evidence [32] that included a stable factor structure that aligned well with theory, and reliability coefficient alphas ranging from 0.87 to 0.90. The overall *Opportunity* scores for women and men were, on average, the same, following expected trends [55, 56]. The overall *Opportunity* scores for racially/ethnically minoritized students (those who identified as Black/African American, Hispanic or Latino, Native American, Pacific Islander, or a multiple of any of these) were, on average, significantly lower than their non-minoritized peers, following prior reported concerns for these students [57].

3.2.2 Social, Cultural, and Material Contexts of Research Experiences

We assessed students' social, cultural, and material contexts in their research experiences identified from the literature by developing nine self-report questions (Table A1 in Appendix A lists the self-report questions and responses). We tested the questions in a cognitive think-aloud process [58] with 12 graduate students in the spring of 2019 to arrive at the final questions [59]. The current analysis uses these nine self-report questions to discern students' REI scores that indicate social, cultural, and material differences in their opportunities to practice as professionals in their research experiences.

3.3 Procedures

We twice administered the REI and self-report questions to collect enough data for the analysis. We first administered the survey in the summer of 2019 semester to approximately 1988 doctoral engineering students at a PWI midwestern institution. We administered the survey again in the fall 2019 semester to an undetermined total of doctoral

Table 1. Conversion of self-report responses into Concept Map sub-group for clustering

Reported context	Conversion	Concept Map sub-group
Response: # of graduate students in the research group	Less than 5 students	Group size: small
	5—20 students	Group size: medium
	More than 20 students	Group size: large
Equipment: Primarily modeling	Not changed	Modeling
Equipment: Primarily testing or combination of modeling and testing	Combined to one sub-group	Physical
Equipment: Other	Not changed	Other
Workspace: Alone or with a few others	Not changed	Isolated
Workspace: Only with research group or shared with multiple research groups	Combined to one sub-group	Shared
Workspace: Other	Not changed	Other

engineering students at U.S. research institutions, which we accessed through email listservs at U.S. institutions and the American Society for Engineering Education (ASEE). After agreeing to participate in the study, students participated through an email link and completed the REI and self-report questions using an online survey. We received 905 responses overall to both surveys, and responses were combined into one sample (called integrative data analysis) [60] so that group differences could be analyzed. We deleted responses using the criteria that all responses needed to (1) be 100% complete, (2) correctly answer a filter question, and (3) be a doctoral engineering student. Using this process, we deleted 454 responses, leaving us a total of 451 responses for analysis. We observed no patterns in the incomplete datasets. We analyzed self-report report questions for responses where students selected 'Other' and wrote a written response rather than one of the selected responses. In several cases, we changed a response based on the rationale that it was obvious that the response should be one of the selected responses and not 'Other.' Table B1 in Appendix B summarizes our changes to students' 'Other' responses.

We performed two analyses to indicate social, cultural, and material differences in students' opportunities to practice as professionals in their research experiences. First, we examined the self-report questions by clustering them into groups according to their social, cultural, and material contexts. In the second analysis, we compared mean scores from the groups formed in the first analysis by comparing the overall REI *Opportunity* score for statistical significance.

In order to cluster the self-report questions into groups for a given social, cultural, or material context, we sorted students' responses in Excel 2016 and tabulated and reported the number of unique clusters of responses. During sorting, we converted three of the self-report responses to have the same sub-groups as the Concept Map (Fig. 1) for grouping, specifically group size, equipment, and workspace. Table 1 summarizes the conversions of self-report responses into Concept Map sub-groups.

As many possible clusters existed based on potential students' responses, we established a threshold to define a group for further analysis. We determined the group threshold based on a statistical power analysis, with the significance criterion set to 0.05 (or 95% confidence interval), the desired statistical power set to 0.80 (set to recommend minimum power per Cohen [61]), and a medium effect size (0.0625). In order to maintain statistical power of 0.80, we set minimum group sizes based on the number of groups we were comparing: ~64 for two groups, ~53 for three groups, and ~45 for four groups. In our later analyses, we used these values as general guidelines when evaluating group sizes.

We calculated each factor score's mean, standard deviation, and overall REI *Opportunity* score using SPSS version 26 [62] for the selected social, cultural, and material groups. We selected twelve groups for statistical significance testing between mean scores based on the overall REI *Opportunity* score difference and the group size based on the established thresholds.

When we examined the mean REI *Opportunity* scores between groups, we used the nonparametric tests for significance due to the data's non-normality. We used the nonparametric tests Mann-Whitney U (for comparing the means between two groups) and Kruskal-Wallis H (for comparing the means between more than two groups). These are ranked-based tests, where REI *Opportunity* scores are converted to ranks so that mean ranks are compared between the groups of interest [63]. The null hypothesis for these tests presumes no differences in score distributions. In cases where the null was rejected, score distributions differed [63]. When comparing groups, we created equal-sized groups so that a larger-sized group would not have bias.

Table 2. Mean factor scores for the entire sample [32]

Factor	*M* (SD)	Score Interpretation
Teamwork	4.21 (1.12)	Occasionally
Collaboration	3.63 (1.29)	Between Rarely and Occasionally
Networking	3.16 (1.17)	Rarely
Modeling	4.23 (1.31)	Occasionally
Experimentation	4.15 (1.66)	Occasionally
Opportunity	19.38 (4.05)	Occasionally
Note. Score interpretation refers to how the mean score listed would be interpreted relative to the scale.		

We created equal-sized groups by randomly sampling from the larger group's responses to match the number of responses in the smaller group. We conducted the nonparametric tests in SPSS version 26 [62]. For each test, we ran one significance test on each sample, setting the significance level to 0.05, and the confidence level to 95%. A total of two tests for significance were run, one using the Mann-Whitney *U* (for comparing the means between two groups) and Kruskal-Wallis *H* (for comparing the means between more than two groups).

4. Results

4.1 Overall Descriptive Statistics

REI item skewness varied from –1.12 to 0.63, while kurtosis varied from –1.22 to 0.83 as the items were non-normally distributed. Factor score means and standard deviations are shown in Table 2, including the score interpretation. Factor scores for the six factors *Teamwork . . . Experimentation* skewness varied from –0.75 to –0.02, and kurtosis varied from –0.87 to –0.13, as these were also non-normally distributed. *Opportunity*, the overall REI score, was very close to being normally distributed, as both skewness and kurtosis were –0.2.

4.2 Results for Most Common Types of Research Experiences Based on the Survey Data

Table 3 presents the overall numbers (*n*) and percentages for the nine social, cultural, and material groups. Table C1 in Appendix C presents these groups' mean factor scores. Due to the large number of engineering disciplines, these values are shown in Table D1 in Appendix D.

Fig. 2 shows the percentages for the nine social, cultural, and material groups in the Concept Map.

Table 4 presents the overall numbers (*n*) and percentages for the four largest social, cultural, and material group combinations. Table E1 in Appendix E presents these groups' mean factor scores.

The percentages of students for the social, cultural, and material group combinations are shown in the Concept Map in Fig. 3 (Social), Fig. 4 (Cultural), and Fig. 5 (Material).

4.3 Discussion of Results for Most Common Types of Research Experiences

In this discussion, we summarize the significant points of understanding of the results of the most common types of research experience doctoral engineering students reported based on their social, cultural, and material group combinations with the Concept Map and how these align with previous literature to provide engineering educators with a further understanding of students' experiences. While only selected groups are discussed below based on their importance, every group is summarized in Table F1 in Appendix F.

Regarding the social combinations shown in Fig. 3, the overall clustering for the four social groups

Table 3. Overall numbers and percentages for the ninesocial, cultural, and material groups

Groups	Values	*n*	%
All	n/a	451	100
(1) Group Size	Small (< 5)	151	34
	Medium (5–20)	290	64
	Large (> 20)	10	2
(2) Group Organization	Group-focused	165	37
	Advisor-dominant	245	54
	Other	41	9
(3) Work Organization	Individual	332	74
	Team	99	22
	Other	20	4
(5) Work type	Basic	123	27
	Applied	314	70
	Other	14	3
(6) Collaborator	Government	125	28
	Industry	98	22
	Research Center	182	40
	Other	46	10
(7) Interactions	Infrequent	222	49
	Frequent	196	44
	Other	33	7
(8) Equipment	Physical	262	58
	Modeling	160	36
	Other	29	6
(9) Workspace	Isolated	90	20
	Shared	350	78
	Other	11	2

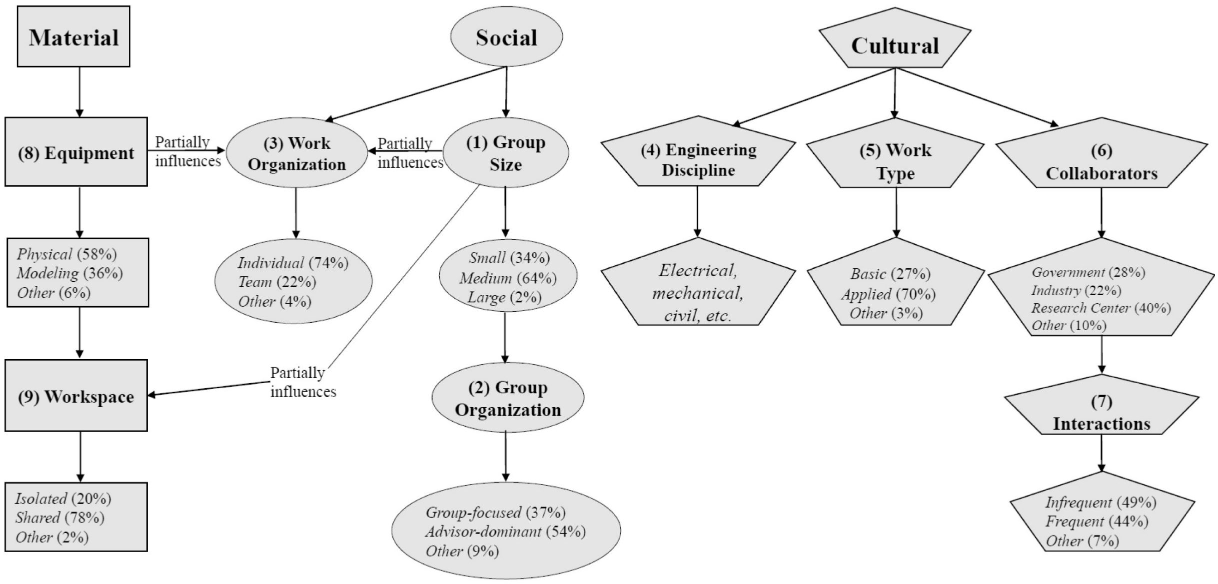

Fig. 2. Percentages for the nine social, cultural, and material groups shown in the Concept Map.

Table 4. Overall numbers and percentages for the four largest social, cultural, and material group combinations

Groups	Values	*n*	%
All	n/a	451	100
Social Groups	Medium / Advisor-dominant / Individual	121	26.8
	Medium / Group-focused / Individual	70	15.5
	Medium / Group-focused / Team	42	9.3
	Small / Advisor-dominant / Individual	82	18.2
	Other combinations	136	30.2
Cultural Groups	Applied / Research Center / Frequent	59	13.1
	Applied / Research Center / Infrequent	48	10.6
	Applied / Government / Infrequent	54	12.0
	Applied / Industry / Frequent	47	10.4
	Other combinations	243	53.9
Material Groups	Modeling / Isolated	43	9.5
	Modeling / Shared	113	25.1
	Physical / Isolated	40	8.9
	Physical / Shared	218	48.3
	Other combinations	37	8.2

accounted for 70% (n = 315) of all the respondents. In other words, social clustering captured most students' social experiences. The main point drawn from the social clustering was that most students worked in an advisor-dominated group organization where students worked mostly individually (45%). Very few students worked in a group-focused group organization where students worked mostly as a team (9%). The overall social group clustering follows Crede & Borrego's original findings [17]. The most notable grouping result regarded Group Size, as almost twice as many students reported being in a medium-sized group (n = 290, 64%) as being in a small group (n = 151, 34%), and very few students (n = 10, 2%) reported being in a large group. These results closely match the percentages reported by Crede and Borrego [17] for the same categories (small: 31%, medium 67%, large 3%), and help us understand that most students are in a medium-sized group.

Regarding the Cultural combinations shown in Fig. 4, the overall clustering for the four selected cultural groups accounted for only 46% (n = 208) of all the respondents. This result does not suggest that the cultural clustering did not capture most student experiences, but it does suggest the cultural cluster is quite diverse in students' research experiences. Four other key points from the overall clustering were: (1) only applied work type generated clusters, as the basic research work type did not; (2) the cultural cluster group sizes were very similar, and relatively small (~10%); (3) there was an even split

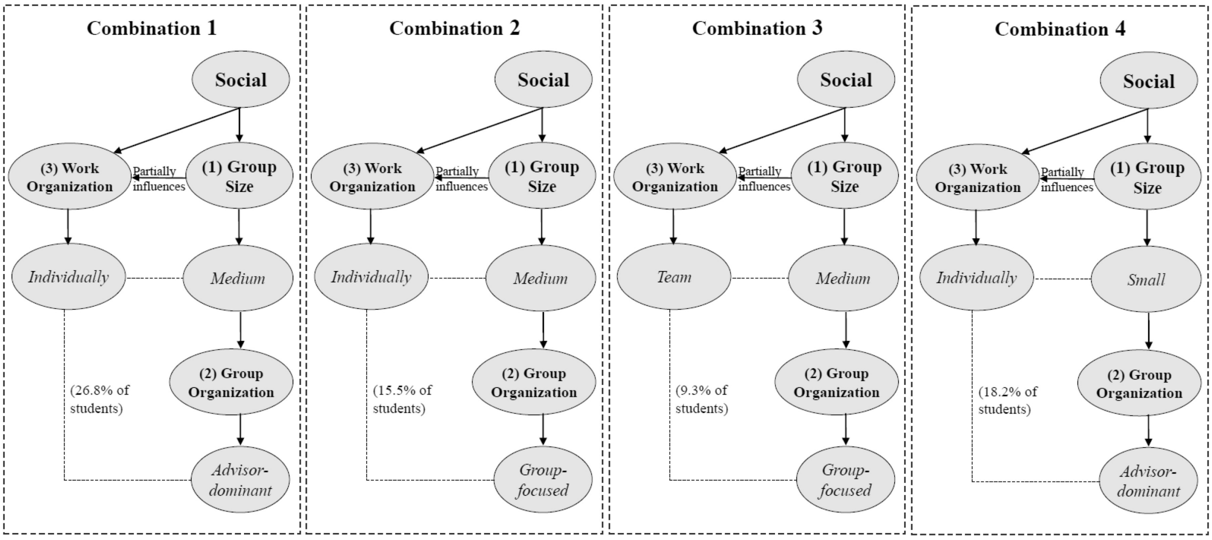

Fig. 3. Percentages of students for the social group combinations shown in the Concept Map.

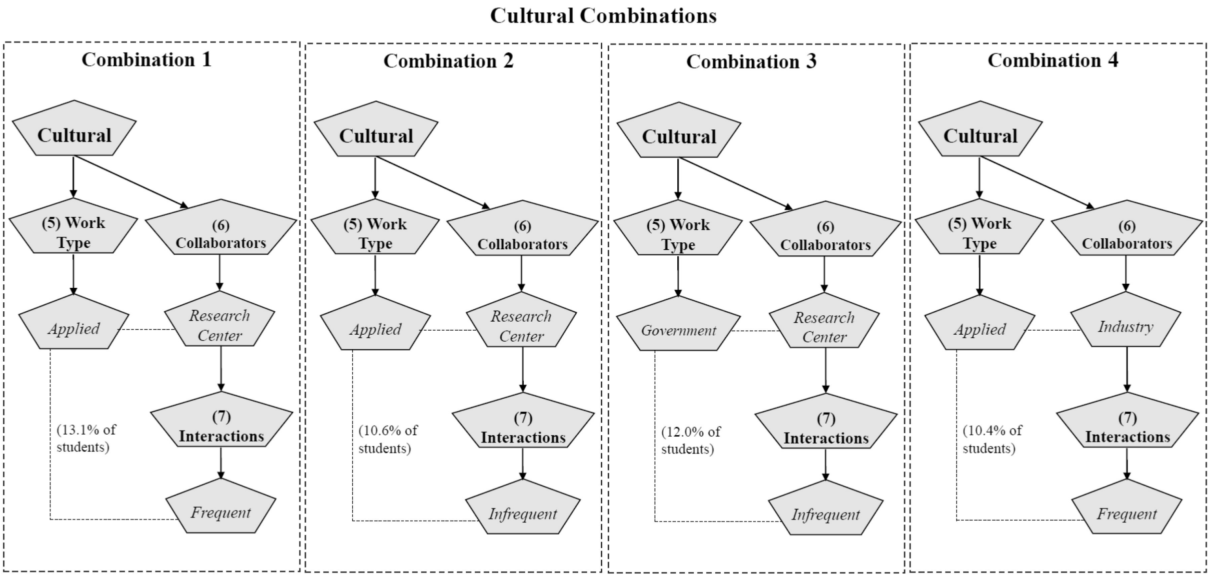

Fig. 4. Percentages of students for the cultural group combinations shown in the Concept Map.

between frequent and infrequent interactions with students' collaborators (both at 23%). (4) Students with government collaborators infrequently interacted, whereas students with industry collaborators frequently interacted, aligning with Gemme and Gingras [46]. The most notable grouping results were in Work Type and Collaborators groups. Regarding Work Type, almost 2.5 times as many students reported working on applied research (n = 314, 70%) as working on basic research (n = 123, 27%). This result was similar to the results Behrens and Gray [26] found that graduate engineering students rated their research as more applied than basic (mean of 3.29 on a 5-pt. scale, or 66%), and helps us understand that most students are working on applied research. Regarding Collaborators, forty percent (n = 182) of students reported their main collaborator as a university research center, followed by a government collaborator at 28% (n = 125) and an industry collaborator at 22% (n = 98). Ten percent (n = 46) of students either did not have a collaborator or could not define their collaborator and were put in the 'Other' category. These percentages are similar to what Behrens and Gray [26] found when graduate engineering students reported sponsorship (a proxy for collaborator), as 37% university research center, 34% government, 17% industry, and 12% other, and helps us understand the approximate breakdown of students' collaborators.

Regarding the Material combinations shown in Fig. 5, the overall clustering for the four selected

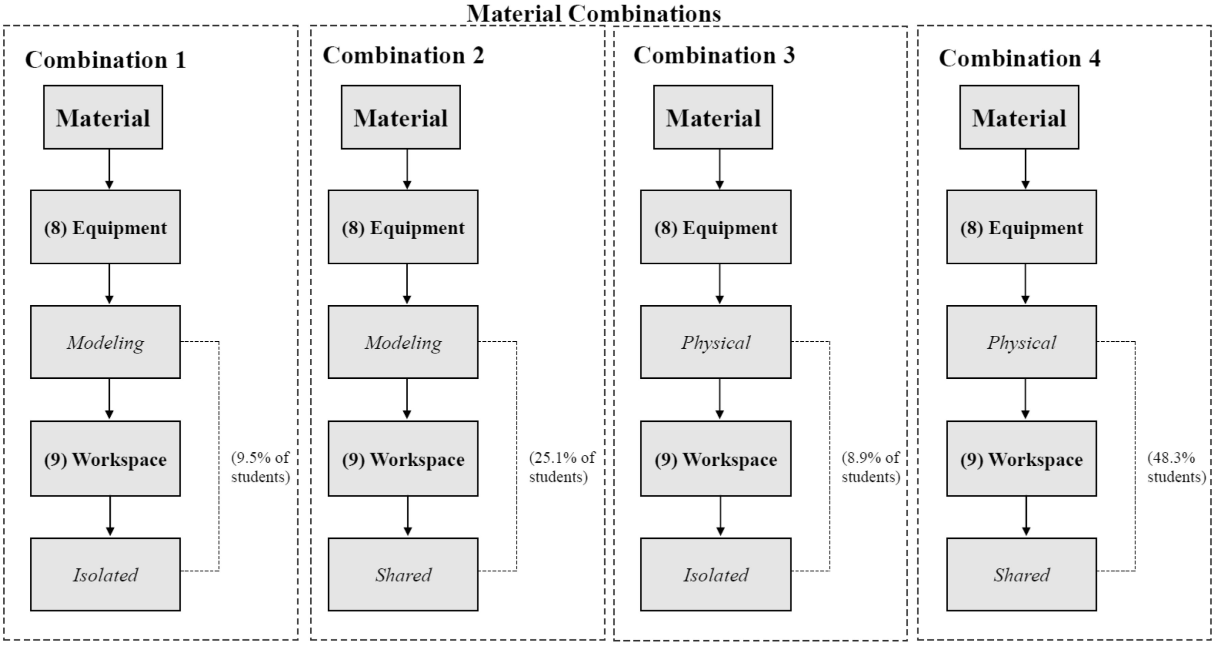

Fig. 5. Percentages of students for the material group combinations shown in the Concept Map.

material groups accounted for 92% (n = 414) of all the respondents. This result suggested that material clustering captured most students' material experiences. The physical equipment type in a shared workspace was the largest cluster by far (48%), almost twice as large as the next biggest, aligning with Crede and Borrego [17]. A combined 18.4% of students worked in an isolated workspace, limiting their opportunities to access equipment [17]. The most notable grouping results were in Equipment and Workspace. Regarding Equipment, slightly more than 1.5 times as many students reported working with testing and physical experiments in their research experiences (n = 262, 58%) as working only with modeling and simulation (n = 160, 36%). These results further support the literature that the traditional experiences of doctoral engineering students are working on physical experiments [17], and help us understand that overall, more students are getting hands-on experiences than are not. Regarding Workspace, almost four times as many students reported working in a shared workspace (n = 350, 78%) as working in an isolated workspace (n = 90, 20%). Crede and Borrego [17] tracked a similar but slightly different metric for workspace, and their metric also tracked at a ratio of 4:1 shared vs. isolated. This result helps us understand that while the vast majority of students are in a shared workspace, many (~20%) still work in isolated spaces.

4.4 Results for Significance Testing between Students' Research Experiences

Table 5 shows the results of the twelve selected comparison groups (the nine social, cultural, and material contexts, and the combination of each context) for significance testing used to determine if there were differences between students' research experiences. We chose groups based on mean REI *Opportunity* scores, indicating a potential difference in research experiences, and the group sizes met the statistical power threshold. Table 5 also shows the sub-groups that we compared. For example, in Group 1: Group size, we compared the 'medium' and 'small' group sizes, as we did not have enough students in the 'large' group size for comparison. Table 5 includes the size of the sample and the group size we selected for the significance testing, which was the minimum sub-group size in the comparison group. For example, the smallest sub-group in Group 1 had a group size of 151, so we set the group size for all groups in Group 1 to 151 for statistical significance testing.

The results of the significance testing for the twelve selected social, cultural, and material group combinations are shown in Table 6 (Mann-Whitney U Tests) and Table 7 (Kruskal-Wallis H Test) below. The results indicated significant differences for ten of the twelve groups in REI *Opportunity* scores. The two groups with no differences in REI *Opportunity* scores were (1) 'Group Organization' and (2) 'Engineering Discipline.' In other words, our tests indicated no difference between an advisor-dominant research group and a group-focused research group, and there were no differences between Chemical, Electrical & Computer, and Mechanical engineering students' research experiences. In the other ten groups with significant

Table 5. The twelve selected groups for comparison

Comparison Groups	**Sub-Groups**	***n***	**%**	**Selected Group Size**	***Opportunity M* (SD)**
Group 1: Group Size	Medium (5–20)	290	64.3	151	19.74 (3.94)
	Small (< 5)	151	33.5		18.63 (4.25)
Group 2: Group Organization	Advisor-dominant (dom.)	245	54.3	165	19.05 (3.97)
	Group-focused(foc.)	165	36.6		19.72 (4.16)
Group 3: Work Organization	Individual(Indiv.)	332	73.6	99	18.93 (4.03)
	Team	99	22.0		20.76 (3.79)
Group 4: Engineering (Engr.) Discipline	Chemical Engr.	50	11.1	50	20.10 (3.35)
	Electrical & Computer Engr.	82	18.2		19.93 (3.94)
	Mechanical Engr.	87	19.3		18.98 (4.41)
Group 5: Work Type	Basic	123	27.3	123	18.15 (4.18)
	Applied	314	69.6		19.86 (3.96)
Group 6: Collaborator	Government	125	27.7	98	19.87 (3.65)
	Industry	98	21.7		20.72 (3.64)
	Research Center (Cen.)	182	40.4		18.93 (3.95)
Group 7: Interactions	Infrequent	222	49.2	196	18.74 (3.81)
	Frequent	196	43.5		20.70 (3.73)
Group 8: Equipment	Model/Simulation Only	160	35.5	160	18.23 (4.25)
	Some facility/test	262	58.1		20.53 (3.45)
Group 9: Workspace	Isolated	90	20.0	90	17.80 (4.48)
	Shared	350	77.6		19.85 (3.81)
Group 10: Social Groups	Medium / Advisor-dom. / Indiv.	121	26.8	42	18.93 (3.74)
	Medium / Group-foc. / Indiv.	70	15.5		19.80 (4.31)
	Medium / Group-foc. / Team	42	9.3		20.60 (3.79)
	Small / Advisor-dom. / Indiv.	82	18.2		18.04 (4.13)
Group 11: Cultural Groups	Applied / Research Cen. / Frequent	59	13.1	47	20.58 (3.72)
	Applied / Research Cen. / Infrequent	48	10.6		18.63 (3.58)
	Applied / Government / Infrequent	54	12.0		19.65 (3.96)
	Applied / Industrial / Frequent	47	10.4		22.07 (3.06)
Group 12: Material Groups	Modeling / Isolated	43	9.5	40	16.62 (4.48)
	Modeling / Shared	113	25.1		18.94 (3.98)
	Physical / Isolated	40	8.9		19.54 (4.04)
	Physical / Shared	218	48.3		20.74 (3.33)

Table 6. Group mean comparison—Mann-Whitney *U* Tests

Groups	**Values**	**Group Size**	**Overall score *M* (SD)**	***U***	***z***	***p***	**Mean Rank**
Group 1: Group Size	Medium	151	19.74 (3.94)	13,452.5	–2.705	0.007	165.1
	Small		18.63 (4.25)				137. 9
Group 2: Group Organization	Advisor-dominant	165	19.05 (3.97)	14,847.0	1.425	0.154	158.0
	Group-focused		19.72 (4.16)				173. 0
Group 3: Work Organization	Individual	99	18.93 (4.03)	6,259.0	3.370	0.001	85.8
	Team		20.76 (3.79)				113. 2
Group 5: Work Type	Basic	123	18.15 (4.18)	9,237.5	2.998	0.003	109.9
	Applied		19.86 (3.96)				137. 1
Group 7: Interactions	Infrequent	196	18.74 (3.81)	24,590.5	4.799	<0.001	169.0
	Frequent		20.70 (3.73)				224. 0
Group 8: Equipment	Modeling	160	18.23 (4.25)	16,976.0	5.047	<0.001	134.4
	Physical		20.53 (3.45)				186. 6
Group 9: Workspace	Isolated	90	17.80 (4.48)	5,274.5	3.503	<0.001	76.9
	Shared		19.85 (3.81)				104.1

Table 7. Group mean comparison—Kruskal-Wallis *H* Test

Groups	Values	Group Size	Overall score *M* (SD)	χ^2	*df*	*p*	Mean Rank (*)	*p (**)*
Group 4: Engineering (Engr.) Discipline	Chemical Engr.	50	20.10 (3.35)	2.856	2	0.240	n/a	n/a
	Electrical & Computer Engr.		19.93 (3.94)					
	Mechanical Engr.		18.98 (4.41)					
Group 6: Collaborator	Government	98	19.87 (3.65)	10.068	2	0.007	150.4	Research Center: Industry, $p = 0.005$
	Industry		20.72 (3.64)				165.2	
	Research Center		18.93 (3.95)				126.9	
Group 10: Social Groups	1—Medium / Advisor-dominant / Individual	42	18.93 (3.74)	8.351	3	0.039	81.1	Group 3: Group 4, $p = 0.029$
	2—Medium / Group-focused / Individual		19.80 (4.31)				87.8	
	3—Medium / Group-focused / Team		20.60 (3.79)				99.5	
	4—Small / Advisor-dominant / Individual		18.04 (4.13)				69.6	
Group 11: Cultural Groups	1—Applied / Research Center / Frequent	47	20.58 (3.72)	22.818	3	<0.001	98.5	Group 2: Group 1, $p = 0.013$
	2—Applied / Research Center / Infrequent		18.63 (3.58)				70.7	Group 2: Group 4, $p<0.001$
	3—Applied / Government / Infrequent		19.65 (3.96)				86.4	Group 3: Group 4, $p = 0.008$
	4—Applied / Industry / Frequent		22.07 (3.06)				122.5	
Group 12: Material Groups	1—Modeling / Isolated	40	16.62 (4.48)	18.372	3	<0.001	56.7	Group 1: Group 3, $p = 0.013$
	2—Modeling / Shared		18.94 (3.98)				77.7	
	3—Physical / Isolated		19.54 (4.04)				88.5	Group 1: Group 4, $p<0.001$
	4—Physical / Shared		20.74 (3.33)				98.2	
Note: (*) Pairwise Dunn's with Bonferroni correction (**) Pairwise significance; If not listed, pairwise not significant.								

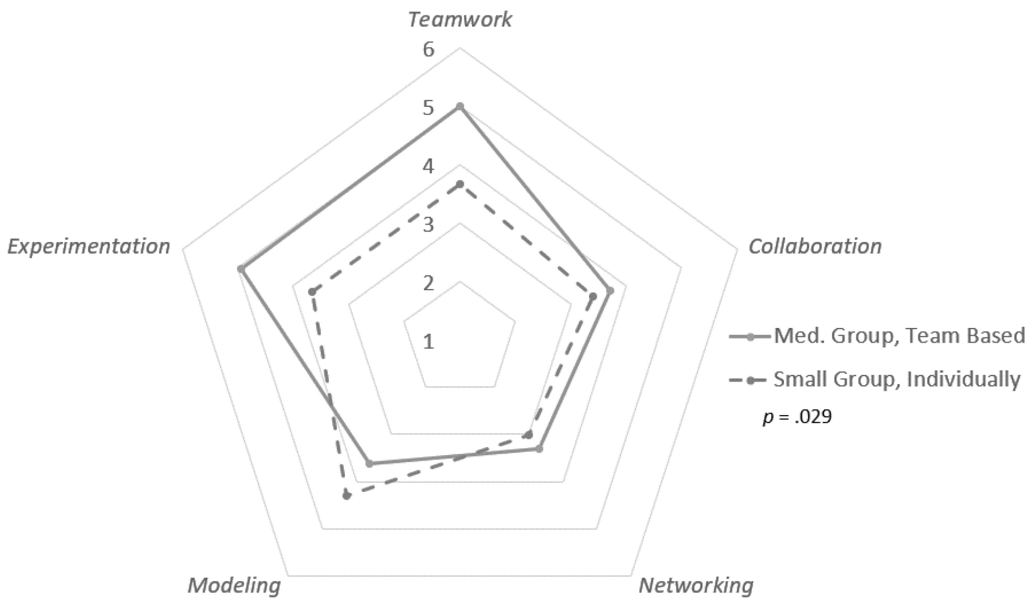

Fig. 6. Radar plot of REI scores for the significant Social Groups.

differences in REI *Opportunity* scores, some students had significantly more opportunities than others in their research experiences to practice being a professional.

4.5 Discussion of Results of Significance Testing between Students' Research Experiences

In this discussion, we summarize the results of the significance testing between the social, cultural, and

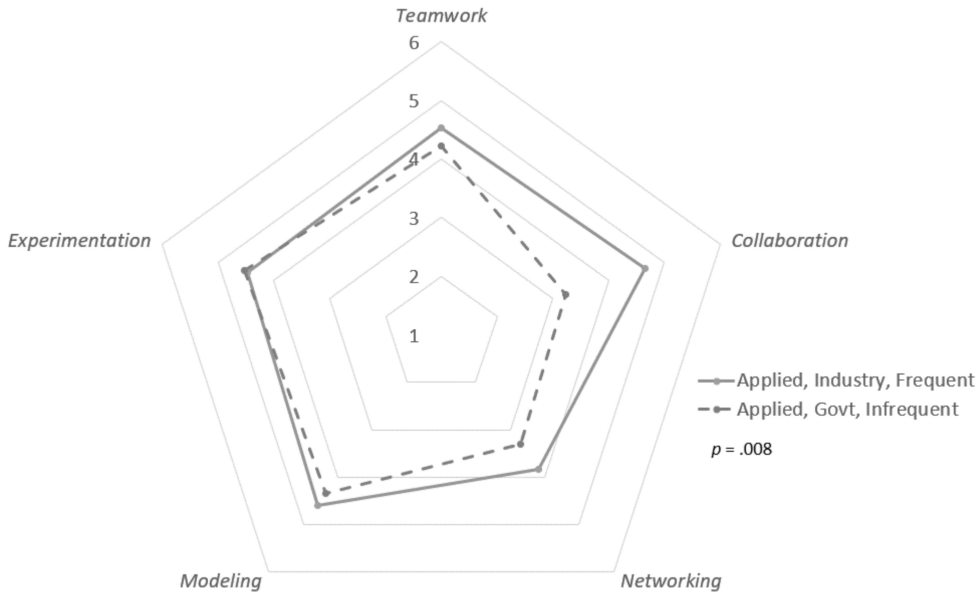

Fig. 7. Radar plot of REI scores for the significant Cultural Groups.

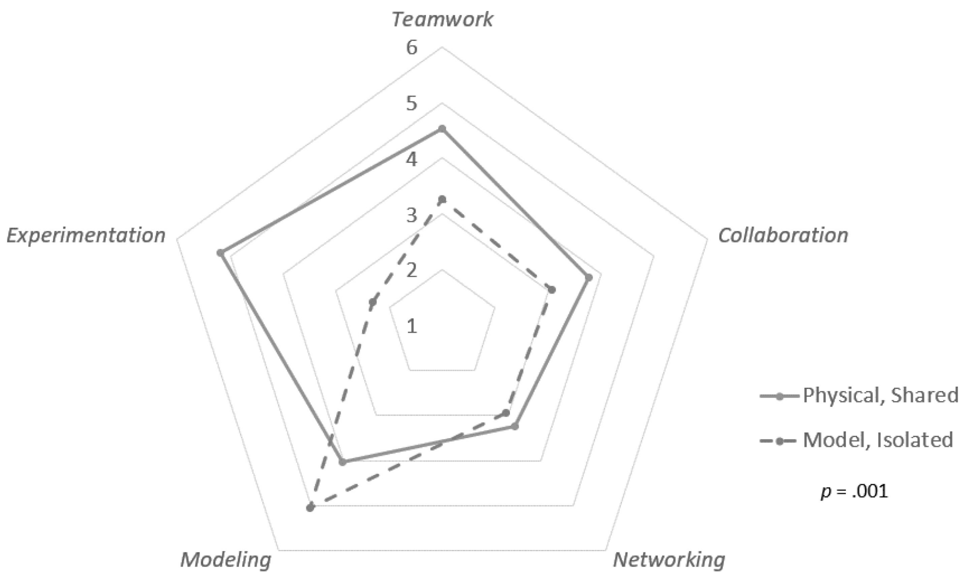

Fig. 8. Radar plot of REI scores for the significant Material Groups.

material group combinations, focused specifically on Group 10 (Social Groups), Group 11 (Cultural Groups), and Group 12 Material Groups), as these group combinations provide insight to the individual groups. Every group is summarized in Table G1 in Appendix G.

In order to understand the overall impact that the social, cultural, and material contexts have on students' research experiences and their opportunity to practice being a professional, it helps to visualize how those contexts impact students' scores on the REI.

Fig. 6 shows the radar plot for REI factor scores for the two groups that were compared for the significance testing for the Social groups. These results indicated that students in a medium-sized research group, with a group organization that is group-focused, and a work organization that is team-based had significantly more opportunities than students in a small-sized research group, with a group organization that is advisor-dominated, and a work organization that is individual-based. Specifically, students had significantly more opportunities to work on teams (note: highest *Teamwork* score for any group in the study, over 1 point higher than the comparison group) and for practical skills from testing environments (i.e., higher *Experimentation* scores, over 1 point higher than the comparison group).

Fig. 7 shows the radar plot for REI factor scores for the groups that were compared for the significance testing for Cultural groups. These results indicated that students with industry collaborators who had frequent interactions while working on applied research had more opportunities than students who had government or research center collaborators who had infrequent interactions while working on applied research. Specifically, students had significantly more opportunities to work on a team (i.e., slightly higher *Teamwork* scores than the comparison group), and to work with both their direct collaborators (i.e., higher *Collaboration* scores, almost 2 points higher than the comparison group) and the wider community of practice (i.e., higher *Networking* scores than the comparison group). The *Opportunity* mean score (M = 22.07) for the industry collaborator Cultural group was the highest of any sub-group, indicating this group had the most opportunities.

Fig. 8 shows the radar plot for REI factor scores for the groups that were compared for the significance testing for Material groups. These results indicated students who worked on physical experiments in a shared workspace had more opportunities than students who worked on modeling and simulation in an isolated workspace. Specifically, students had significantly more opportunities in all aspects except modeling and simulation tasks (i.e., similar *Modeling* scores). The Material group combination of modeling and simulation work in an isolated workspace was particularly impactful on students' scores in that these students had many fewer opportunities, especially to work on a team (i.e., slightly lower *Teamwork* scores than the comparison group), and to work with both their direct collaborator (i.e., lower *Collaboration* scores, almost 2 points lower than the comparison group) and the wider community of practice (i.e., lower *Networking* scores, almost 1 point lower than the comparison group).

5. Discussion

The primary goals of this study were to identify the most common types of doctoral engineering research experiences, determine if there were significant differences among those experiences, and ascribe meaning to differences in students' experiences that prepare them for professional practice. We developed a new conceptual framework to understand the important aspects of students' research experiences that are important to their professional development by utilizing Dall'Alba's Ways of Being framework [18] as a lens for reviewing the literature. We uncovered that nine contexts of students' research experiences, based on the social, cultural, and material significance [30], are essential to their professional development. We wrote self-report questions based on these nine social, cultural, and material contexts, which we used to survey 451 doctoral engineering students from 30 different universities over two different data collection periods in the summer and fall of 2019, where we also assessed these students with the REI, a measurement of their opportunities in their research experiences to practice being professionals. Next, we tabulated and clustered the self-report questions to form 12 groups of students' research experiences that were aligned with their social, cultural, and material significance. Then, we reported the numbers and percentages of students in each social, cultural, and material group, along with how these aligned with previous values reported in the literature. Finally, we calculated mean REI *Opportunity* scores for each of the twelve social, cultural, and material groups and compared those for statistical significance to indicate which groups of students had significant differences in their research experiences. We found that 10 of the groups showed significant differences, and we compared individual REI factor scores to help ascribe meaning to differences and reviewed how our results aligned with previous literature. We discuss the most common types of doctoral engineering research experiences and how those results align with the literature in Table 8.

The conceptual framework we developed for examining students' research experiences related to important aspects for professional practice preparation utilized a social, cultural, and material perspective to do so [37]. The evidence we presented suggests that this lens was very effective for this purpose, as the social and material context captured a very large percentage of respondents (70% and 92%, respectively), and the cultural context captured the diversity of experiences within the cultural context. The evidence suggests this conceptual framework, and hence the Concept Map we developed, has evidence of its validity for examining doctoral engineering students' research experiences, as many results found were similar to previous research results [17, 26, 46]. We expected these results because we built the conceptual framework upon the previous literature, yet this also suggests that new results from this study have evidence of validity when applied to the use of examining research experiences of doctoral engineering students.

As we found significant differences among students' research experiences, as indicated by their REI scores, we emphasize four main takeaways from these results. First and most importantly, the evidence showed that there were indeed differences

Table 8. Most commonly reported student research experiences

Groups	Most common types of research experiences	Alignment with Concept Map/Literature
Group 1: Group Size	Most students on a medium size team; twice as many as small (64% vs. 34%). Very few in large (2%).	Aligned with Concept Map and literature [17].
Group 2: Group Organization	More than half of students work in an advisor-dominated group; 1.5 times as many as group-focused (54% vs. 37%).	Aligned with Concept Map and literature [17]
Group 3: Work Organization	Most students work individually; three times as many as team-focused (74% vs. 22%).	Not specified in Concept Map. New finding not previously reported in literature.
Group 5: Work Type	Most students work on applied research; 2.5 times as many as basic (70% vs. 27%).	Aligned with Concept Map and literature [26].
Group 6: Collaborator	Diverse experiences 40% research center 28% government 22% industry	Aligned with Concept Map and literature [26].
Group 7: Interactions	Roughly even distribution 49% infrequent 44% frequent	Not specified in Concept Map. New findings not previously reported in literature.
Group 8: Equipment	More than half of students work with testing and experiments; 1.5 times as many as modeling (58% vs. 36%)	Aligned with Concept Map and literature [17].
Group 9: Workspace	Most students work in a shared workspace; almost four times as many as isolated (78% vs. 20%).	Aligned with Concept Map and literature [17].
Group 10: Social Group	Four groups were formed in the social cluster, for which the groups accounted for 70% of respondents. The largest group was the medium research group size, in an advisor-dominated group organization, where students work mostly individually.	Overall alignment with Concept Map and the literature [17]. New findings presented with social clustering.
Group 11: Cultural Group	Four groups were formed in the cultural cluster, accounting for 46% of respondents. All four groups were roughly the same size (~11%), and all were applied research work. The most common wastwo groups of research center collaborators, one with frequent interactions and one without.	While there was alignment with Concept Map and literature [46], the low clustering (46%) and the dual clusters for research centers indicate the needed future work to obtain a larger sample for the cultural group and a deeper categorization of the research center experiences. New findings presented with cultural clustering.
Group 12: Material Group	Four groups were formed in the material cluster, for which the groups accounted for 92% of respondents. The largest group was the physical/testing equipment type in a shared workspace, which was the expected result.	Overall alignment with Concept Map and the literature [17]. New findings presented with material clustering statistics.

between research experiences, where some research experiences contributed more, and some contributed fewer opportunities for students. Second, the evidence indicated which *context* of the research experiences contributed more or fewer opportunities for students (i.e., which context from the Concept Map). For example, in some cases, the context identified was the size of the research group, or type of workspace, etc. This result is also significant as a diagnostic, as it opens up the possibility of ways to provide more opportunities for students. Third, the evidence indicated which *aspects* of the research experiences students had more or fewer opportunities (i.e., which REI factor score was low). For example, in some cases, the opportunity was to work on a team. In other cases, the opportunity was to work with their collaborators, etc. This result can serve as a diagnostic, similar to the previous result, as it offers a roadmap for providing more opportunities for students. Fourth, the evidence indicated alignment with the Concept Map and previous literature [17, 20, 26, 29, 46], while also presenting new results for the engineering education community.

As a whole, there are many ways for faculty and administrators to help students seek more opportunities to be/become professionals based on the results of this study, summarized in Table 9.

If students need more opportunities to work on a team, faculty and administrators can help by involving undergraduate students in the research process [64]. If students are in an isolated workspace, faculty and administrators can consider if students could be moved to collaborative locations with others, preferably with their groupmates, to have more team interactions. Students can take some initiative on their own to seek out opportunities to work as team members, such as serving on committees, joining teams of graduate student associations, and others where teamwork is essential [65].

If students need more opportunities to work with their direct collaborators and the wider community of practice, faculty can help students by asking their current collaborators to find more opportunities to

Table 9. Summary of recommendations for ways to help doctoral engineering students get more targeted opportunities in their research experiences

Groups	Suggestions for ways for faculty and administrators to help students get more targeted opportunities
Group 1: Group Size	Help students who **work in small-size research groups** to get opportunities to **work as team members**.
Group 3: Work Organization	Help students who **mostly work alone or with their advisors only** to get opportunities to **work as team members**.
Group 5: Work Type	Help students who **work on basic research** to get opportunities to (1) **involve them with their direct collaborators** and (2) **the wider community of practice**.
Group 6: Collaborator	Help students **who work with research centers or government collaborators** to get opportunities to (1) **involve them with their direct collaborators** and (2) **the wider community of practice**.
Group 7: Interactions	Help students who **infrequently work with their collaborators** to get opportunities to (1) **involve them with their direct collaborators** and (2) **the wider community of practice**.
Group 8: Equipment	Help studentswho **work only on modeling and simulation** to get opportunities to **work as team members**.
Group 9: Workspace	Help students who **work in isolated workspaces** to get opportunities to (1) **work as team members** and (2) **involve them with their direct collaborators**.
Group 10: Social Group	Help students who **work in small-size research groups, with a group organization that is advisor-dominated**, and a **work organization that is individual-based**, to get opportunities to **work as team members**.
Group 11: Cultural Group	Help students **who work with government or research center collaborators**, who **had infrequent interactions**, to get opportunities to (1) **work as team members**, (2) **involve them with their direct collaborators,** and (3) **the wider community of practice**.
Group 12: Material Group	Help students who **work on modeling and simulation** in **an isolated workspace** to get opportunities to (1) **work as team members**, (2) **involve them with their direct collaborators**, and (3) **the wider community of practice**.

engage with them. Most working professionals (especially alums) are happy to participate with and help mentor students, and some universities have formal programs for such opportunities for graduate students [66]. Faculty can be more flexible in letting students intern at some point in their doctoral studies. Students are often concerned about approaching their advisors about an internship for fear that they will be seen as unserious [67], and faculty may be hesitant to let students participate in an internship due to research progress. Students seeking opportunities to work with their direct collaborators and the wider community of practice could consider advocating to their faculty advisor to be included in interactions with collaborators, such as presenting research results, and for opportunities to interact with other professionals for feedback. Students can also advocate for other opportunities, such as co-ops or internships, or get involved in multiple research projects with different experiences. Students can also pursue some opportunities on their own, such as joining and becoming active in professional engineering societies and other opportunities, as long as those opportunities bring students closer to understanding the essential parts of the transformation process *to be and become a professional*.

The evidence we have presented about the significant differences in students' research experiences allows us to return to the validity evidence for the REI, specifically the consequential aspect of validity [68]. For this type of validity evidence, the instrument's developers consider how it will be used, specifically the practical and ethical implications [68]. We provided an initial evaluation of such in our previous work [32]. We can go a step further and acknowledge evidence that the REI measures differences in students' opportunities in their research experience, but the REI is not a measurement of research experiences being "better" or "worse." For example, we contrast students in the cultural "work type" experience. Students who worked in an "applied research" experience had more overall opportunities (i.e., higher *Opportunity* scores) than those who worked in a "basic research" experience. They also had more opportunities to work with both their direct collaborator and the wider community of practice (i.e., higher *Collaboration* and *Networking* scores) than those who worked in a "basic research" experience (see Table 5). These results do not mean that a "basic research" experience is inferior compared to an "applied research" experience for students. Rather, the results indicate that students in a "basic research" experience likely need other experiences in teamwork and working with professionals to supplement their overall professional development.

6. Limitations and Future Work

Our sampling strategy is a limitation. We collected data from 30 institutions that were not randomly selected. However, these institutions provide insight into engineering doctoral students' research preparation. In addition, our findings are consistent with previous literature. Future research might involve administering the REI to a random sample to better approximate the experiences of engineering doctoral students at a national level.

Finally, we review what results of the NSF-funded ERC experiences would *likely be* when assessed by the REI. ERCs strive to support students with more opportunities in their research experiences outside traditional basic ones through several specific student initiatives: work on applied research, interact more frequently with sponsors from industry and government, work that hones skills in modeling and experimentation, and work on a team [16, 22, 27]. These attributes would imply students working in ERCs should have higher REI scores in *Teamwork*, *Collaboration*, *Networking*, *Modeling*, *Experimentation*, and hence *Opportunity* scores. In the report, *A New Vision for Center-Based Engineering Research* [22], the National Academy of Engineering issued recommendations for the vision and future of NSF-funded ERCs. These recommendations included those explicitly focused on students' engineering education, including their opportunities for teamwork, industrial and governmental collaborations, workshops and seminars, and practical skills. Future studies can focus on the REI as an assessment instrument for students in ERC experiences.

7. Conclusions

The goal of this work was to provide a deeper understanding of how doctoral engineering students' research experiences prepare them for practice upon graduation by investigating the types of research experiences they report that are aligned with professional practice. Overall, this study supports that goal, as we provided empirical evidence of what engineering faculty see intuitively every day: that doctoral engineering students have different opportunities for professional practice preparation based on the contexts in which they conduct their research. Based on the developed Concept Map, in which we identified nine social, cultural, and material contexts of importance for students' professional development in their research, and using the Research Experiences Instrument (REI), we provided empirical evidence in the form of overall numbers and percentages of students' research experiences in the social, cultural, and material contexts aligned with previous literature. This evidence suggests that Concept Map has evidence of validity and is a valuable way to examine doctoral engineering students' professional development opportunities in their research. We provided empirical evidence that ten groups of social, cultural, and material contexts had significant differences in opportunities for professional development in students' research experiences. More importantly, we identified the *specific* social, cultural, and material contexts of students' research experiences where they will likely have significantly *fewer* opportunities and which aspects of students' skills will likely be affected in those environments. This evidence suggests that some students are missing out on their professional development opportunities, likely leading to the gaps seen by industry and others once in the workforce.

The implications for the faculty, administrators, students, and researchers are clear. Faculty and administrators should look for opportunities to make research spaces more collaborative (so that students are not working alone), to work with outside collaborators (so that students can interact with professionals and network), and to work on applied projects (so that students develop more practical skills). Students also need to realize where their research experiences may be falling short based on their setup and look for opportunities to get more experience in teamwork, working with outside collaborators, and practical skills – this may include advocating to their advisor for new experiences, including internships and co-ops. Finally, for researchers, our study contributes to the small number of studies and literature related to the research experiences of graduate engineering students and how those are critical in students' preparation for practice. The REI offers a diagnostic for measuring students' various opportunities in their research experiences. It provides researchers with a tool to understand where their students may lack professional development opportunities that can help students be better prepared for professional work.

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Appendix A: REI self-report questions and responses with literature references

Table A1 List of REI self-report questions and responses

Group	Self-Report Question	Literature Reference
(1) Group Size	Question: Including yourself, approximately how many graduate student members are in your research group?	Similar to questions asked in Crede and Borrego [69].
(2) Group Organization	How is your Ph.D. research group organized? Response Option 1: The research group is structured where the advisor sets most of the interactions, communication, and mentoring of students. Response Option 2: The research group is structured where much of the communication and mentoring is student-to-student, with the faculty advisor leading in a functional role. Response Option 3: Other (explain)	Similar to questions asked in Crede and Borrego [69].
(3) Work Organization	Question: How is your Ph.D. research work organized? Response Option 1: Most of the day-to-day work involves working by myself or with my advisor. Response Option 2: Most of the day-to-day work involves interaction with a broader team within the research group. Response Option 3: Other (explain)	Similar to questions asked in Crede and Borrego [69].
(4) Engineering Discipline	Question: What is your engineering Ph.D. major? Response Options: (1) Aeronautics and Astronautics, (2) Agricultural & Biological, (3) Biomedical, (4) Chemical, (5) Civil, (6) Construction Engineering & Management, (7) Electrical & Computer, (8) Engineering Education, (9) Environmental and Ecological Engineering, (10) Industrial, (11) Materials, (12), Mechanical, (13) Nuclear, (14) Other (explain)	Similar to questions asked in [70].
(5) Work Type	Question: What type of Ph.D. research are you primarily working on? Response Option 1: Basic (fundamental research without specific applications towards processes or products in mind). Response Option 2: Applied (research that has specific applications towards processes or products). Response Option 3: Other (explain)	Based on [71].
(6) Collaborator	Question: What type of collaborators, either internal or external, do you work with primarily in your Ph.D. research? Response Option 1: a strong emphasis on government collaborations. Response Option 2: a strong emphasis on industry collaborations. Response Option 3: a strong emphasis on research center collaborations. Response Option 4: Other (explain)	None.
(7) Interactions	Question: What type of interactions do you have with the collaborators identified in the previous question? Response Option 1: collaborations consist of infrequent contact, mostly written reports, resulting in a relationship with the collaborators that are not very deep. Response Option 2: collaborations consist of frequent contact, including email and face-to-face interaction for reporting results, resulting in a deep relationship with the collaborators. Response Option 3: Other (explain)	None.
(8) Equipment	Question: What type of equipment do you primarily use to conduct your Ph.D. research? Response Option 1: the primary nature of the research work relies on modeling and simulation with sophisticated computer equipment and software tools. Response Option 2: the primary nature of the research work relies on facilities, test equipment, and physical experiments. Response Option 3: A combination of 1 & 2 above. Response Option 4: Other (explain)	None.
(9) Workspace	Question: How is the workspace for your Ph.D. research group organized? Response Option 1: housed in a lab space or office where I work mostly alone or near a few others. Response Option 2: housed in lab space or office that is shared with my research group only. Response Option 3: housed in a lab space that is shared with multiple different types of research groups. Response Option 4: Other (explain)	Similar to questions asked in Crede and Borrego [69]

Appendix B: Changes made to self-report questions with examples

Table B1. Changes made to self-report 'Other' responses

Question	Responses modified	Example
Q1: Including yourself, approximately how many graduate student members are in your research group?	14	Three responses were changed from 0 (which is not possible) to 1.
Q2: How is your Ph.D. research group organized?	12	A response of "the research group is over micro-managed by the advisor with no room for new ideas and execution" was changed to '(1) Research group is structured where the advisor sets most of the interactions, communication, and mentoring of students.'
Q3: How is your Ph.D. research work organized?	14	A response of "most of the day-to-day involves working by myself, but I can discuss ideas with my colleagues in the lab if I need help" was changed to '(1) Most of the day-to-day work involves working by myself or with my advisor.'
Q4: What is your engineering Ph.D. major?	3	A response of 'Other – ECE & Statistics' was changed to '(7) ECE.'
Q5: What type of Ph.D. research are you primarily working on?	4	A response of "Applied social" was changed to '(2) Applied (research that has specific applications towards processes or products).'
Q6; What type of collaborators do you work with primarily in your Ph.D. research?	17	A response of "National Labs" was changed to '(1) A strong emphasis on government collaborations.'
Q7: What type of interactions do you have with the collaborators identified in the previous question?	8	A response of "Collaboration consists of infrequent contact but mostly face to face" was changed to '(1) Collaborations consist of infrequent contact, mostly written reports, resulting in a relationship with the collaborators that are not very deep.'
Q8: What type of equipment do you primarily use to conduct your Ph.D. research?	1	A response "the scope of our work related to both robust modeling and simulation as well as experimental systems. I personally work on modeling" was changed to '(1) The primary nature of the research work relies on modeling and simulation with sophisticated computer equipment and software tools.'
Q9: How is the workspace for your Ph.D. research group organized?	8	A response of "no designated lab space" was changed to '(1) Housed in a lab space or office where I work mostly alone or near a few others.'

Appendix C: Social, Cultural, and Material Contexts Scores

Table C1. Mean factor scores for the social, cultural, and materialsub-groups

Groups	Values	*n*	%	Mean Scores					
				Teamwork	Collabora-tion	Networking	Modeling	Experi-mentation	Opportunity *M* (SD)
All	n/a	451	100	4.21	3.63	3.16	4.23	4.15	19.38 (4.05)
(1) Group Size	Large (> 20)	10	2.2	4.50	3.55	3.33	3.58	5.12	20.08 (2.47)
	Medium (5–20)	290	64.3	4.34	3.65	3.18	4.30	4.26	19.74 (3.94)
	Small (< 5)	151	33.5	3.96	3.58	3.10	4.12	3.87	18.63 (4.25)
(2) Group Organization	Advisor-dominant	245	54.3	3.95	3.52	3.07	4.46	4.05	19.05 (3.97)
	Group-focused	165	36.6	4.58	3.64	3.22	3.93	4.35	19.72 (4.16)
	Other	41	9.1	4.31	4.18	3.46	4.06	3.92	19.93 (3.99)
(3) Work Organization	Individual	332	73.6	4.00	3.54	3.08	4.35	3.96	18.93 (4.03)
	Team	99	22.0	4.87	3.88	3.40	3.82	4.78	20.76 (3.79)
	Other	20	4.4	4.50	3.83	3.31	4.30	4.04	19.99 (4.44)
(5) Work Type	Basic	123	27.3	4.07	3.38	2.78	4.05	3.87	18.15 (4.18)
	Applied	314	69.6	4.24	3.73	3.31	4.31	4.26	19.86 (3.96)
	Other	14	3.1	4.77	3.55	3.02	3.98	4.05	19.36 (2.68)

Table C1. (*Continued*)

Groups	Values	*n*	%	Mean Scores					
				Teamwork	Collabora-tion	Networking	Modeling	Experi-mentation	Opportunity *M* (SD)
(6) Collaborator	Government	125	27.7	4.22	3.53	3.36	4.37	4.40	19.87 (3.65)
	Industry	98	21.7	4.29	3.98	3.49	4.52	4.43	20.72 (3.64)
	Research Center	182	40.4	4.29	3.64	2.94	4.02	4.04	18.93 (3.95)
	Other	46	10.2	3.72	3.08	2.76	4.10	3.29	16.95 (4.96)
(7) Interactions	Infrequent	222	49.2	4.14	3.24	2.95	4.24	4.17	18.74 (3.81)
	Frequent	196	43.5	4.43	4.21	3.49	4.28	4.28	20.70 (3.73)
	Other	33	7.3	3.42	2.69	2.55	3.91	3.23	15.81 (4.32)
(8) Equipment	Modeling	160	35.5	3.86	3.54	3.15	4.91	2.76	18.23 (4.25)
	Physical	262	58.1	4.42	3.70	3.20	4.01	5.20	20.53 (3.45)
	Other	29	6.4	4.24	3.51	2.78	2.43	2.28	15.24 (3.57)
(9) Workspace	Isolated	90	20.0	3.58	3.20	3.01	4.33	3.67	17.80 (4.48)
	Shared	350	77.6	4.30	3.76	3.21	4.21	4.29	19.85 (3.81)
	Other	11	2.4	3.45	3.08	2.77	4.24	3.59	17.13 (4.26)

Appendix D: Engineering Discipline Scores

Table D1. Mean factor scores for all engineering (Engr.) discipline sub-groups [32]

Engineering Discipline Group	*n*	%	Mean Scores					
			Teamwork	Collabora-tion	Networking	Modeling	Experi-mentation	Opportunity *M* (SD)
All	451	100	4.21	3.63	3.16	4.23	4.15	19.38 (4.05)
Aeronautics and Astronautics Engr. students	35	7.8	4.22	3.51	3.34	4.66	3.66	19.39 (4.15)
Agricultural and Biological Engr. students	1	0.2	3.25	3.17	1.50	4.33	4.33	16.58
Biomedical Engr. students	39	8.6	4.62	3.73	3.01	3.91	4.86	20.14 (3.04)
Chemical Engr. students	50	11.1	4.82	3.43	3.07	4.07	4.72	20.10 (3.35)
Civil Engr. students	35	7.8	4.14	3.74	3.36	4.56	4.15	20.00 (3.67)
Construction Engr. and Managementstudents	3	0.7	3.08	4.11	3.17	4.11	3.28	17.75 (6.87)
Electrical and Computer Engr. students	82	18.2	4.07	3.67	3.36	4.82	4.01	19.93 (3.94)
Engineering Education students	28	6.2	4.64	3.85	2.68	2.34	2.26	15.76 (3.73)
Environmental and Ecological Engr. students	12	2.7	3.69	3.60	3.52	3.89	3.85	18.54 (4.27)
Industrial Engr. students	20	4.4	3.26	3.31	3.11	4.14	3.30	17.13 (4.81)
Materials Engr. students	32	7.1	4.35	4.18	3.45	3.63	5.16	20.76 (3.07)
Mechanical Engr. students	87	19.3	4.02	3.27	2.86	4.47	4.36	18.98 (4.41)
Nuclear Engr. students	8	1.8	4.22	4.00	3.34	4.54	4.15	20.25 (3.11)
Other Engr. major students	19	4.2	4.09	4.27	3.54	4.24	3.99	20.13 (4.50)

Appendix E: Combined Social, Cultural, and Material Contexts Scores

Table E1. Mean factor scores for the combination of social, cultural, and material sub-groups

Groups	Values	*n*	%	Mean Scores: Teamwork	Collaboration	Networking	Modeling	Experimentation	Opportunity *M* (SD)
All	n/a	451	100	4.21	3.63	3.16	4.23	4.15	19.38 (4.05)
Social Groups	1—Medium / Advisor-dominant / Individual	121	26.8	3.82	3.49	3.00	4.60	4.01	18.93 (3.74)
	2—Medium / Group-focused / Individual	70	15.5	4.53	3.69	3.22	4.21	4.14	19.80 (4.31)
	3—Medium / Group-focused / Team	42	9.3	5.01	3.72	3.31	3.62	4.94	20.60 (3.79)
	4—Small / Advisor-dominant / Individual	82	18.2	3.68	3.40	3.02	4.29	3.65	18.04 (4.13)
Cultural Groups	1—Applied / ResearchCenter / Frequent	59	13.1	4.46	4.05	3.29	4.27	4.51	20.58 (3.72)
	2—Applied / ResearchCenter / Infrequent	48	10.6	4.30	3.35	2.90	4.08	3.99	18.63 (3.58)
	3—Applied / Government / Infrequent	54	12.0	4.23	3.23	3.30	4.34	4.53	19.65 (3.96)
	4—Applied / Industry / Frequent	47	10.4	4.53	4.65	3.83	4.59	4.47	22.07 (3.06)
Material Groups	1—Modeling / Isolated	43	9.5	3.26	3.07	2.93	5.04	2.32	16.62 (4.48)
	2—Modeling / Shared	113	25.1	4.13	3.75	3.26	4.85	2.95	18.94 (3.98)
	3—Physical / Isolated	40	8.9	3.89	3.37	3.09	3.88	5.32	19.54 (4.04)
	4—Physical / Shared	218	48.3	4.53	3.77	3.23	4.04	5.18	20.74 (3.33)

Appendix F: Results of Most Common Types of Research Experiences

Table F1. Discussion of most common types of research experiences

Groups	Summary of the most common type of research experiences for each group and alignment with literature
Group 1: Group Size	Almost twice as many students reported being in a medium-size group (n = 290, 64%) as being in a small group (n = 151, 34%), and very few students (n = 10, 2%) reported being in a large group. These results very closely match the percentages reported by Crede and Borrego [17] for the same categories (small: 31%, medium 67%, large 3%).
Group 2: Group Org.	Almost 1.5 times as many students reported working in an advisor-dominated research group (n = 245, 54%) as working in a group-focused research group where the advisor takes a functional role (n = 165, 37%). Crede and Borrego [17] indicated that, in general, small research groups would be advisor-dominated, large research groups would be group-focused, and medium groups would be a mix of the two. This result further supports Crede and Borrego's [17] original findings explained above.
Group 3: Work Org.	More than three times as many students reported primarily working individually or with their advisor (n = 332, 74%) as primarily working on a broader team (n = 99, 22%). Recall that work organization is shaped by the size of the research team [17], where small groups are more likelyto work more individually, and large groups work more team-based. This result would suggest that students in medium-size research groups also work primarily individually.
Group 5: Work Type	Almost 2.5 times as many students reported working on applied research (n = 314, 70%) as working on basic research (n = 123, 27%). This result was similar to results Behrens and Gray [26] found that graduate engineering students rated their research as more applied than basic (mean of 3.29 on a 5 pt. scale, or 66%).
Group 6: Collaborator	Forty percent (n = 182) of students reported their main collaborator as a university research center, followed by a government collaborator at 28% (n = 125) and an industry collaborator at 22% (n = 98). Ten percent (n = 46) of students either did not have a collaborator or could not define their collaborator and were put in the 'Other' category. These percentages are similar to what Behrens and Gray [26] found when graduate engineering students reported sponsorship (a proxy for collaborator), as 37% university research center, 34% government, 17% industry, and 12% other.
Group 7: Interactions	Slightly more students reported infrequently interacting with their collaborator (n = 222, 49%) as frequently interacting with their collaborator (n = 196, 44%).

Table F1. (*Continued*)

Groups	Summary of the most common type of research experiences for each group and alignment with literature
Group 8: Equipment	Slightly more than 1.5 times as many students reported working with testing and physical experiments in their research experiences (n = 262, 58%) as working only with modeling and simulation (n = 160, 36%). These results further support the literature that the traditional experiences of doctoral engineering students are working on physical experiments [17].
Group 9: Workspace	Almost four times as many students reported working in a shared workspace (n = 350, 78%) as working in an isolated workspace (n = 90, 20%). Crede and Borrego [17] tracked a similar but slightly different metric for workspace, and their metric also tracked at a ratio of 4:1 shared vs. isolated.
Group 10: Social Groups	The overall clustering for the four selected social groups accounted for 70% (n = 315) of all the respondents. This result suggested that social clustering captured the vast majority of students' social experiences. The main point drawn from the social clustering was that most students clustered into an advisor-dominated group organization where students work mostly individually (45%) vs. very few that clustered into a group-focused group organization where students work mostly as a team (9%). The overall social group clustering follows Crede & Borrego's original findings [17].
Group 11: Cultural Groups	The overall clustering for the four selected cultural groups accounted for only 46% (n = 208) of all the respondents. This result did not suggest that the cultural clustering did not capture the vast majority of student experiences, but it did suggest the cultural cluster is quite diverse in students' research experiences. Four other key points from the overall clustering were: (1) only applied work type generated clusters, as the basic research work type did not; (2) the cultural cluster group sizes were very similar, and relatively small (~10%); (3) there was an even split between frequent and infrequent interactions with students' collaborators (both at 23%). (4) Students who had government collaborators infrequently interacted, whereas students who had industry collaborators frequently interacted, aligning with Gemme and Gingras [46].
Group 12: Material Groups	The overall clustering for the four selected material groups accounted for 92% (n = 414) of all the respondents. This result suggested that material clustering captured the vast majority of students' material experiences. The physical equipment type in a shared workspace was the largest cluster by far (48%), almost twice as large as the next biggest, aligning with Crede and Borrego [17]. A combined 18.4% of students worked in an isolated workspace, limiting their opportunities to access equipment [17].

Appendix G: Results of Most Common Types of Research Experiences

Table G1. Discussion of the ten groups with significant differences in professional practice opportunities

Groups	Summary of Mean REI*Opportunity* Score Indication about Students' Professional Practice Opportunities
Group 1: Group Size	*Opportunity* scores indicated that students in medium-size research groups had more opportunities than students on small-size research groups. Specifically, students had more opportunities to work on teams (i.e., higher *Teamwork* scores) and for practical skills from testing environments (i.e., higher *Experimentation* scores). This result was expected based on the Concept Map and the literature [17].
Group 3: Work Organization	*Opportunity* scores indicated that students who did most of their work on a team had more opportunities than students who mainly worked individually. Specifically, students had more opportunities to work on teams (i.e., higher *Teamwork* scores). While this result seems obvious, it can be noted that students workingon a team in testing environments also gained more practical skills (i.e., higher *Experimentation* scores). This result was expected based on the Concept Map and the literature [17].
Group 5: Work Type	*Opportunity* scores indicated that students who worked on applied research had more opportunities than those who worked on basic research.Specifically, students had more opportunities to work with both their direct collaborator (i.e., higher *Collaboration* scores) and the wider community of practice (i.e., higher *Networking* scores). While this result might have been expected at least in part, the REI provides clear empirical evidence for it.
Group 6: Collaborator	*Opportunity* scores indicated that students who worked with industry collaborators had more opportunities than students who worked with research center collaborators. Specifically, students had more opportunities in all aspects except to work on teams (i.e., similar *Teaming* scores). While it is known that industry collaborators typically provide more opportunities for interactions [20, 29], the REI provides clear empirical evidence of the nature of industry's impact on opportunities.
Group 7: Interactions	*Opportunity* scores indicated that students who frequently worked with their collaborators had more opportunities than students who infrequently worked with their collaborators. Specifically, students had more opportunities to work with both their direct collaborator (i.e., higher *Collaboration* scores) and the wider community of practice (i.e., higher *Networking* scores). While this result might have been expected at least in part, the REI provides clear empirical evidence.
Group 8: Equipment	*Opportunity* scores indicated that students who worked on testing/physical experiments had more opportunities overall than students who worked only on modeling and simulation. Specifically, students had more opportunities to work on teams (i.e., higher *Teamwork* scores), and more opportunities for practical skills from testing environments (i.e., higher *Experimentation* scores). Students who worked only on modeling and simulation had more opportunities to work on modeling and simulation tasks (i.e., higher *Modeling* scores). These results were expected based on the Concept Map and the published literature, as Thune [29] indicated, students who work on testing/physical experiments were more likely to work on teams.

Table G1. (*Continued*)

Groups	Summary of Mean REI*Opportunity* Score Indication about Students' Professional Practice Opportunities
Group 9: Workspace	*Opportunity* scores indicated that students who worked in a shared workspace had more opportunities than students who worked in isolated workspaces. Specifically, students had more opportunities in all aspects except modeling and simulation tasks (i.e., similar *Modeling* scores). This result might have been expected based on the Concept Map, and the literature from the workspace effects [17]. However, the REI provides valuable new empirical evidence for all the aspects influenced by workspace.
Group 10: Social Groups	*Opportunity* scores indicated that students on medium-size research groups, with a group organization that is group-focused, and a work organization that is team-based had more opportunities than students on small-size research groups, with a group organization that is advisor-dominated, and a work organization that is individual-based. Specifically, students had more opportunities to work on teams (note: highest *Teamwork* score for any group) and for practical skills from testing environments (i.e., higher *Experimentation* scores). These results might have been expected based on the Concept Map, and the literature [17]. However, the REI provides valuable new empirical evidence.
Group 11: Cultural Groups	*Opportunity* scores indicated two different groups of cultural research experiences with differences: (1) Scores indicated that students with frequent interactions with their research center collaborators working on applied research had more opportunities than those who had infrequent interactions with their research center collaborators working on applied research. Specifically, students had more opportunities to work with both their direct collaborator (i.e., higher *Collaboration* scores) and the wider community of practice (i.e., higher *Networking* scores). While this might have been anticipated, at least in part, the REI provides clear empirical evidence for it. (2) Scores indicated that students with industry collaborators who had frequent interactions while working on applied research had more opportunities than students who had government or research center collaborators who had infrequent interactions while working on applied research. Specifically, students had more opportunities to work on a team (i.e., higher *Teamwork* scores), and for work with both their direct collaborator (i.e., higher *Collaboration* scores) and the wider community of practice (i.e., higher *Networking* scores). The *Opportunity* score for the industry collaborator cultural group was the highest of any sub-group, indicating this group had the most opportunities. While this might have been anticipated, at least in part, the REI provides clear empirical evidence for it.
Group 12: Material Groups	*Opportunity* scores indicated that students who worked on physical experiments in a shared workspace had more opportunities than students who worked on modeling and simulation in an isolated workspace. Specifically, students had more opportunities in all aspects except modeling and simulation tasks (i.e., similar *Modeling* scores). The material group combination of modeling and simulation work in an isolated workspace was particularly impactful on students' scores in that these students had many fewer opportunities, especially to work on a team (i.e., lower *Teamwork* scores), and to work with both their direct collaborator (i.e., lower *Collaboration* scores) and the wider community of practice (i.e., lower *Networking* scores). This result might have been expected based on the Concept Map, and the literature from the workspace effects [17]. However, the REI provides valuable new empirical evidence for it.

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