DEVELOPMENT AND VALIDATION OF AN ASSESSMENT OF ENGINEERING PH.D. STUDENTS' RESEARCH EXPERIENCES

by

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Dedicated to my family: my wife Beth, and my grown-up adult son and daughter, Reese and Riley, Purdue engineers all! You all make me so proud. Thank you for supporting me in this endeavor, as it would have been impossible without your love and support!

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ABSTRACT

Global concerns about the preparedness of engineering Ph.D. students for professional practice are not new. In the U.S., educational reform has focused on the research experiences of students to foster better preparation. Yet, little is known about which aspects of students' research experiences are essential to prepare them for practice due to the heterogeneity of the experiences, and what opportunities they have in their research to practice being a professional. The goal of this study was to develop and initially validate an instrument that measures students' perceptions of their research experiences utilizing an ontological theoretical framework that focuses on what it means to become a professional. This framework simplified the heterogeneity and allowed for the investigation of how the research experiences of engineering Ph.D. students are providing opportunities for students to practice being a professional. Four distinct phases of development were utilized to accumulate validity evidence for the instrument: a development phase that focused on question generation and review: an initial pilot test that centered on an Exploratory Factor Analysis on responses (*n* = 236) from a large Midwestern University; a second pilot test that centered on a Confirmatory Factor Analysis on responses (*n* = 215) from multiple universities; and a Group Analysis phase that tested statistical differences between groups. Three key results emanated from this work. First, the accumulated validity evidence justifies the intended use of the instrument as a research and program evaluation survey to assess engineering Ph.D. students' research experiences for opportunities to practice being a professional. Second, the results suggest that, on average, students had fewer opportunities to work with professionals (i.e., take on others' forms of practice) in their research experiences than other types of opportunities. Third, the results suggest that research experiences can be categorized into those that provide significantly more and significantly fewer opportunities for students to practice being a professional. Higher education tends to focus on the epistemological aspects of professional practice preparation, but utilizing an ontological approach can identify gaps in preparation. Implications of the opportunities identified in this study are discussed for faculty, students, other researchers, instrument users, engineering administrators, and national program administrators, with a focus on providing more opportunities to students to practice being a professional. The utilization of an ontological approach for engineering Ph.D. students' research experiences, including tangible examples and a call for a new vision for U.S. engineering Ph.D. research experiences, are discussed.

1. INTRODUCTION

The critical need to better prepare U.S. engineering Ph.D. students for professional practice is perhaps best understood by examining the concerns raised by the National Academies over the past twenty-five years. The National Academy of Engineering (NAE) report *Guidelines for Engineering Research Centers* (1983) observed pointedly that the research training of engineering Ph.D. students places "an overemphasis on analytical research, with less opportunity for 'hands-on' experimental research; inadequate exposure of engineering students to engineering practice; a widening gap between academic engineering programs and industrial practice, and a lack of interaction between faculty and industrial practitioners of systems engineering" (National Academy of Engineering, 1983, p. 2). A decade later, the NAE report *Forces Shaping the US Academic Engineering Research Enterprise* (1995) raised an additional concern that "the training of new Ph.D.'s is too narrow intellectually, too campus-centered, and too long" (National Academy of Engineering, 1995, p. 2). More recently, the NAE report *A New Vision for Center-Based Engineering Research* (National Academy of Engineering, 2017b) noted that some research experiences better prepare engineering Ph.D. students for professional practice by "include[ing] a greater emphasis on collaborative, team-based experiential learning and a focus on creativity and design activities and entrepreneurship, as well as ethical aspects, which better prepare students to succeed in center-like, multidisciplinary environments throughout their careers" (National Academy of Engineering, 2017b, p. 48). Finally, the National Academies of Sciences, Engineering and Medicine recent report *Graduate STEM Education for the 21st Century* expressed the concern that many engineering Ph.D. students are not prepared for professional practice, as "many graduate programs do not adequately prepare students to translate their knowledge into impact in multiple careers" (National Academies of Sciences, 2018, p. 1).

Similar concerns are echoed globally about Ph.D. students not being adequately prepared for professional practice. In the U.S., the report *The Path Forward* (Wendler et al., 2010), a joint report by The Council of Graduate Schools and Educational Testing Service about the future of graduate education in the U.S., highlighted the lack of a robust professional development component in graduate programs and the need to provide better preparation for professional practice "that provide doctoral students with transferable skills valued by employers" (Wendler et al., 2010, p. 56). In Canada, the report *Inside and Outside the Academy: Valuing and Preparing*

Ph.D.s for Careers (Edge & Munro, 2015), published by the Conference Board of Canada, highlighting similar concerns about the need to provide Ph.D. students with individual career advising, discipline-specific programs, and experiential learning opportunities to help better prepare Ph.D. students for professional practice.

In Europe, concerns over Ph.D. student preparedness is being addressed by the European University Association (EUA). The first effort began with the EUA Doctoral Programs Project (European University Association, 2005b) in 2004-05, which grew from the "need to adapt research training to meet the challenges of the global labour market, technological advances, new profiles and demands of doctoral candidates" (European University Association, 2005b, p. 6). This baseline study of the practices and experiences in doctoral programs from forty-eight universities in twenty-two countries across Europe led to the creation of ten principles recommended to guide doctoral programs (European University Association, 2005a). One of the principles was to recognize Ph.D. candidates as professionals who make a key contribution to knowledge creation. A follow-up study, called *DOC-CAREERS* (Borrell-Damian, 2009), incorporated an industry perspective to the university setting to better prepare Ph.D. graduates for industry careers. The study involved thirty-three universities across twenty European countries. The report indicated that "companies were very satisfied with the acquired knowledge and research skills of doctorate graduates educated in Europe, but also pointed to the need for greater communication skills, and the limited awareness of intellectual property issues and understanding of how businesses operate" (Borrell-Damian, 2009, p. 8). The report provided several recommendations for universities to improve their graduate programs for better-prepared Ph.D. graduates for industry. A third European study, called *DOC-CAREER II* (Borrell-Damian, Morais, & Smith, 2015), focused on promoting collaborative research opportunities for Ph.D. students to enhance career opportunities, as there was a strong need for "collaborative doctoral programmes and the skills that doctoral candidates acquire through their education and training" (Borrell-Damian et al., 2015, p. 8). The study found that Ph.D. graduates from a collaborative industry experience had more job opportunities than students from traditional programs, as the development of transferable industry skills was identified as critical (Borrell-Damian et al., 2015).

In 2016, the Australian Council of Learned Academies (ACOLA) published a report called *Review of Australia's Research Training System* (McGagh et al., 2016). This report was deeply concerned about Australia's Ph.D. research training system, especially with industry-university collaborations. The report highlighted issues in the areas of Ph.D. students' transferable skills development, which are "not as strongly embedded in our research training system as it is in some other comparable research training systems around the world." (McGagh et al., 2016, p. 22). The report provided several recommendations for Australian universities to improve their Ph.D. research training, among which included closer ties to industry in research, more opportunities for students to practice professional skills, and more specific professional development programs during Ph.D. training (McGagh et al., 2016).

Returning to the case of the U.S. engineering Ph.D. students, it is generally agreed that the U.S. graduate engineering system has attracted the best students and has been the driving force behind the technical innovations over the past thirty years (Akay, 2008). Yet, with evidence that other countries are catching up with the U.S. system (Akay, 2008), the continuing concerns raised about the preparedness of U.S. engineering Ph.D. students must be addressed to maintain the competitive advantage of the U.S. graduate engineering system and prepare graduates for leadership in today's global economy. Until U.S. engineering Ph.D. students are better prepared for professional practice, other countries will continue to draw near, and perhaps surpass the U.S. graduate engineering system.

1.1 Research Problem

Education reform of the U.S. graduate engineering system has focused on the research experiences of students, especially for engineering Ph.D. students, with some evidence of success at better preparing students for professional practice. The preeminent example of a national effort aimed at reforming the engineering Ph.D. student research experiences is the advent of the National Science Foundation (NSF) university-led Engineering Research Centers (ERCs). ERCs and similar types of programs typically offer different engineering Ph.D. student research experiences than traditional basic research experiences, requiring more applied research projects, greater interaction with industry and government sponsors, and different student skill sets (Kannankutty, Morgan, & Strickland, 1999; Morgan, Kannankutty, & Strickland, 1996).

One of the original goals of ERCs was "to improve engineering research so that U.S. engineers will be better prepared to contribute to engineering practice" (Parker, 1997, p. 3). To accomplish this goal, ERCs incorporated a focus on teamwork skills, a different problem-solving approach, and the needs of industry into the engineering Ph.D. student research experiences

(Parker, 1997). ERCs have been shown to have significant impacts on the engineering Ph.D. students' educational process and outcomes from the standpoint of improving industry's perceptions of engineering Ph.D. students' preparedness for professional practice (Parker, 1997; Ponomariov, Welch, & Melkers, 2009). Beyond this one example, how the engineering Ph.D. research experiences influence students' preparedness for professional practice is not well understood as the engineering Ph.D. students' research experiences are not well understood.

Despite the calls for improving the graduate engineering education system, there has been little research devoted to the topic of the research experiences of engineering Ph.D. students (Crede & Borrego, 2012; Rogers & Goktas, 2010). The few studies focused on the research experiences of engineering Ph.D. students have looked at specific aspects of the research experiences, not the research experience holistically (e.g., Crede & Borrego, 2012; Ponomariov et al., 2009; Rogers & Goktas, 2010). Other studies about engineering Ph.D. students, while not directly about the engineering Ph.D. student research experiences, such funding impacts (Behrens & Gray, 2001) and type of engineering research work (Morgan et al., 1996), can inform the understanding of how the engineering Ph.D. research experiences influence students' preparedness for professional practice.

One reason that the engineering Ph.D. student research experiences remain understudied is the perception that students' research experiences are unique and diverse, or as Thune explained, a heterogeneous phenomenon (Thune, 2009, 2010). However, examining how the research experiences of engineering Ph.D. students shape their preparedness for professional practice can simplify the heterogeneity of the research experiences by allowing the focus to be on the important aspects related to professional practice. There is evidence (previously mentioned) that the engineering Ph.D. student research experiences are influencing students' preparedness for professional practice (Parker, 1997; Roessner, Cheney, & Coward, 2004) and that the research experiences of students are not well understood from that standpoint (Crede & Borrego, 2012; Rogers & Goktas, 2010). These results point to the need to (i), identify and characterize the most important aspects of the engineering Ph.D. student research experiences related to professional practice that can be derived from a broad review of the literature, and (ii), utilizing the literature findings, develop an instrument to measure the most important aspects of the engineering Ph.D. student research experiences related to professional practice preparedness.

The success or failure of educational reforms of the design of engineering student Ph.D. research experiences has typically been evaluated by assessing, either directly or through the perceptions of others, the knowledge, skills, and abilities of engineering Ph.D. students. For example, multiple instrument development studies that measured the perceived knowledge, skills, and abilities of alumni of ERCs compared to those who did not have an ERC experience found that ERCs were beneficial to the development of the knowledge, skills, and abilities of ERC alumni (Parker, 1997; Roessner et al., 2004). Typically, these assessments measure aspects such as teamwork, breadth and depth of technical knowledge, and problem-solving ability (Parker, 1997; Roessner et al., 2004). Other assessments tend to focus directly on the Ph.D. students' research skills, such as their skills at developing research proposals, and how those skills changed over time (Timmerman, Feldon, Maher, Strickland, & Gilmore, 2013). However, there are no assessments that measure aspects related to the opportunities that are present (or not) in engineering Ph.D. students' research experiences to practice becoming a professional, for example, through interactions with other professionals or through experiences where students gain skills that matter to professional practice. Opportunities to practice becoming a professional have been shown to be a significant contributor to Ph.D. students' being prepared for actual professional practice upon graduation (Dall'Alba, 2009; Dall'Alba & Sandberg, 2010). As such, there is a need to (i), understand what in the engineering Ph.D. student research experiences are the most important opportunities for students to practice becoming a professional, and, (ii), to measure the extent to which the engineering Ph.D. research experiences contribute to those identified opportunities for students to practice becoming a professional.

1.2 Purpose of the Study

The goal of this study was to develop a deeper understanding of engineering Ph.D. students' research experiences and how those experiences were providing opportunities for students to practice becoming a professional. In order to accomplish this goal, this study developed and conducted an initial validation of the use of an instrument to measure engineering Ph.D. students' perceptions of their research experiences. The primary purpose of this study was to develop and validate the use of a psychometrically sound engineering-specific Research Experiences Instrument (REI) that measures engineering Ph.D. students':

1. Self-report of the most important aspects of their engineering Ph.D. research experiences related to professional practice as identified and characterized from the literature.
2. Perceptions of the extent to which their engineering Ph.D. research experiences contributed to opportunities to practice becoming a professional.

Figure 1.1 below provides an overview of the study's purpose. As Figure 1.1 indicates, the data from the self-report measurement were used to identify and group the engineering Ph.D. students by their research experiences and other demographic data. The scores from the perception measurement (REI scores) were used to indicate the extent to which their research experiences contributed to the opportunities to practice becoming a professional. Finally, the REI scores were analyzed by the groups of research experiences and demographic groups identified in the self-report data.

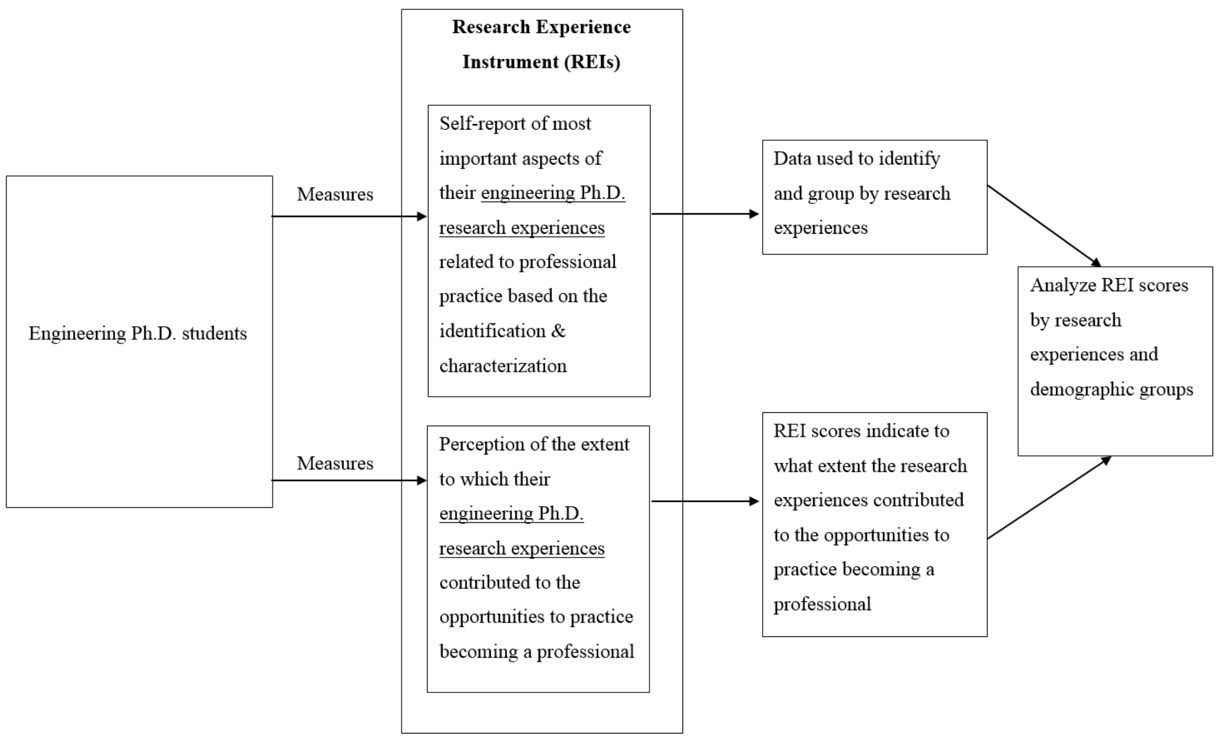

Figure 1.1: Overview of Purpose of the Study

1.3 Research Questions

The instrument-level research questions for this study were as follows:

RQ1: To what degree does the REI measure engineering Ph.D. students' perceptions of the extent to which their engineering Ph.D. research experiences contributed to the opportunities to practice becoming a professional?

a. Which assessment questions demonstrate evidence of measuring engineering Ph.D. students' research experiences?
b. To what extent do the REI scale scores support the theoretical factor structure?
c. To what extent do the REI scale scores demonstrate evidence of reliability and validity based on the responses of engineering Ph.D. students?

The study-level research questions for this study were as follows:

RQ2: What are the most common types of engineering Ph.D. research experiences based on the data, and how do the results align with the identification and characterization of those experiences from the literature?

RQ3: Are there significant differences in the mean REI scores between research experiences that indicate certain research experiences contribute more or fewer opportunities to practice becoming a professional?

RQ4: Are there significant differences in the mean REI scores between demographic groups (discipline, gender, ethnicity, etc.) that indicate certain group's research experiences contribute more or fewer opportunities to practice becoming a professional?

1.4 Significance of the Study

This study has the potential to shape future policy, organizational arrangements, and practice around the design of the engineering student Ph.D. research experience. First, this study has the potential to advance knowledge at a national level by helping program managers at NSF and similar organizations understand which engineering Ph.D. research experiences are contributing more to students' opportunities to practice becoming a professional than other engineering Ph.D. research experiences. This type of knowledge could help program managers decide which programs to fund, which initiatives to pursue that will improve opportunities to practice becoming a professional, or what initiatives could incentivize providing more opportunities for students to practice becoming a professional. Second, this study has the potential to contribute to the educational field by helping higher education administrators in engineering understand more about the engineering Ph.D. research experiences of their students and which students might need more help with opportunities to practice becoming a professional. Finally, this study has the potential to improve engineering educational practice by helping engineering faculty and students understand more about the engineering Ph.D. research experiences so that they can make decisions about their own research trajectory, practices, and additional opportunities that engineering Ph.D. students need to pursue to acquire more opportunities to practice becoming a professional.

1.5 Organization of the Study

As the purpose of this study was to develop and validate the Research Experiences Instrument (REI), Chapter 2 provides the theoretical framework and literature review in support of the measurement constructs for the REI. Chapter 3 provides an overview of the research design of the study, and how the development of REI is broken up into four phases. Each phase of the REI development is summarized in a Chapter, Chapters 4 through 7 respectively, and both the methodologies and results of developing the REI and conducting pilot testing to collect evidence of validity are provided. The methods and results for these four Chapters are combined, as there are several phases of development and pilot testing, and the results from one phase are used in subsequent phases. Chapter 8 provides a discussion of the results, with a focus on answering the research questions, along with discussions about the larger implications and limitations of the study. The final chapter, Chapter 9, discusses the conclusions from the study, along with future research questions that emanate from the study.

2. THEORETICAL FRAMEWORK AND LITERATURE REVIEW

This chapter establishes the theoretical framework utilized for the study and reviews the essential literature, and is comprised of four sections. The first section introduces a review of the literature on why becoming a professional, and learning to do so, is difficult for engineering Ph.D. students. The purpose is to provide the ontological theoretical framework that was utilized in the study. This section also reviews previous measurements of engineering Ph.D. students' research experience in the context of the ontological theoretical framework and frameworks for understanding professional engineering practice. The second section involves a focused literature review of engineering Ph.D. students' research experiences utilizing the same ontological theoretical framework in order to identify and initially characterize the most important aspects of students' research experiences as it relates to what happens in their research experiences and how their research experiences relate to preparation for professional practice. The third section utilizes the results of the focused literature to define six key characteristics or constructs that form a new Conceptual Framework for understanding professional development in engineering Ph.D. students' research experience, that are later utilized for measurement. Finally, in the fourth section, the six key characteristics and the Conceptual Framework are operationalized by identifying the main ontological aspects of engineering Ph.D. students' research experiences that may be present or absent. This process involved a further review of relevant literature and provided the basis for developing an instrument for measuring the engineering Ph.D. student research experiences from an ontological perspective.

2.1 An Ontological Theoretical Framework on Becoming a Professional

This section introduces an ontological theoretical framework that guided and situated this study around professional practice and what it means to become professional. The ontological theoretical framework is briefly introduced in order to examine what it means to "become a professional", and what that framework and other literature indicate about why becoming a professional, and learning to do so, is difficult for Ph.D. students. Relevant literature on the ontological theoretical framework used in this study is then examined in detail in the context of engineering Ph.D. students' research experiences and contrasted with alternative frameworks that take a predominately epistemological approach. The logic of how the ontological theoretical framework was used in this study is presented in a flow diagram.

2.1.1 Becoming a Professional is Difficult for Engineering Ph.D. Students

From the various critiques of the engineering Ph.D. experience, it is clear that many students find it difficult to make the transition from a Ph.D. student to becoming a professional. But what does it mean to "become a professional"? Dall'Alba helps answer this question with her prior work on this topic, and this study approached that question through the utilization of her 'ways of being' framework (Dall'Alba, 2009). The 'ways of being' framework adds an ontological (being) aspect onto the typical epistemological (knowing) aspect in the process of becoming a professional. Adding the ontological aspect allows the focus to be on what it means to develop professional ways of being (ontological - being), and not just focus on the acquisition of knowledge and skills (epistemological - knowing) (Dall'Alba, 2009). Dall'Alba provides two definitions that are important for the context of this study: the process of <u>becoming a professional</u>, and <u>learning to become a professional</u>, as follows:

> *<u>Becoming a professional</u> involves transformation of the self through embodying the routines and traditions of the profession in question* (Dall'Alba, 2009, p. 37).
>
> *<u>Learning to become a professional</u> involves not only what we know and can do, but also who we are (becoming). It involves integration of knowing, acting, and being in the form of professional ways of being that unfold over time* (Dall'Alba, 2009, p. 34).

Dall'Alba indicates that becoming a professional, and learning to do so, is difficult for Ph.D. students for a host of reasons. These reasons include: 1) the process of becoming a professional is ambiguous, and this ambiguity makes it difficult (Dall'Alba, 2009); 2) the engineering Ph.D. student research experiences are a period of great transition that requires a substantial change in how students view themselves within the context of professional practice, and this substantial change is difficult for students (Dall'Alba, 2009); 3) the lack of a focus on the ontological process of becoming a professional makes it difficult for engineering Ph.D. students to situate their technical knowledge when integrating that knowledge into practice (Dall'Alba & Barnacle, 2007). These reasons are investigated in more detail in the next section.

Others also indicate that becoming a professional, and learning to do so, is difficult for Ph.D. students. Ronfeldt and Grossman (2008) indicate the process is difficult because of the change in identity Ph.D. students must go through to become a professional. Shulman (1998) indicates the process is difficult because the complex forms of reasoning required for professional practice are very difficult for higher education to teach. Taylor (2007) argues that traditional Ph.D. students have a difficult process to become professionals because students are learning skills that focus on learning new knowledge more than applicable professional skills. Regardless of the reasons at this point, the consensus seems clear: becoming a professional, and learning to do so, is *difficult* for engineering Ph.D. students.

2.1.2 Dall'Alba's 'Ways of Being' Framework

Dall'Alba provides three reasons why becoming a professional, and learning to do so, is difficult for engineering Ph.D. students (Dall'Alba, 2009). First, the process of becoming a professional is ambiguous, and this ambiguity makes it difficult. Second, the engineering Ph.D. student research experiences are a period of great transition that requires a substantial change in how students view professional practice, and this substantial change is difficult for Ph.D. students. Third, the lack of a focus on the ontological process of becoming a professional makes it difficult for engineering Ph.D. students to situate their technical knowledge when integrating that knowledge into practice.

With regard to the ambiguity in the process of becoming a professional researcher, Dall'Alba (2009) indicates that there are several types of ambiguity that aspiring professionals such as engineering Ph.D. students have to navigate as they learn to become professionals. These ambiguities as described by Dall'Alba are complex and include: "*continuity* over time *with change* in ways of being professionals; *possibilities* in the ways we can be *with constraints* on those possibilities; *openness* in taking up possibilities *with resistance* to doing so; and *individuals* who are becoming professionals *with others* involved in that process" (Dall'Alba, 2009, p. 38). *Continuity with change* (Dall'Alba, 2009) involves the process of change over time related to who we are as professionals, and there is ambiguity in who we are becoming as professionals that are especially difficult for aspiring professionals to understand and adjust to in their daily professional lives. *Possibilities with constraints* (Dall'Alba, 2009) involves the many opportunities to explore the different ways of becoming a professional while at the same time experiencing constraints on those possibilities. Ambiguity occurs because possibilities and constraints do not occur neutrally, for example, as “practice traditions and social structures constrain opportunities for some, while opening them to others” (Dall’Alba, 2009, p. 41). *Openness with resistance* (Dall’Alba, 2009) involves aspiring professionals being open to new opportunities to learn how to become professionals while encountering resistance from others during the process. This ambiguity presents “difficulties for aspiring and recently graduated professionals, as well as for experienced professionals, who see the potential for improved practices but experience resistance or disapproval from others” (Dall’Alba, 2009, p. 42), often caused by issues of power dynamics. *Individuals with others* (Dall’Alba, 2009) involves aspiring professionals engaging with others, typically practicing professionals, to learn how to become professionals, which is key to thinking and acting as professionals do. The ambiguity for students occurs as many times the only interaction that students get with professionals is inside the academy. Dall’Alba points out that “an individual does not become a professional in isolation” (Dall’Alba, 2009, p. 42).

With regard to the engineering Ph.D. student research experiences and how this is a period of great transition that requires a substantial change in how students view themselves within the context of professional practice, Dall’Alba (2009) describes the process of graduate education as the transformation of the self, and the process of becoming a professional as the transformation of the self “through embodying the routines and traditions of the profession in question” (Dall’Alba, 2009, p. 37). This change in how students view themselves as a professional is difficult for engineering Ph.D. students because it requires students to form a new identity of themselves, or “becoming” someone new and different. Dall’Alba (2009) reminds the reader that becoming someone new (a professional) is “not a wholly individual or isolated experience” (2009, p. 37) and that “the traditions of which we are a part of tend to be taken for granted and are not transparent to us: the fish is the last to discover water” (2009, p. 37). In other words, the engineering Ph.D. student research experiences, which are a period of great change for students as they are beginning to become professionals, is difficult because becoming someone new is difficult.

With regard to the lack of a focus on the ontological process of becoming a professional and how that makes it difficult for engineering Ph.D. students to situate their technical knowledge when integrating it into practice, Dall’Alba (2009) indicates that “when a professional education program focuses on the acquisition and application of knowledge and skills, it falls short of facilitating their integration into professional ways of being” (2009, p. 34). Fundamentally, Dall'Alba argues that the epistemological focus on the engineering Ph.D. student research experiences overlooks the ontological side of what it means to become a professional and that overlooking the ontological side makes it difficult for students to make the necessary adjustments to fully understand and experience what it means to become a professional. In the context of the engineering Ph.D. student research experiences, the typical Ph.D. training program does a very good job of providing students with technical knowledge and skills, but a poor job in preparing students for professional practice (National Academy of Engineering, 2017b). Dall'Alba's 'ways of being' framework would say this problem happens because students do not get exposure to the ontological aspects of what it means to be a professional.

2.1.3 Other Frameworks – Why Becoming a Professional is Difficult for Ph.D. Students

Two other frameworks point to similar yet not as specific reasons as Dall'Alba for why becoming a professional is difficult for Ph.D. students. Chi's (2012) coherence framework and Säljö's (1999) sociocultural framework provide high-level insight into why becoming a professional is difficult for Ph.D. students without going into the detail that Dall'Alba provides for why becoming a professional is difficult for Ph.D. students.

Chi's (2012) coherence framework explains why some concepts are difficult for Ph.D. students by utilizing an approach that suggests there are missing ontological categories in students' knowledge, which are typically emergent. Like Dall'Alba, the ontological categories are also important to Chi (2012), as students are making a category mistake "when a concept has been assigned inappropriately to a lateral or alternative ontological category" (M. T. Chi, 2008, p. 65). When applied to the situation of becoming a professional, the missing ontological category would be the ontological aspect of what it means to become a professional. In Chi's language, the process of becoming a professional is likely an emergent process, indicating it would be difficult for students. For Chi, the mistake students would be making is to assume the knowledge they are learning will directly apply in a professional setting. The students will need to make an ontological shift to apply the knowledge they have learned in a professional setting.

Säljö's (1999) sociocultural framework explains why some concepts are difficult for Ph.D. students by utilizing an approach that suggests that the difficult concepts are discursive and not situated in a social or cultural meaning until students can provide meaning to the concepts. Säljö summarizes this framework by indicating "when learning conceptual knowledge, individuals are socialized into patterns of thinking, and into concrete practices that go along with these patterns, which provide them with perspectives and resources that have been cultivated by others and that are made for action in specialized settings" (Säljö, 1999, p. 90). Applied to the situation of becoming a professional, Säljö is indicating that Ph.D. students who are learning the knowledge and skills with which to become professionals have little to no social or cultural meaning of what it means to be a professional for which to situate their knowledge and skills.

2.1.4 Comparing Dall'Alba's 'Ways of Being' Framework to Other Frameworks

Dall'Alba's 'ways of being' framework is essentially a specific example of Chi's coherence framework and Säljö's sociocultural framework, but in much greater detail. While Chi and Säljö are providing somewhat generic frameworks for why many different concepts are difficult, Dall'Alba's 'ways of being' framework is very specific for the application of becoming a professional. In fact, Dall'Alba references Säljö (but not Chi) several times in her work. One of the key references to Säljö occurs when Dall'Alba describes the development of 'ways of being':

> *"As the development of ways of being is embedded within particular social, historical, cultural, material contexts, it is not surprising that learning is coloured by context*" (Dall'Alba & Sandberg, 2010, p. 111).

A fundamental way to compare the Chi and Säljö frameworks with Dall'Alba's is that the Chi's and Säljö's are complementary to Dall'Alba's, but Dall'Alba's 'ways of being' framework provides better overall depth and specificity for what it means to become a professional.

2.1.5 Diagram of the Ontological Framework Applied to this Study

Figure 2.1 below provides an overview of how Dall'Alba's 'ways of being' framework was utilized in this study. As Figure 2.1 indicates, from an ontological perspective, the research experiences of engineering Ph.D. students contribute to opportunities for students to practice becoming a professional. These opportunities to practice becoming a professional are critical from an ontological perspective in preparing students to be a professional practitioner in industry, government, or academia. Figure 2.1 also ties in the needs of the study discussed in Chapter 1.

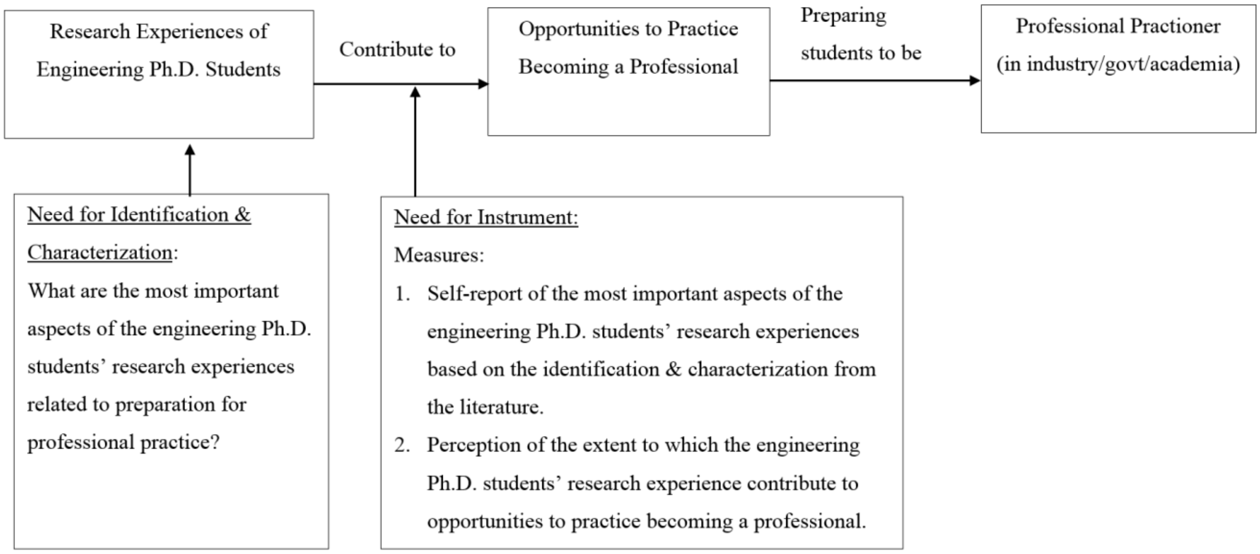

Figure 2.1: Overview of Dall'Alba's 'ways of being' Framework Utilized in this Study

2.1.6 Measurement of the Engineering Ph.D. Student Preparation for Professional Practice Influenced by the Research Experiences

As mentioned in Chapter 1, most measurement studies of the engineering Ph.D. student research experiences have centered on assessing their knowledge, skills, and abilities. This epistemological approach measures what students know or are perceived to know, and the utilization of an epistemological approach is common in higher education (Dall'Alba, 2009). An alternative way, using an ontological approach, meaning it measures who students are becoming, is less common in higher education (Dall'Alba, 2009). A review of measurement studies utilizing both approaches is provided below.

From an epistemological approach, a study by Timmerman et al. (2013) assessed 100 STEM graduate students to determine if their research skills changed over time. They did so by having the STEM graduate students write a research proposal, in both the fall and spring semester, on any topic, which was assessed qualitatively by trained staff using a rubric across ten different criteria (context, hypothesis(es), primary literature, validity/reliability, experimental design, data section, data presentation, data analysis, conclusion, limitations) (Timmerman et al., 2013). They found that more experienced students significantly outperform less experienced students and that less experienced students gain significantly on certain criteria (Timmerman et al., 2013).

Also, from an epistemological approach, some previous studies have focused on instrument development to measure how engineering Ph.D. students' research experiences influenced their preparation for professional practice. One such study was the work done by NSF to assess the outcomes of ERCs (Parker, 1997). This work comprised of two different scale development studies, both of which were conducted by Abt Associates Inc. and were focused on measuring how the knowledge, skills, and abilities of alumni of ERCs compared to those who did not have an ERC experience. The first study developed a scale for a self-assessment of ERC alumni of their perception of their knowledge, skills, and abilities as compared to their peers. The second study developed a scale for an assessment of supervisors of ERC graduates and corporate representatives involved with the ERC about the knowledge, skills, and abilities of ERC graduates compared to non-ERC graduates. Both studies found that ERCs were beneficial to the development of knowledge, skills, and abilities of ERC alumni, especially in the areas of ability to grasp new things quickly, contributing to technical work, breadth of technical knowledge, and ability to define steps to solve new problems. However, neither survey was developed with sound psychometric principles. For example, neither of the scales were developed with a theoretical framework for the construct, and no evidence of score reliability (such as internal consistency) or validity evidence was reported for the scales (Parker, 1997).

A similar study by Roessner et al. (2004) repeated parts of the Parker (1997) study that focused on the knowledge, skills, and abilities of ERC graduates compared to non-ERC graduates, but also developed a new scale. As with Parker's 1997 study, the results of the Roessner et al. (2004) study showed better performance by the ERC graduates as compared to non-ERC graduates, especially in the areas of preparedness for working in industry, ability to work in interdisciplinary teams, and breadth of technical knowledge. However, similar to the Parker 1997 study, the scale was not developed with a theoretical framework for the construct, and no evidence of reliability or validity was reported (Roessner et al., 2004).

From an ontological approach, as a follow-up to the Crede and Borrego (2012) study where they used ethnographically guided observations and interviews to develop a survey of over 800 graduate engineering students to understand how research groups develop graduate engineering students, Borrego, Knight, and Choe (2017) performed factor analysis on the survey items. Utilizing exploratory factor analysis, they identified four factors that describe research group experience of graduate engineering students from an ontological perspective: agency, defined as "being resourceful, self-sufficient and effective in locating resources for conducting research" (Borrego et al., 2017, p. 117); support, defined as "the basic resources needed to provide a stable research environment for an engineering graduate student" (Borrego et al., 2017, p. 117); international diversity, defined as "the value of international research group settings and preparation for later international work" (Borrego et al., 2017, p. 118); and group climate, defined as "whether the student perceives the research group as supportive and collaborative" (Borrego et al., 2017, p. 118).

Another ontological study by Choe et al. (2017) developed a pilot instrument to assess graduate engineering students' engineering identity and research identity and how both developed. As they discussed in their study, engineering identity is a relatively well-understood construct, while research identity is much less understood (Choe et al., 2017). In their literature review, they highlight the fact that Burt (2014) found that graduate engineering students developed their identity through their research experiences. Choe et al. (2017) developed an engineering and research identity scale and surveyed 115 mechanical graduate engineering students. They performed exploratory factor analysis, and identified six factors: engineering competence, engineering interest, research competence, research interest, math/science competence, and interpersonal skill competence (Choe et al., 2017). Both engineering and research identity significantly correlated with all factors except for interpersonal skill competence (Choe et al., 2017).

Another ontological study by Patrick et al. (2017), studied undergraduate students' affect (or affinity) toward professional practice. This study is interesting for two reasons: its relevance toward professional practice and its struggle to find a professional practice framework. The study discussed the difficulty of finding a framework for professional engineering practice and ended up choosing the ABET *EC2000* a-k criteria (Patrick et al., 2017). They developed a survey of 34 items that measured students' affect toward elements of engineering practice utilizing *EC2000* a-k criteria and administered the survey to 1465 engineering undergraduates. They performed both exploratory and confirmatory factor analysis, but had issues with the factors loading correctly with the ABET *EC2000* a-k criteria, and concluded there was much more work to be done to understand "the connection, if any, between affect, identity, and observed persistence" (Patrick et al., 2017, p. 14).

The reviewed epistemological measurement studies (Parker, 1997; Roessner et al., 2004; Timmerman et al., 2013) showed that engineering research experiences are influencing the learning, and in some cases, the perceptions of students' abilities to practice professionally. The reviewed ontological measurement studies (Borrego et al., 2017; Choe et al., 2017; Patrick et al.,

2017) showed the benefits of looking at the ontological perspective of engineering Ph.D. students and engineering professional practice. Second, these studies indicate there are no studies that investigate the opportunities that students have to practice becoming a professional during their engineering Ph.D. research experience. Third, it showed the struggle with finding and using a professional practice framework that could be applied to what students understood about professional practice. The issue of a useful professional practice framework was also important to this study and is addressed in the next section.

2.1.7 Frameworks for Professional Engineering Practice in Students' Research Experiences

While this study utilizes an ontological theoretical framework for assessing the engineering Ph.D. research experiences for professional practice, it is still necessary to understand what knowledge, skills, and abilities engineering Ph.D. students should be aspiring to in their engineering Ph.D. work in this study. For example, the need existed in this study to measure the extent to which the engineering Ph.D. student research experiences are proving opportunities to practice becoming a professional relative to those skills. As demonstrated by Patrick et al. (2017) study, understanding the knowledge, skills, and abilities needed for professional practice is not straightforward.

There are several professional engineering practice frameworks for undergraduate engineering students in the U.S., such as ABET *EC2000*, NAE Engineer of 2020 list of student attributes, and American Society for Engineering Education (ASEE)'s Transforming Undergraduate Engineering Education (TUEE) report. Holloway and Radcliffe (2018) reviewed these frameworks and concluded that "these frameworks all have common characteristics, in that each focuses on student outcomes, and each was generated by surveying a combination of industry experts, academics, and other stakeholders to arrive at a consensus on the appropriate professional outcomes for engineering graduates from baccalaureate programs" (2018, p. 2). The most well-known and influential of these frameworks has been ABET *EC2000,* previously mentioned. The ABET *EC2000* established eleven student outcomes, commonly known as *EC2000* a-k criteria (Engineering Accreditation Commission, 2007), for which all undergraduate engineering programs in the U.S. must demonstrate compliance for accreditation. Recently, the *EC2000* a-k criteria have been modified into a revised list of seven outcomes (Engineering Accreditation

Commission, 2017), known as ABET Criteria 3, which took effect in the 2019-20 accreditation cycle. Another framework, listed in the NAE report *The Engineer of 2020* (National Academy of Engineering, 2004), lists nine attributes for which it is important for engineers of the future to possess. The attributes listed in this report are short, concise, and clear. The report led to some universities, such as Purdue University, to implement their own version of the engineer of 2020 outcomes (Jones et al., 2009). Another framework, the ASEE's TUEE report, lists 36 knowledge, skills, and abilities (KSAs) that graduating engineering undergraduate students should possess (American Society for Engineering Education, 2013). Holloway and Radcliffe (2018) provide a summary table comparing the four frameworks, repeated below in Table 2.1.

Table 2.1: *Undergraduate Professional Engineering Practice Framework Commonalities and Differences (Holloway & Radcliffe, 2018)*

Framework	Differences	Commonalities of All Frameworks
1. ABET EC2000 a-k	EC2000 a-k is more than a list of attributes, tries to give some context.	1. Similar methods in which the frameworks were generated.
2. ABET Criteria 3	Criteria 3 goes to the next level in providing context. Note: for both ABET lists, almost everything is an "ability".	2. Sharing of many of the same student outcomes (problem-solving, communication, and teamwork).
3. Engineer of 2020	2020 list is short and concise, trade-off with no context, which is assumed. Pushes attributes beyond ABET.	3. Have successfully brought about change in the curriculum (except TUEE which is brand new).
4. ASEE TUEE	TUEE differentiates between knowledge, skills, and abilities (although many are still "abilities"). Prioritizes list.	

One of the few, if only, professional practice frameworks that exist from the context of Ph.D. students and what it means to be a professional researcher, is the Vitae Researcher Development Framework (RDF) (Vitae, 2011). The Vitae RDF "is a professional development framework for planning, promoting and supporting the personal, professional and career development of researchers in higher education. It articulates the knowledge, behaviors, and attributes of successful researchers and encourages them to realize their potential." (Vitae, 2011,

p. 1). The Vitae RDF "consists of four domains, 12 subdomains and 63 descriptors encompassing the knowledge, intellectual abilities, techniques, and professional standards to do research, as well as the personal qualities and skills to work with others and ensure the wider impact of research" (Reeves, Denicolo, Metcalfe, & Roberts, 2012, p. 4). The Vitae RDF was developed in the United Kingdom (UK) in 2011 by the Careers Research and Advisory Centre and has been adopted by most UK universities (Edge & Munro, 2015). Table A.1 in Appendix A shows the organization of the four domains, twelve subdomains, and sixty-three descriptors of the Vitae RDF.

Each descriptor in Vitae RDF has multiple levels of attainment, which are achieved progressively over time, and this allows utilization of the Vitae RDF as an assessment tool. The Vitae RDF accomplishes this by having each of the sixty-three descriptors "contains between three to five phases, representing distinct stages of development or levels of performance within that descriptor" (Vitae, 2011, p. 2). For example, the phases for A2: Cognitive abilities, Descriptor #12 – Problem Solving are listed below in Table 2.2. Ph.D. students are likely to be in either approaching phase 1 or 2, yet also benefit from seeing the likely path for career progression in each phase.

Table 2.2: *Vitae RDF Phases for Descriptor #12 – Problem Solving* (Vitae, 2011, p. 6)

Descriptor	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Problem Solving	Isolates basic themes of own research; formulates basic research questions and hypotheses.	Formulates and applies solutions to a range of research problems and effectively analyses and interprets research results.	Identifies new trends, complex questions and broader problems; designs substantial projects.	Leads a research agenda by making major contributions to understanding.	
			Challenges particular hypotheses and refines them in the light of results.	Asks the pertinent questions and designs projects that challenge traditional thinking in general and progress research themes.	

The Vitae RDF is designed to be used as either a self-assessment tool by students or professional researchers, or as an assessment tool of students/employees by supervisors or mentors. The Vitae RDF has both freely available materials and paid membership materials, yet there are enough materials freely available for anyone to perform an assessment/self-assessment. The paid materials allow for a way to formally track one's progress over time.

The Vitae RDF also has an engineering-specific version, called the "Engineering Lens" on the Vitae RDF (Vitae, 2014), which applies the UK chartered engineering standard to the Vitae RDF. The "Engineering Lens" allows an engineering perspective on the entire Vitae RDF. Another aspect that sets the Vitae RDF apart from other professional development frameworks is the inclusion of Domain B, focused on personal effectiveness, which includes the sub-domains for personal qualities, self-management, and professional and career development. As compared with ABET, Engineer of 2020, and TUEE, personal effectiveness aspects are typically not included in professional practice frameworks.

While the Vitae RDF is epistemological in its focus, and not suitable for the ontological focus of this study, the Vitae RDF is later utilized to help operationalize the ontological aspects that are selected for measurement in students' research experience. The Vitae RDF is utilized for this purpose in the final section of this chapter.

2.2 A Focused Literature Review of the Engineering Ph.D. Student Research Experiences

As the need was established in this study to characterize the engineering Ph.D. student research experiences to understand how those experiences influence students' preparedness from professional practice, this section involves a focused literature review of the engineering Ph.D. student research experiences. First, a framework was established that was utilized to guide and evaluate the literature concerning the engineering Ph.D. student research experiences. Second, utilizing the framework, the literature concerning the engineering Ph.D. student research experiences was reviewed and synthesized in detail to identify the most important characteristics of the engineering Ph.D. student research experiences.

2.2.1 Framework for Understanding the Engineering Ph.D. Student Research Experiences

In order to keep aligned with the overall framework of this study and to keep the focus on the ontological aspect of becoming a professional, Dall'Alba 'ways of being' framework (Dall'Alba, 2009) was again utilized as explained below to review the literature concerning the engineering Ph.D. student research experiences. In the perspective of higher education, she explained the 'ways of being' framework as follows: "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" (Dall'Alba & Sandberg, 2010, p. 111). As an example use of this framework, Dall'Alba (2009) utilized these four contexts, the social, historical, cultural, and material, to evaluate and set in perspective the different educational experiences of medical school students, especially from the ontological perspective of becoming a professional. As such, these four contexts, the social, historical, cultural, and material, were used to for similar purposes to understand the engineering Ph.D. student research experiences in the work that follows.

The following definitions are based on the work of Sandberg & Dall'Alba (2009) and framed for the engineering Ph.D. student research experiences.

- Social is defined as the way in which engineering Ph.D. students are being with others and "taking over others ways" (2009, p. 1357) of doing engineering Ph.D. student research.
- Historical is defined as the historical context within which the social, cultural, and material context of the engineering Ph.D. student research experiences has taken or is currently taking place.
- Cultural is defined as the shared meanings that are ascribed to the engineering Ph.D. student research experiences that govern human action and social order.
- Material is defined as the equipment used in the engineering Ph.D. student research experiences that is "purposeful, instrumental, directed at achieving a particular end" (2009, p. 1359).

2.2.2 Historical Context of the Engineering Ph.D. Student Research Experiences

The history of engineering Ph.D. student research in the United States is long and always evolving. From starting out with a focus on the mechanical arts and industry, to the shift to basic science in the 1950s with Sputnik and the space race, to today's highly global and interconnected world, the history of engineering Ph.D. student research is always changing (Seely, 1999). As the entire framework of social, historical, cultural, and material was analyzed for the purposes of understanding and describing the engineering Ph.D. student research experiences, it became clear that the historical context was the umbrella under which the other three contexts (social, cultural, and material) are understood. In other words, from the perspective of the engineering Ph.D. student research experiences, the historical context is right now, i.e., the present, or as close to the present as one can get in the literature. Moreover, the social, cultural, and material contexts are to be understood in the present context also. This argument is further supported by the rationale that from an ontological perspective, *being* a profession is occurring in the here and now (Dall'Alba & Sandberg, 2010, p. 107). Another way to look at the historical context of the engineering Ph.D. student research experiences is that any historically significant characteristic that is currently influencing the engineering Ph.D. student research experiences will be present in the literature for the social, cultural, and material contexts. One obvious consequence of utilizing this approach is that over time, the historical context of the engineering Ph.D. student research experiences will change and the findings generated will have to be refreshed with the times.

2.2.3 Social Context of the Engineering Ph.D. Student Research Experiences

There are three main social aspects of the engineering Ph.D. research experiences: the research group size, the research organization style, and the research work organization. Each is examined in detail below.

Research Group Size and Organization Style

The social context of the engineering Ph.D. student research experiences is very much centered on students being part of a research group, as the vast majority of engineering students will participate in a research group during their Ph.D. program (Hakala, 2009). This result was confirmed as part of a study done by Crede and Borrego (2012), where they used ethnographically guided observations and interviews to develop a survey of over 800 graduate engineering students to understand how research groups develop graduate engineering students. In their literature review, they found that engineering research groups are typically structured around the research area of the students' Ph.D. advisor (Adams, Black, Clemmons, & Stephan, 2005), and that students work as a team under the direction of their Ph.D. advisor, frequently in a shared laboratory that houses multiple other research groups (Louis, Holdsworth, Anderson, & Campbell, 2007). Most importantly, Crede and Borrego's (2012) study found that the research group size was the primary characteristic that influenced the entire social order of the research group. For example, for small research groups (less than 5 students), the group is organized where the faculty advisor leads the group interactions and communications. However, for large groups (over 20 students), the group interactions and communications are more student-to-student, and the faculty advisor takes on a functional role. A summary of the research findings of the characteristics of Crede and Borrego's (2012) study is below in Table 2.3.

Table 2.3: *Summary Characteristics of Graduate Research Groups (Crede & Borrego, 2012, p. 574)*

	Small (less than 5 students)	Medium (5 – 20 students)	Large (more than 20 students)
Interactions and Communication	Advisor Dominated	Mixed	Student/Group Dominated
Mentoring	Peer – Low Faculty – High	Peer – Moderate Faculty – Moderate	Peer – High Faculty – Low
Space	Individual Offices	Combination Lab and Offices	Common Lab Area
Equipment	Few (however less competition)	Moderate	Many (however higher chance of competition)
Funding	Funding – Moderate	Funding – High	Funding – High
Supervisor Role	Enculturation, Critical Thinking	Enculturation, Gatekeeper	Functional

Work Organization

Another characteristic that has been found to influence the social context of the engineering Ph.D. student research experiences is how the research work is organized, from the perspective of the research work being done individually or together as a team within the research group. For example, there are research groups where most research data are collected by an individual student, and others where a small team of students that are part of the larger research group collects the data. Crede and Borrego (2012) addressed this by indicating that small research groups (less than 5 students) tended not to have shared office/laboratory spaces and that the small group dynamic was "quiet, independent study" (Crede & Borrego, 2012, p. 578). They also mentioned that for large research groups (more than 20 students), students typically have a shared laboratory where they "used this space to socialize, work in teams on homework problems, discuss research and meet as a large group with the faculty members" (Crede & Borrego, 2012, p. 578). The type of equipment also plays a role, as large, complicated equipment that has a safety element often takes more than one student to be present for the operation of experiments and collection of data (George & Thomas, 2015). Crede and Borrego (2012) also indicate that medium and large size groups tend to have access to more equipment than smaller groups.

To synthesize these findings in order to be able to describe the various types of engineering Ph.D. student research experiences, the most important characteristic identified from the social aspect is the size of the research group (small, medium, and large). The size of the group directly influences how the research group is organized, including the interactions and communication, mentoring, space, equipment access, funding, and supervisor role. The second most important characteristic is how the research work is organized, where either a student typically works mostly individually on the research or together with others as part of a team. While the work organization has been found to be influenced somewhat by both the research group size and the type of equipment being used, whether or not a student is working a significant part of their time on a team has been found to be a contributing characteristic to how and what they learn (Salas, Cooke, & Rosen, 2008).

2.2.4 Cultural Context of the Engineering Ph.D. Student Research Experiences

There are four main cultural aspects of the engineering Ph.D. research experiences: the engineering discipline (i.e., major), the type of research work being conducted, the collaborators (i.e., sponsors, consumers of the research, etc.) involved in the research, and the type of interaction with those collaborators. Each is examined in detail below.

Engineering Discipline

When examining the shared meanings that are ascribed to the engineering Ph.D. student research experiences, one must first look at what groups exist in the culture. The most obvious group in engineering culture are the groups of engineering disciplines (i.e., mechanical, electrical, industrial, etc.). The engineering Ph.D. student research experiences for each engineering discipline is unique because the administration of the engineering Ph.D. student process is decentralized and discipline-specific (Hirt & Muffo, 1998). For example, each discipline admits/rejects applicants, determines their discipline qualification exam requirements, and sets the standards for the preliminary and final dissertation defenses. Finally, the engineering discipline determines, to a great extent, the technical content of the research being conducted (Hirt & Muffo, 1998).

Type of Research

Another large characteristic in the cultural context of the engineering Ph.D. student research experiences is the type of research work being conducted. In the literature, there are three types of research work: basic research, applied research, and educational research. Basic research is defined as “the systematic study directed toward greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications towards processes or products in mind” ("32 CFR - National Defense," 2005). Applied research is intended “to solve real-world, practical problems” (Proctor & Zandt, 2018, p. 25). Educational research in engineering, which is a relatively new field, is research related to education and learning in engineering (Jesiek, Newswander, & Borrego, 2009).

When comparing the engineering Ph.D. student research experiences for basic research to applied research in engineering, basic research is thought to be more theory focused (vs. experiment focused), more analysis focused (vs. synthesis focused), more publication focused (vs. market focused), and more long-term focused (vs. short-term focused) (Morgan et al., 1996). In addition, basic research vs. applied research in engineering is sometimes discipline-specific, (e.g., materials vs. civil) (Kannankutty et al., 1999; Morgan et al., 1996), topic-specific (e.g., nanotechnology vs. manufacturing) (National Academy of Engineering, 1995), funding specific (e.g., government vs. industrial) (Behrens & Gray, 2001; Morgan et al., 1996), and research intensity specific as measured by annual engineering research expenditures (e.g., high intensity/expenditures vs. low intensity/expenditures) (Kannankutty et al., 1999). The key point here is that students who are working on basic research are more likely to work on theory-based projects that last over the course of their dissertations, which are likely funded by the government. Students who are working on applied research projects are more likely to work on experiment-based projects, more likely to work on multiple short-term projects over the course of their dissertation, and more likely to be funded by industry. For educational research in engineering, Ph.D. students tackle a broad range of educational topics related to engineering education utilizing quantitative, qualitative, and mixed-method techniques, typically utilized in the social sciences and traditional education fields (Borrego, Douglas, & Amelink, 2009). While Ph.D. students in engineering education typically utilize engineering as the context of their study, their engineering Ph.D. student research experiences have the cultural aspects of engineering but the tools and methods from social science.

Collaborators

The third characteristic in the cultural context of the engineering Ph.D. student research experiences is the collaborators (i.e., sponsors, consumers of the research, etc.) involved in the research, either internal or external, that the students are working with during their research. In Dall'Alba's 'ways of being' framework, she refers to working with collaborators as the "forms of practice" (Dall'Alba & Sandberg, 2010, p. 105) for students. In other words, the collaborators that are involved with the engineering Ph.D. students are exposing students to certain forms of professional practice that situates the knowledge and skills that students are gaining and models professional practice for the students. In Dall'Alba's words, students get the opportunity to "take over others' ways of being" as a professional (Dall'Alba & Sandberg, 2010, p. 113).

In engineering, one view of collaborations that faculty and students are involved with is to look at the funding sponsor for the research project and to call the funding sponsor the collaborator (Behrens & Gray, 2001). However, that is not accurate enough when looking at the cultural aspect of whom the students are interacting with as collaborators in terms of a form of professional practice. An example of this would be an Advanced Research Projects Agency-Energy (ARPA-E) project, which focuses on getting technology to market. ARPA-E is a Department of Energy (government) funded project, but the collaborators of a typical ARPA-E project are industry and other academic institutions (National Academy of Engineering, 2017a). So in this example, the students are collaborating (i.e., form of practice) mostly with industry and other universities, not the government.

There are typically three types of collaborators that expose students to a certain form of professional practice: government, corporate, and research centers. Traditional government collaborators examples that engineering faculty and students interact with include civilian government agencies (Behrens & Gray, 2001) such as the National Science Foundation (NSF), the Department of Energy (DoE), and the National Institutes of Health (NIH). Another type of government collaborators includes defense agencies (Behrens & Gray, 2001), such as the

Department of Defense (DoD) or the Air Force Research Laboratory (AFRL). Finally, another type of government collaborators includes national laboratories (Etzkowitz, Webster, Gebhardt, & Terra, 2000), such as Los Alamos National Laboratory, Argonne National Laboratories, and Lawrence Livermore National Laboratory. The key point is that students' form of professional practice exposure is to government agencies.

Corporate collaborators examples that engineering faculty and students interact with include industrial companies and start-ups (Behrens & Gray, 2001). Industry interacts with university engineering research in many different ways. Traditionally, direct funding of a research project is the most common (Behrens & Gray, 2001). However, many other ways exist that industry supports university engineering research, such as industrial consortiums (Behrens & Gray, 2001), collaborating on projects that are funded by government agencies such as previously mentioned ARPA projects, and getting involved in large research centers, which is covered next. The key point is that students' form of professional practice exposure is to corporate collaborators.

There are several different types of research centers that students may be exposed to as their main collaborators. First, there is the traditional university research center, made up of a large group of faculty and students conducting research in a multidisciplinary area, typically housed near each other, "intended to foster interactions and collaborations among researchers" (Boardman & Corley, 2008, p. 900). An example of such a center would be Purdue University's Center for Materials Under eXtreme Environment. This center has seven faculty, two staff, nine graduate students, and eight undergraduate students that are part of the center (Center for Materials Under eXtreme Environment, 2018), and focuses on mostly basic research related to interactions of high-intensity, modulated energy beams. The second type of center that is common in engineering is NSF university-led Engineering Research Centers (ERCs) and Science and Technology Centers (STCs). While an ERC tends to focus more on engineering and an STC tends to focus more on science, both are set up in a similar manner involving large research teams from multi-universities, with industry collaborators, and both often involve engineers and scientists working together on research (National Academy of Engineering, 2017b). ERCs, in particular, were set up with a mission to affect change in the engineering Ph.D. student research process, as one of the goals of ERCs was "to improve engineering research so that U.S. engineers will be better prepared to contribute to engineering practice" (Parker, 1997, p. 3). The final type of research centers, mostly discussed in the corporate collaborator section above, are research centers that focus mostly on industry. Typically these centers follow an industry consortium models (Behrens & Gray, 2001), but can also follow the model of an NSF funded Industry-University Cooperative Research Centers Program (I-UCRC), which “enables industrially-relevant, pre-competitive research via a multi-member, sustained partnerships among industry, academe, and government” (National Science Foundation, 2018b). The difficult point to differentiate with regard to research centers is the students’ form of professional practice exposure. In the case of a traditional university center, it is likely the faculty themselves or the sponsoring government agencies. With ERCs, many students get exposed to industry, which is part of the point of ERCs (Parker, 1997). To understand students’ form of professional practice exposure, one must look closely at the type of center.

Collaborator Interactions

The interaction among the collaborators also plays a role in the engineering Ph.D. student experiences. For example, the collaborators’ interaction frequency affects the type of relationship that faculty and students develop with collaborators, and tends to be in one of three categories: infrequent, intermittent or recurrent (Bruneel, D’Este, & Salter, 2010). Research with industry partners, including ERCs, tends to have more frequent and deeper relationships (Parker, 1997; Thune, 2010). These relationships are often attributed to the fact that many of the industrial firms want to hire Ph.D. students after graduation (Slaughter, Campbell, Holleman, & Morgan, 2002). Typically, government collaborations are seen to fall into the infrequent category, with faculty and students providing written reports, resulting in relationships that are not very deep (Gemme & Gingras, 2012). With regard to students’ form of professional practice exposure, this means that students with an industry collaboration are likely to be exposed more frequently to their collaborator's form of practice. This frequent collaboration could be one reason why students with an industry collaboration experience tended to be hired by industry (Thune, 2010).

2.2.5 Material Context of the Engineering Ph.D. Student Research Experiences

There are two main material aspects of the engineering Ph.D. research experiences: the type of equipment, and the work space organization. Each is examined in detail below.

Equipment Type

When evaluating the material used in the engineering Ph.D. student research experiences that are "purposeful, instrumental, directed at achieving a particular end" (Sandberg & Dall'Alba, 2009, p. 1359), the main differentiating characteristic is the type of equipment experiences that students obtain during their research work. Three types of equipment characteristics are evident in the literature. The first type is students who primarily rely on computer modeling and simulation in their research. The second type is students who primarily rely on test facilities and equipment for physical experiments in their research. The third type is students who have limited reliance on equipment beyond common computers and information technology in their research.

When looking at the experiences of engineering Ph.D. students who primarily rely on computer modeling and simulation, it must be clarified that most engineering Ph.D. students utilize mathematical modeling and simulation at some point in their engineering Ph.D. studies (Duka & Zeidmane, 2012). However, some students primarily utilize modeling and complex computer simulations to meet their primary research objectives (Sarjoughian, Cochran, Collofello, Goss, & Zeigler, 2004). These students are often exposed to high-throughput computer systems and sophisticated software systems beyond traditional engineering analysis packages in order to solve complex problems (Sarjoughian et al., 2004). While sometimes in engineering research, modeling and simulation results are taken to the lab for physical experiments to verify the results, at other times, the modeling and simulation results are the stopping point due to costs or feasibility of experiments (Sterman, 2002). The key point here is that engineering Ph.D. students who primarily rely on computer modeling are typically getting experience with high-end computer systems and software and learning mostly through a simulated, or theoretical environments.

The traditional engineering Ph.D. student research experiences are for students to be involved in physical experiments that require advanced test facilities and equipment (Crede & Borrego, 2012; National Academy of Engineering, 1995). This need for equipment is present in both basic and applied research (Morgan et al., 1996), and for government and industry collaborations (Thune, 2010). Engineering Ph.D. students conducting physical experiments often get the opportunity to get more hands-on skills, often including things such as operating and maintaining equipment, safety, and troubleshooting (Parker, 1997). Also, utilizing physical equipment tends to require a more team-based approach due to the complexity of the equipment and safety concerns, enhancing the collaboration aspect of research that relies heavily on equipment for experiments (Thune, 2010). The key point here is that engineering Ph.D. students who primarily rely on physical experiments with equipment are typically getting hands-on, team-based experiences as compared to those students in less equipment based research environment.

Finally, some engineering Ph.D. students have little access to or need for equipment in their research, beyond standard computers and information technology. This can be due to the size of the research group, where small research groups tend to work with little equipment initially (Crede & Borrego, 2012), or due to the type of work, such as educational research, which usually has little need for sophisticated test equipment (Crawley, Malmqvist, Ostlund, & Brodeur, 2007).

In summary, from an equipment characteristic standpoint, the key point is that engineering Ph.D. students who primarily rely on physical experiments with equipment are typically getting more hands-on experiences than engineering Ph.D. students who are working primarily on modeling and simulation-based research projects, or projects with limited equipment needs. These hands-on research experiences likely lead to different learning outcomes in those students (Thune, 2010).

Work Space

The equipment aspect of the material context also influences the workspace environment of the engineering Ph.D. student experiences. As mentioned previously in the social context section, the research group size is one influence on the workspace environment, with small research groups (less than 5 students) tending to have an isolated office/laboratory space and medium (between 5 to 20 students) and large research groups (more than 20 students) tending to have a shared laboratory workspace (Crede & Borrego, 2012). However, the equipment aspect also influences the workspace, as the reliance on equipment and facilities tend to promote shared facilities and workspaces with multiple research teams (Crede & Borrego, 2012; George & Thomas, 2015). The opposite tends to be the case where engineering Ph.D. student with little needs for equipment tend to work in isolated workspaces alone or with only a few others (Crede & Borrego, 2012). The key point is that the workspace experiences of the engineering Ph.D. student, be it in a shared or isolated workspace, is influenced by both the equipment aspect and the research group size aspect.

2.3 A New Conceptual Framework for Measuring the Engineering Ph.D. Research Experience

A Concept Map (Figure 2.2 below) was synthesized to show how the social, historical, cultural, and material contexts might be experienced by an engineering Ph.D. student in their research experience. It was constructed around six key characteristics: 1) social: research group size, 2) social: work organization, 3) cultural: engineering discipline, 4) cultural: work type, 5) culture: collaborators, and 6) material: equipment. Each of these is defined below.

2.3.1 Research Group Size

Arising from the social context, the research group size (small vs. medium vs. large) was identified as a significant influencing factor in the research experience. This research group size is probably the most influential characteristic identified, as it influences other characteristics of the engineering Ph.D. student research experiences, namely the how the work is organized (individual vs. team), how the workspace is organized (isolated vs. shared), and how the research group is organized (advisor focused vs. group focused).

2.3.2 Work Organization

Also arising from the social context, the work organization, or how the research work is organized (individual vs. team), has been identified to influence the research experiences. As mentioned above, the work organization is partially influenced by the research team size, but is also influenced by the type of equipment being used (physical vs. modeling vs. limited).

2.3.3 Engineering Discipline

The first of three facets of the cultural context, the engineering discipline (i.e., mechanical, electrical, industrial, etc.), was identified to influence the research experiences, as the administration of the engineering Ph.D. student process is decentralized and discipline-specific.

2.3.4 Work Type

The second aspect of the cultural context that was identified as being critical to the research experience is the type of work type, i.e., basic research vs. applied research vs. educational research.

These different types of work all influence the duration of projects, and are shaped by the source of funding.

2.3.5 Collaborators

The third aspect of the cultural context is the type of collaborators, for example, government vs. corporate vs. research centers that students work with have been identified to influence the research experiences, as the type of collaborators is the students' form of professional practice exposure. In the context of becoming a professional, this is likely one of the most important characteristics of the engineering Ph.D. student research experiences (Dall'Alba, 2009).

2.3.6 Type of Equipment

Finally, from the material context, is the type of equipment (physical vs. modeling vs. limited) that students work with has been identified to influence the research experiences, as the students who are working with physical experiments and equipment are having different experiences than students who do not typically work with equipment. Also, as mentioned previously, the type of equipment being used, along with the size of the research team, influences the organization of the workspace (isolated vs. shared) and the experiences of the engineering Ph.D. students.

2.3.7 Operationalizing the Engineering Ph.D. Student Research Experiences

The six key characteristics that were identified as important were operationalized into self-report questions about the organization and structure of the engineering Ph.D. students' research experiences. This process is explained further in Chapter 4 – Instrument Development.

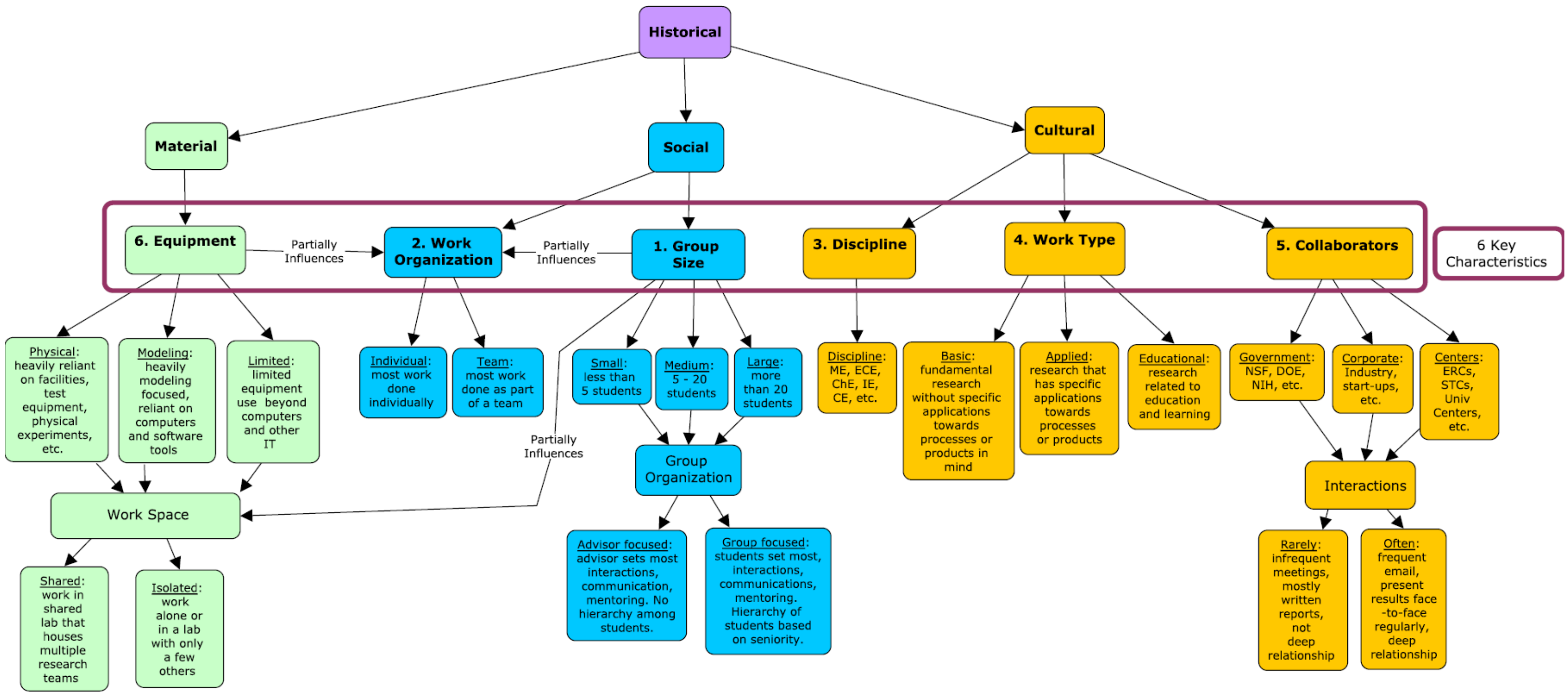

Figure 2.2: Concept Map of the Social, Historical, Cultural, and Material Contexts of the Engineering Ph.D. Student Research Experience

2.4 Ontological Aspects of the Engineering Ph.D. Student Research Experiences

Now that the six key characteristics of the engineering Ph.D. student research experiences have been identified, the process of operationalizing and defining these aspects in more detail with the intent of measurement was evaluated. The key question asked was which of these characteristics are important to assess from an ontological perspective for professional practice preparation?

2.4.1 Identifying the Ontological Aspects of the Engineering Ph.D. Student Research Experiences

In keeping with Dall'Alba's 'ways of being' framework when assessing the engineering Ph.D. student research experiences, she has several recommendations in the literature for higher education to better help students become professionals. First, she recommends that higher education move beyond the epistemological aspects of the acquisition of knowledge and skills and put much more focus on the ontological aspect of becoming a professional (Dall'Alba, 2009). Second, she recommends the focus of the ontological aspect of becoming a professional be on "integrating what aspiring professionals know and can do with who they are (becoming), including the challenges, risk, commitment and resistance that are involved. In other words, learning professional ways of being occurs through the integration of knowing, acting and being the professionals in question" (Dall'Alba, 2009, p. 43). Third, to practically address the lack of focus on the ontological aspect of becoming a profession and to integrate the knowing, acting, and being, she recommends a 'lifeworld perspective' that focuses on providing students access to a "multiplicity of practice, in contrast to a prevalent view of practice as a singular, relational whole" (Dall'Alba & Sandberg, 2010, p. 117).

When considering how to take Dall'Alba's recommendations (Dall'Alba, 2009) and apply those to the engineering Ph.D. student research experiences, the key point is to examine the research experiences from an ontological perspective and determine what ontological aspects are present or absent from the student research experiences of becoming a professional. Below in Table 2.4 is an ontological evaluation applied to the six key characteristics of the engineering Ph.D. student research experiences that have been identified. For each of the six key characteristics below, the ontological aspects are identified.

Table 2.4: *Ontological Aspects of the Six Key Characteristics of the Engineering Ph.D. Student Research Experiences*

#	Key Characteristics	Ontological Aspects
1	Group Size	Not a direct ontological aspect; Influences work organization.
2	Work Organization	1. Opportunity for students to work as a team member on research.
3	Discipline	Not an ontological aspect
4	Work Type	Not an ontological aspect
5	Collaborator	2. Opportunity for students to be exposed to their collaborator's form of practice.
		3. Opportunity for students to have relevant exposure to professional practice based on later employment.
6	Equipment	4. Opportunity for students to gain experiences with modeling and simulation tasks.
		5. Opportunity to gain experiences with hands-on and troubleshooting tasks.

In synthesizing the results of Table 2.4, a total of five ontological aspects have been identified that are potentially present or absent from the engineering Ph.D. student research experiences that influence the preparedness for professional practice, as follows:

1. Opportunity for students to work as a team member on research: based upon the size to the research team (small, medium, large), the opportunity for students to work as a team member on research, from providing and receiving mentoring to/from fellow students, and for working in an environment where teamwork is easily supported, is potentially absent (for small groups) or present (for medium/large groups).
2. Opportunity for students to be exposed to their collaborator's forms of practice: based upon their interactions frequency and intensity with their collaborators, the opportunity for students to be exposed to their collaborator's form of practice is potentially absent (for government collaborators) or present (for industry/center collaborators).
3. Opportunity for students to have relevant exposure to professional practice based on later employment: depending on what type of professional practice exposure is relevant to students based on expected later employment, the opportunity for students to be exposed to the relevant professional practice could be absent (for a mismatch between the research experience and where students end up practicing) or present (for the relevant exposure based upon where

students end up practicing). Examples where students might get relevant professional practice exposure include: from academia – from their advisors or other faculty; from industry or government – from their collaborators; from activities such as internships or co-ops.

4. Opportunity for students to gain experiences with modeling and simulation tasks: as mentioned previously, most engineering Ph.D. students utilize modeling at some point in their engineering Ph.D. studies (Duka & Zeidmane, 2012). Therefore the opportunity to work on modeling and simulation in students' research experience should mostly be present (i.e., rarely be absent). However, some engineering Ph.D. students will primarily work on modeling and simulation in their research work, so understanding the extent to which the research experience provides this opportunity is the goal of measurement.
5. Opportunity for students to gain experiences with hands-on and troubleshooting tasks: based upon their how heavily focused their work is on modeling and simulation, the opportunity for students to gain practice with hands-on and troubleshooting tasks sought by many employers is potentially absent (for modeling/simulation work) or present (for physical experiment work).

2.4.2 Operationalizing the Ontological Aspects of the Engineering Ph.D. Student Research Experiences

The operationalization of the ontological aspects of the engineering Ph.D. student research experiences for measurement is accomplished through a three-step process. First, the Vitae RDF, previously introduced, is justified as a viable framework for this study by evaluating it against the 'Assessment Triangle' framework. Second, the Vitae RDF is utilized to conceptualize the five ontological aspects that have been identified that are potentially present or absent from the engineering Ph.D. student research experiences that influence the preparedness for professional practice. Third, the relevant literature is reviewed for relevant operational definitions that are utilized for initial operational definitions of the five ontological aspects that have been identified for this study.

Step 1: The Vitae RDF Evaluated Utilizing the 'Assessment Triangle' Framework

As the Vitae RDF is designed for professional researchers, including engineering Ph.D. students, with an "Engineering Lens", certain Vitae Descriptors were utilized to operationalize the ontological aspects of the engineering Ph.D. student research experiences. While the Vitae RDF will not directly be used as an assessment tool in this study, when the Vitae RDF is evaluated utilizing the 'Assessment Triangle' framework, close alignment with Dall'Alba's 'ways of being" framework was found.

The 'Assessment Triangle' Framework

The 'Assessment Triangle' framework was introduced by Pellegrino, Chudowsky, & Glaser (2001) as a way to design or evaluate assessments. The 'Assessment Triangle' consists of three fundamental aspects, or what is referred to as 'corners of the triangle' to consider when designing or evaluating assessments. The 'corners of the triangle' are the 'cognition corner', the 'observation corner', and the 'interpretation corner'.

The 'cognition corner' consists of the underlying theory that is used to design or evaluate the assessment and is tied to how students learn the concept (Pellegrino et al., 2001). In the context of conceptual change, questions one would ask when evaluating or designing assessments for the 'cognition corner' include: What concepts are difficult? What are the misconceptions? Why are the concepts difficult (i.e., theory)? How do students learn these concepts?

The 'observation corner' consists of the type of tasks that students are asked to complete (Pellegrino et al., 2001). In the context of conceptual change, questions one would ask when evaluating or designing assessments for the 'observation corner' include: What procedures are used to create the assessment?

The 'interpretation corner' consists of the methods and tools used to interpret the results of the assessments (Pellegrino et al., 2001). In the context of conceptual change, questions one would ask when evaluating or designing assessments for the 'interpretation corner' include: What analyses will be done on the results of the assessment?

Vitae RDF: The 'Cognition Corner'

With regard to what concepts are difficult, the creators of the Vitae RDF started with concerns about how researchers' skills and careers were developed and promoted to help ensure research capability and economic success (Reeves et al., 2012). The developers recognized the difficult concepts as being the "substantial cultural change in the way researchers are perceived, managed and conduct themselves" (Reeves et al., 2012, p. 5). Fundamentally, the developers are saying that researchers, and those that manage them, do not have a good understanding of what is required of them, and that the Vitae RDF will identify for researchers what is required. This cultural change is similar to what Dall'Alba identified as ambiguous in the process of becoming a professional and is similar to the period of great transition that she identified that students go through in how they view professional practice (2009). With regard to why these concepts are difficult (i.e., theory), the developers indicate that "the lack of clarity about what constitutes a research job/career, and about the defining characteristics of a 'researcher'. There is no overarching 'framework' on which to contextualize the mapping of research careers" (Reeves et al., 2012, p. 5). This lack of clarity is similar to what Dall'Alba identified as ambiguous in the process of becoming a professional (2009). Dall'Alba explained how this ambiguity (i.e., lack of clarity) made it difficult for students to become professionals. Utilizing the Vitae RDF can begin to provide clarity to that process.

While the Vitae RDF does not specifically address how students learn these concepts, as mentioned previously, the levels of skill phases are attained progressively over time (see Table 2.2). The skill attainment over time aligns well with Dall'Alba's (2009) 'process of becoming' a professional, which is learning by being situated ontologically in being a professional.

Vitae RDF: The 'Observation Corner'

With regard to what procedures are used to create the assessment, the Vitae RDF was rigorously developed using an interpretive, phenomenographic research approach (Reeves et al., 2012). The developers first utilized several sets of semi-structured interviews and focus groups to collect the main data about the aspects needed for skills and career trajectory (Reeves et al., 2012). Once the main data was analyzed (see 'Interpretation Corner') and a draft framework was produced, the results of the draft were reviewed by sectors of higher education, researchers, and other stakeholders. These reviews produced additional changes, and an expert panel review was given as evidence of validity for the final framework (see 'Interpretation Corner') (Reeves et al., 2012). Fundamentally, the Vitae RDF utilized several procedures to develop the assessment (interviews, focus groups, iteration, and feedback from experts) during the development process.

Vitae RDF: The 'Interpretation Corner'

With regard to what analyses were done on the results of the assessment, the Vitae RDF utilized several analyses. First, after semi-structured interviews and focus groups data was taken (see 'Observation Corner'), the developers analyzed the data utilizing cluster analysis and literature reviews, which produced the first draft of the framework (Reeves et al., 2012). Next, after additional changes were made to the draft framework based on reviews by sectors of higher education, researchers, and other stakeholders (see 'Observation Corner'), evidence of validity of the final version of the Vitae RDF was provided by an external independent advisory group of experts (Reeves et al., 2012). Finally, on the Vitae website, several researcher profiles (Vitae, 2018) are provided that show examples of people who have utilized the Vitae RDF. The Vitae RDF has been referenced as the best government-supported effort "to recognize this deficiency in the traditional research doctoral preparation, and […] fill this gap" (Wendler et al., 2010).

Step 2: Utilizing the Vitae RDF to Conceptualize the Five Ontological Aspects

In order to conceptualize the five ontological aspects that have been identified, each of the aspects were mapped to one of the most applicable Vitae RDF descriptors, as follows:

1. <u>Opportunity for students to work as a team member on research</u>: maps best to Vitae descriptor **D1: team working** for a possible present or absent ontological aspect to measure in the students' research experiences.
2. <u>Opportunity for students to be exposed to their collaborator's forms of practice</u>: maps best to Vitae descriptor **B3: continuing professional development** for a possible present or absent ontological aspect to measure in the students' research experiences.
3. <u>Opportunity for students to have relevant exposure to professional practice based on later employment</u>: maps best to Vitae descriptor **B3: continuing professional development** for a possible present or absent ontological aspect to measure in the students' research experiences.
4. <u>Opportunity for students to gain experience with modeling and simulation tasks</u>: maps best to Vitae descriptor **A1: research method – theoretical knowledge** for a possible present or absent ontological aspect to measure in the students' research experiences.

5. Opportunity for students to gain practice with hands-on and troubleshooting tasks: maps best to **A1: research method – practical knowledge** for a possible present or absent ontological aspect to measure in the students' research experiences.

Step 3: Initial Operational Definitions

Once the Vitae RDF was initially used to conceptualize the five ontological aspects relative to professional practice, the next step was to conceptualize further and operationalize the five ontological aspects for measurement. This process is explained further in Chapter 4 – Instrument Development.

3. RESEARCH DESIGN

As described from Chapter 1, the primary purpose of this study was to develop and examine the validity evidence for an engineering-specific Research Experiences Instrument (REI) that measures engineering Ph.D. students' perceptions of:

1. The most important aspects of their research experiences related to professional practice based on the identification and characterization identified from the literature.
2. The extent to which their engineering Ph.D. research experiences contributed to opportunities to practice becoming a professional.

The Research Experiences Instrument (REI) that was developed in this study had a primary purpose, intended use, and inferences that guided the overall development and validation process, as follows:

Purpose of the REI: the purpose of the REI is to assess engineering Ph.D. students about perceptions of their research experiences to determine how these research experiences provided them with opportunities to practice becoming a professional and if there were differences in opportunities between types of research experiences.

Intended use of the REI: the REI is intended to be used as a research and program evaluation survey to examine opportunities of engineering Ph.D. students for professional preparedness in their research experiences. The REI is not intended for the assessment of individual students.

Inferences to be made with the REI: scores from the REI are to be interpreted such that higher scores indicated more opportunities to practice becoming a professional while lower scores indicated fewer opportunities to practice becoming a professional. Desired claims were to include that certain research experiences provided, on average, more or fewer opportunities to practice becoming a professional than other research experiences.

3.1 Research Design Overview

This study was fundamentally an instrument development and validation investigation. As such, it followed an instrument development and validation process specified by Netemeyer, Bearden, and Sharma (2003). They specify a four-step process focused on 1) construct definition;

2) generating and expert review of assessment questions; 3) designing and conducting studies to develop the assessment; and 4) finalizing the assessment. For this study and the reporting of methods, analyses, and results, there were four phases of distinct development that utilized the process specified Netemeyer et al. (2003) as shown in Table 3.1 in chronological order of study development: Instrument Development; Instrument Validation – Pilot Test 1; Instrument Validation – Pilot Test 2; Instrument Scoring and Group Analysis. Each phase is allocated its own Chapter in this study.

Table 3.1: *Chronology of Study Development by Phase*

Study Phase	Study Chapter	Dates	Analyses/Results
Instrument Development	Chapter 4	January '18 – April '19	Literature Review, Construct Development, Question Generation and Question Review
Instrument Validation – Pilot Test 1	Chapter 5	May '19 – September '19	Exploratory Factor Analysis from data collected from a large Midwestern University
Instrument Validation – Pilot Test 2	Chapter 6	October '19 – Jan '20	Confirmatory Factor Analysis from data collected at U.S. institutions
Instrument Scoring and Group Analysis	Chapter 7	February '20 – March '20	Nonparametric analysis of variance tests for group differences in scores

As the development of each phase was dependent on results from the previous phase, this Chapter presents detailed descriptions of each of the phases and the results. Each phase was organized as follows: purposes of each phase, methods (i.e., procedures, participants, and analyses), results, and a summary of validity evidence.

3.2 Approach to Instrument Development and Validation: A Validity Framework

Before discussing each phase of this study, it is important to have a common understanding of the approach to instrument development and validation that was used in this study, as this approach guided the design. Validity in instrument development is commonly understood to be the degree to which the measure is actually measuring the construct it is intended to measure, supported by the evidence (Messick, 1995; Netemeyer et al., 2003). Historically, instrument development has focused on three types of validity evidence: content-related, criterion-related, and construct-related (Douglas, Rynearson, Purzer, & Strobel, 2016). This historical approach has been criticized for an "overemphasis on statistical procedures and lack of explicit attention to the foundations of assessment" (Douglas et al., 2016, p. 1963). Accordingly, this study utilized Messick's Unified Theory of Validity (Messick, 1995), in which all sources of validity evidence support the aspects of construct validity in an accumulation of evidence and subsequent justification of the evidence. Messick identified six aspects of validity that support construct validity in a unified concept: content, substantive, structural, generalizability, external, and consequential. Douglas et al. (2016) summarized these six aspects, with examples, in a table that is partially repeated in Table 3.2, as shown.

Table 3.2: *Descriptions of Aspects of Validity and Uses (Douglas et al., 2016, p. 1693)*

Aspect of Validity	What it Evaluates	Types of Questions Asked
Content	Technical quality, relevance, and content representativeness, face validity/appearance	How well does the table of specifications or blueprints match the intended purpose of the assessment? What is the level of alignment between test objectives and actual questions?
Substantive	Respondents engage with, read, and understand the assessment questions as intended	Is the group of interest interpreting the questions as intended? Are the cognitive processes the test is designed to measure being assessed?
Structural	Fidelity of scoring structure. Questions can be summed together in a scale and labeled as a single construct	Is the internal structure of the instrument congruent with the structure of the construct domain?
External	Scores are convergent or discriminate with other variables as hypothesized	Do the scores correlate with other variables as expected, either convergent or discriminant?
Generalizability	Extent to which technical qualities of instrument generalize to a group, across groups, tasks, and contexts	Can the scale be generalized to other situations under which it will be used?
Consequential	Potential and social implications of using the results are in alignment with purpose and ethical	What is the evidence that the consequences of the test scores are justifiable? Who will determine the usage of the test scores?

Messick's framework is more aligned with the latest approach taken by the joint committee of the American Educational Research Association, the American Psychological Association, and the National Council on Measurement in Education which controls the *Standards for Educational and Psychological Testing* (American Educational Research Association, American Psychological Association, National Council on Measurement in Education, & Joint Committee on Standards for

Educational and Psychological Testing, 2014). This approach views validity not as a checklist of tasks to be completed or as a property of the instrument, but as a summary of the evidence and the justification of the interpretations and uses of the instrument. Or, as Messick summarized, "what is required is a compelling argument that the available evidence justifies the test interpretation and use" (Messick, 1995, p. 774). Each aspect of validity is discussed in the phase for which the evidence was provided. For this study, Table 3.3, as shown, provides a brief overview of each aspect of validity, the type of evidence provided in this study, and the phase in the study where the evidence was provided.

Table 3.3*: Summary of Validity Evidence Provided*

Aspect of Validity	Summary of Evidence	Study Phase
Internal consistency (reliability)	Cronbach's alpha	Instrument Validation – Pilot Test 1
	Cronbach's alpha	Instrument Validation – Pilot Test 2
Content	Utilization of a theoretical framework, literature review, construct definitions	Instrument Development
	Review of survey questions by experts	
Substantive	Think-alouds with engineering Ph.D. students	Instrument Development
Structural	Question analysis	Instrument Validation – Pilot Test 1
	Exploratory Factor Analysis (EFA)	
	Confirmatory Factor Analysis (CFA)	Instrument Validation – Pilot Test 2
External	Nonparametric analysis of variance tests for group differences in scores	Instrument Scoring and Group Analysis
Generalizability	Nonparametric analysis of variance tests for group differences in scores	Instrument Scoring and Group Analysis
Consequential	Discussion of validity evidence	Discussed in Chapter 8

3.3 Approach to Likert-type Scale Data

As will be explained in the sections that follow, the REI utilized Likert-type assessment questions and responses. Therefore, the type of data collected in pilot tests of the REI was technically ordinal (i.e., categorical data), as the REI has different categorical choices for which respondents could choose. However, it is common practice in education (Harwell & Gatti, 2001) to treat Likert-type ordinal data as interval data (i.e., continuous data) because it is useful to do so to make sense of the data. Certain parametric statistical methods, such as analysis of variance, regression, and correlation have been shown to be robust to small sample sizes, issues of non-normality in the data, and Likert-type scales, and can be treated as interval data (i.e., continuous data) (Norman, 2010). Likert-type data typically has some degree of skew and kurtosis, and Kline (2015) provided recommendations on the thresholds used in this study that EFA and CFA are appropriate analyses when the skew is less than 3.0, and the kurtosis is less than 10.0. Accordingly, this study treated the REI Likert-type scale data as interval data (i.e., continuous data) for most analyses in subsequent sections, and when not, an explanation was provided.

4. INSTRUMENT DEVELOPMENT

The primary purpose of the Instrument Development phase was to generate assessment questions and collect evidence of the content and substantive aspects of validity. The content aspect of validity refers to evidence of the measurement constructs technical quality based on theory and how well assessment questions represent the constructs (Messick, 1995). The substantive aspect of validity refers to evidence of how respondents engage with assessment questions as intended (Messick, 1995). The purpose of this Chapter was accomplished by following the steps specified by Netemeyer et al. (2003) focused on 1) generating assessment questions through the utilization of a theoretical framework, literature review, and construct definitions; 2) reviewing of the assessment questions by experts to modify the questions as needed based on feedback; 3) conducting think-alouds with engineering Ph.D. students to ensure assessment questions are understood as intended, and modifying the questions as needed.

4.1 Methods of Instrument Development

Generation of Assessment Questions

The first step in the instrument development process was to generate assessment questions through the utilization of a theoretical framework, literature review, and construct definitions, and in doing so, provide evidence of the content aspect of validity. Chapter 2 presented the ontological framework that guided this study about what it means for engineering Ph.D. students to become professionals through their research experiences. This framework was utilized as a lens for a review of the literature around engineering Ph.D. research experiences, and five ontological aspects of the engineering Ph.D. research experiences were defined and conceptualized, including operational definitions that were established for measurement. The theoretical underpinnings and careful definitions in this framework were intended to provide clear bounds of the measurement that meet the purpose and intended use of the REI, and allowed for assessment question development to follow.

The generation of an initial list of assessment questions was a deliberative, sequential process. First, Likert-type questions were generated for each of the five ontological aspects. In guiding the assessment question generation process, a critical question was asked about each ontological aspect, such that: “what is the significant essence of this aspect?” A minimum of five assessment questions per aspect was developed, knowing that a balance must be maintained between the overall number of questions and the inclusiveness of the construct. As Netemeyer et al. (2003) concluded, there are no set guidelines in the literature for an initial question pool, other than “overinclusiveness is more desirable than underinclusiveness” (2003, p. 102). Assessment questions were developed based on the experience of the researcher working with and observing engineering graduate students conducting research, a review of other instruments mentioned in the literature review, several consultations with the dissertation committee, many informal discussions with other engineering faculty, and other experiences development developing assessment questions. The assessment questions were intentionally developed to cover as much of the range of engineering Ph.D. students’ research experiences across each particular aspect as possible.

Next, the stem of the assessment questions was developed. One of the more difficult decisions was to decide what the stem of the assessment questions should be. For example, the original stem of the assessment questions at the preliminary defense was “to what extent did your research experience contribute to…”. However, upon further consideration during assessment question development, the stem was changed to “how often in your graduate research experience did you…”, as this stem more accurately reflected the ontological aspect of ‘being’ and ‘doing’ involved in becoming a professional.

Finally, the number of responses to the Likert-type questions was developed, which again was a difficult decision. The literature is mixed on whether it is better to provide an odd or even number of responses (Netemeyer et al., 2003). It was decided for the REI to provide an even number of responses, which forced respondents to make a non-neutral choice when answering questions, which was determined was the preferred option for the REI. Six Likert-type responses were provided to respondents, as follows: 1) never, 2) very rarely, 3) rarely, 4) occasionally, 5) frequently, 6) very frequently. This type of scale is common for scales used to measure the frequency of occurrence (Vagias, 2006). In total, twenty-nine Likert type assessment questions were initially developed. The initial assessment questions, along with the essence, conceptualization, and operational definition, are provided in Table B.1 in Appendix B.

Nine self-report questions about the organization and structure of the engineering Ph.D. students’ research experiences were initially developed based on the Concept Map developed in the Chapter 2 literature review. The self-report questions are simple, direct questions about students' research experiences, intended to be answered either with a direct response, such as a number, or from students choosing from a few selected responses, listed in Table 4.1 below.

Table 4.1: *Initial Self-Report Questions About Engineering Ph.D. Students' Research Experiences*

Key Characteristics	Sub Characteristics		Initial Self-Report Question	Literature Reference
Group Information	Size	1.	Including yourself, approximately how many members are in your research group?	Similar to questions asked in Crede and Borrego (2013).
	Organization	2.	How is your research group organized? Response Option 1: 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.	
Work Organization		3.	How is your 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.	Similar to questions asked in Crede and Borrego (2013).
Discipline		4.	What is your graduate engineering major? Response Options: all the engineering majors, including none of the above.	Similar to the question asked in (Huff, Zoltowski, & Oakes, 2016).
Work Type		5.	What type of 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).	None.

Table 4.1 continued

Key Characteristics	Sub Characteristics	Initial Self-Report Question	Literature Reference
Collaborator	Type	6. What type of collaborators, either internal or external, do you work with primarily in your 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.	None.
	Interaction	7. 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.	None.
Equipment	Type	8. What type of equipment do you primarily use to conduct your 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 of the research work relies on facilities, test equipment, and physical experiments.	None.
	Work space	9. How is the work space for your 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 a lab space that is shared with multiple different types of research groups.	Similar to questions asked in Crede and Borrego (2013).

Eight demographic questions were also initially developed that were important to the study and are listed in Table 4.2 below, along with the reason why the questions were asked.

Table 4.2*: Initial Demographic Questions*

	Initial Demographic Question	Why Question Was Asked
1.	What is your gender? <u>Response Options</u>: 1) male, 2) female, 3) other.	Understand if group differences exist by gender.
2.	What degree are you seeking? <u>Response Options</u>: 1) Master's, 2) Ph.D., 3) Both, 4) not applicable.	To ensure that students are a Ph.D. student.
3.	Have you completed your department/school qualification exam? <u>Response Options</u>: 1) yes, 2) no, 3) not applicable.	Understand if completion of the qualification exam might be a limiting factor in results.
4.	What is your ethnicity of origin? Please check any that you identify with. <u>Response Options</u>: 1) White/Caucasian, 2) Black/African American, 3) Hispanic or Latino, 4) Native American, 5) Asian, 6) Pacific Islander, 7) Other, 8) Other -TEXT ENTER-, 9) I prefer not to respond	Understand group differences exist by ethnicity.
5.	Have you ever worked full-time in industry (not including internships or co-ops)? <u>Response Options</u>: 1) yes, 2) no, 3) not applicable.	Understand if working full-time in industry affects the results in results. Allows for overall percentage reporting in results.
6.	If you had an internship or co-op during graduate school, was it related to your research work? <u>Response Options</u>: 1) yes, 2) no, 3) not applicable.	Allows for overall percentage reporting in results.
7.	Have you been a Teaching Assistant or Instructor during graduate school? <u>Response Options</u>: 1) yes, 2) no, 3) not applicable.	Allows for overall percentage reporting in results.
8.	What is the primary source of funding for your research? <u>Response Options</u>: government (e.g., NSF, DOE, etc.), 2) industry, 3) not funded, 4) other.	Allows for overall percentage reporting in results.

Reviewing of Assessment Questions

The second step in the instrument development process was to have the assessment questions reviewed by experts so that the questions could be modified as needed based on their feedback, and in doing so, provide evidence of the content aspect of validity. Netemeyer et al. (2003) recommend such feedback come from at least five experts in assessment question development and subject matter. This recommendation guided the process of expert feedback for this study.

Procedure and Participants

The twenty-nine assessment questions and the operational definition for each ontological aspect listed in Table B.1 in Appendix B were taken from its draft paper form and put into an online electronic form using Qualtrics (2019) (an online survey tool) so that a survey link was provided to the selected experts. In the Qualtrics survey, participants were asked to rate how each assessment question aligned with the operational definition. Response options included three choices: 1) not aligned, 2) somewhat aligned, 3) clearly aligned. For each set of assessment questions related to the definition, respondents were asked to enter their feedback for the assessment questions, such as the clarity, conciseness, or other aspects of the assessment questions that should also be included. As the final question in the Qualtrics survey, respondents were asked to enter their feedback about any concerns they have about the approach, or anything they saw in the initial development of the assessment or aspects they thought might be missing.

Twelve experts were emailed with a request to complete the Qualtrics survey described above. These experts included five faculty with expertise in assessment development; three faculty with expertise in engineering Ph.D. student research experiences; and four engineering Ph.D. students with experiences in assessment development. Reminder emails were sent where necessary to achieve the desired 100% response rate.

Analyses

Once data were collected from the online Qualtrics survey and downloaded, several analyses were performed. First, the ratings were visually inspected in Excel 2016 to check for any assessment question that received a single response of being rated as ‘not aligned’ by any expert. Second, any assessment question that received a ‘somewhat aligned’ rating by more than one expert was flagged for follow-up. Third, based on the visual inspection of the data, it was apparent that the calculation of a mean and standard deviation of the ratings would not provide meaningful information, so instead, the frequencies of the scores were examined. Fourth, the written feedback data was copied from Excel 2016 into a Word 2016 document, along with the frequencies of rating scores, so that the feedback for the set of assessment questions could be examined from all experts together in a single document. All feedback and rating scores were reviewed together in a holistic process that included consultation with dissertation committee members as needed. Modification to the assessment questions and operational definitions were made, including the addition of an assessment question (explained in results) to bring the total to thirty assessment questions.

The experts only reviewed the assessment questions, and not the self-report questions or the demographics questions, as the self-report and demographic questions primarily derived from the literature in most cases, and were quite straightforward. However, the self-report and demographics questions were reviewed during the think-aloud processes with engineering Ph.D. students, described next.

Think-Alouds with Engineering Ph.D. Students

The third step in the instrument development process was to conduct think-alouds with engineering Ph.D. students to ensure assessment questions were understood as intended, and in doing so, provide evidence of the substantive aspect of validity. A think-aloud process is a widely used technique in assessment development where participants "think-aloud", verbalizing their thinking as they completed the assessment (Czaja & Blair, 2004). The principal focus is on the cognitive thought process that students go through when answering the assessment questions (Czaja & Blair, 2004), and as such, allowed for the opportunity to make sure students were cognitively understanding the assessment questions as intended.

Procedure and Participants

Two-rounds of think-alouds were scheduled: the first round of think-alouds to understand students' thought processes and make changes to the assessment questions; and the second round of think-alouds to verify changes from the first round and make any final changes to the assessment questions. Purdue Institutional Review Board (IRB) approval was received to conduct the think-alouds (see Appendix B). Included in the IRB materials was the interview protocol used during the think-alouds (see Appendix B), the list of assessment questions used by students during the think-aloud (see Appendix B), the recruitment flyer used to recruit students for the think-aloud interviews (see Appendix B), and the consent form that participants signed to indicate they were willing to be part of the study (see Appendix B).

The recruitment flyer was placed in various engineering buildings on a large Midwestern University's campus, and any engineering Ph.D. student who responded to the flyer by email was scheduled for a think-aloud interview at a time that was convenient for the student. Per the protocol in Appendix B, which was developed using the guidelines of Czaja and Blair (2004), the think-aloud interview involved several steps. First, each student was provided the IRB approved consent form, and provided time to read it and ask questions about the form. After signing the consent form, the student was provided a copy for their records and the original retained. Second, each student was provided a paper copy of the assessment questions (Appendix B), and given verbal direction to read the instructions on top of the paper copy of the assessment questions. They were also reminded that the interviewer could not answer questions about the assessment questions once the interview had begun.

Each student was given the opportunity to ask questions about the instructions. At that point in the interview, the audio recording device was started, and the student was asked to begin by reading the first assessment question out loud and selecting their response. The student was asked to interpret what they thought the questions were asking, to describe what their thought process was in selecting their responses, and to justify their selections. After the student responded to each assessment question, if the interviewer needed clarification about the cognitive thought process the student was using, a follow-up question was asked based on the context of the particular assessment question. Finally, at the end of the interview, the audio recording was stopped and saved, and the student was thanked for their participation. The paper copy of the assessment questions was collected for later evaluation, as often a student indicated their responses on the paper copy. Both the audio file and the paper copy of the assessment were coded to anonymize the participant information.

For the first round of think-alouds, seven engineering Ph.D. students responded to the recruiting flyer and were interviewed. Audio recordings were transcribed and analyzed, and the assessment questions were modified (both processes described later).

For the second round of think-alouds, the process described above was used, except a modified set of questions based on the results of the first think-aloud were used (see Appendix B). For the second round of think-alouds, five engineering Ph.D. responded to the recruiting flyer and were interviewed. Again, audio recordings were transcribed and analyzed, and the assessment questions were modified (both processes described later).

Analyses

For the first-round of think-alouds, the audio recording of a think-aloud interview was transcribed within a few days of the interview being completed, and was examined shortly thereafter so that the interview was still fresh. A transcript was evaluated by printing it out and reading through the transcripts of the student responses, along with examining the student's paper copy of the assessment questions in which they indicated their responses during the think-aloud. Any cognitive issue a student had with an assessment question was noted in a Word 2016 document, so that once all student think-aloud interviews were conducted, transcribed, and evaluated, the results and any issues were contained in a single, summary document. The summary was used to make changes to many aspects of the assessment, including changes to the essence, conceptualization, operational definition, assessment questions, self-report questions, and demographic questions. The changes were reviewed with members of the dissertation committee. Details of the changes are provided in the Results section.

For the second-round of think-alouds, the exact same process was used as described above, as audio recordings were transcribed and analyzed within a few days of the interview. As before, any cognitive issues a student had with an assessment question were recorded in a Word 2016 document, and the summary of cognitive issues was used to make changes, this time only to assessment questions, self-reports questions, and demographic questions. The changes were again reviewed with members of the dissertation committee. Details of the changes are provided in the Results section.

4.2 Results of Instrument Development

Generation of Assessment Questions

The initial list of twenty-nine assessment questions, developed through the utilization of a theoretical framework, literature review, and construct definitions was provided previously in Table B.1 in Appendix B. The initial list of self-report questions generated were provided previously in Table 4.1, and the initial list of demographic questions generated was provided previously in Table 4.2.

Reviewing of Assessment Questions

Of the twelve experts that were emailed with a request to complete the Qualtrics survey to review the assessment questions and provide feedback, eleven responded. Ten experts completed the entire survey, including written feedback, and one expert supplied only written feedback. A summary of the frequency of the ratings to each assessment question from the ten experts who completed the entire survey is provided in Table B.2 in Appendix B. None of the experts rated any of the assessment questions as ‘not aligned’ with the provided definition.

Seven assessment questions were changed based on the frequencies of scores and the written feedback from the experts, as shown in Table 4.3 below.

Table 4.3*: Assessment Questions Changed After Expert Review*

	Assessment Question	Justification
Before:	Q4: develop different skill sets to complement the needs of the research team’s goals?	Four experts rated this question as ‘somewhat aligned’. Experts expressed concerns about the question being too vague. Question modified to focus more on new skills and the needs of the team.
After:	Q4: develop new skills based on the needs of the research team’s goals?	
Before:	Q5: depend on other graduate students to meet the desired research outcomes?	Two experts rated this question as ‘somewhat aligned’. Experts expressed concerns about the word “depend”. The word “mutually” added to convey a collaborative team perspective.
After:	Q5: mutually depend on other graduate students to meet the desired research outcomes?	
Before:	Q7: meet at your institution with your sponsors or collaborators (i.e., practicing professional engineers) who are involved in your research work?	Two experts rated this question as ‘somewhat aligned’. Experts expressed concerns about the word “meet”. The word “interact” more appropriately conveyed the type of involvement with the sponsor/collaborators.
After:	Q7: interact with your sponsors or collaborators (i.e., practicing professional engineers) at your institution who are involved in your research work?	
Before:	Q9: meet with your sponsors or collaborators at their place of work to discuss your research or results?	Two experts rated this question as ‘somewhat aligned’. Experts expressed concerns about the word “meet”. The word “interact” more appropriately conveyed the type of involvement with the sponsor/collaborators.
After:	Q9: interact with your sponsors or collaborators at their place of work related to your research work?	
Before:	Q12: develop professional relationships with working engineers through your research work?	Two experts rated this question as ‘somewhat aligned’. Experts expressed concerns about the word “engineer”. The word “professional” was deemed more appropriate, and clarification was added that was different than the students’ sponsors/collaborators.
After:	Q12: develop professional relationships with working professionals (other than your sponsors or collaborators) through your research work?	

Table 4.3 continued

	Assessment Question	Justification
Before:	Q13: attend industry or government trade shows as part of your research work?	Two experts rated this question as 'somewhat aligned'. Experts expressed concerns that trade shows were one example of a type of event. The wording was changed to clarify the word events, and provide examples.
After:	Q13: attend industry or government events (e.g., trade shows, exhibitions, etc.) as part of your research work?	
Before:	Q20: utilize complex engineering modeling or simulation tools to help solve a research problem?	One expert rated this question as 'somewhat aligned', however, two experts expressed concerns with the word "complex". The word "sophisticated" was deemed to reflect the nature of the type of tools utilized more accurately.
After:	Q20: utilize sophisticated engineering modeling or simulation tools to help solve a research problem?	

Assessment questions Q1, Q18, and Q27, also had instances of at least two 'somewhat aligned' scores from the expert reviews. However, based on the written feedback provided by the experts, along with the determination of the researcher (in consultation with members of the dissertation committee), Q1, Q18, and Q27 were not modified.

Additional changes were made to overall assessment based on the feedback from the experts, and are shown summarized in Table 4.4 below, including the justification for the change.

Table 4.4*: Additional Changes Made to REI Assessment After Expert Review*

Change Made to REI Assessment	Justification
1. The operation definition for the ontological aspect "Modeling and simulation tasks" was modified to use the word "sophisticated" rather than "complex". <u>New definition</u>: The process of graduate engineering students identifying engineering problems, specifying constraints and assumptions in order to design and develop a mathematical model, often utilizing sophisticated engineering tools. The process continues with the verification and optimization of the model by evaluating the simulated performance of the system in an iterative process that utilizes refinement of the constraints, assumptions, and the model itself, facilitated by knowledge and discovery (adapted from (Magana & Coutinho, 2017); Radcliffe (2014)).	The definition was modified based on the changes to assessment question #20.

Table 4.4 continued

Change Made to REI Assessment	Justification
2. An additional assessment question was added for the ontological aspect "Modeling and simulation tasks" based on expert feedback. This question was added as question #20 in the overall list. New question: specify constraints or assumptions in development of a mathematical model to help solve a research problem?	The expert feedback identified that problem identification, constraint, and assumption specification were missing from the question list.
3. The operation definition for the ontological aspect "Practical skills" was modified based on expert feedback. New definition: Engineering research tasks in which graduate engineering students plan, use, and/or deploy physical equipment or instrumentation, ensuring proper operation, collection and interpretation of data, and troubleshooting and repair of the equipment or instrumentation to support the research endeavor (adapted from Lumpe and Oliver (1991); (Rivera-Reyes & Boyles, 2013)).	There was a consensus from the experts that the assessment questions were acceptable but that the definition lacked specificity. The definition was modified to use straightforward, clear language.

The final result from the expert review of the initial assessment question is an updated list of assessment questions used with engineering Ph.D. students during the first round of think-aloud (see Appendix B). This list included the thirty assessment questions (reviewed by experts), the nine self-report questions, and the eight demographic questions.

Think-Alouds with Engineering Ph.D. Students

As mentioned previously, seven engineering Ph.D. students were interviewed in the first round of think-alouds, and five engineering Ph.D. students were interviewed in the second round of think-alouds. Relevant demographics of the think-aloud participants are summarized in Table B.3 in Appendix B.

Twenty-eight of the thirty assessment questions were modified after the first round of think-alouds with seven engineering Ph.D. students, including the overall stem of the assessment questions. The changes made to the twenty-eight assessment questions were put into two categories: 1) cognitive issues encountered by students, which resulted in changes to six assessment question and the overall stem, summarized in Table 4.5 below; 2) the opportunity to clarify the assessment questions, made to twenty-two assessment questions to clarify a word, or the removal of a single word or phrase, summarized in Table 4.6 below.

Table 4.5*: Assessment Questions Changed Due to Cognitive Issues After Round 1 of Think-Alouds*

Assessment Question		Justification
Before:	Overall stem: How often in your graduate research experience did you:	Some students had different masters and Ph.D. research experiences, and were not sure which experience to use when answering questions. The stem was modified to clarify the emphasis on only Ph.D. research experiences.
After:	Overall stem: How often in your Ph.D. research experience did you:	
Before:	Q4: develop new skills based on the needs of the research team's goals?	Some students who are quite experienced struggled to come up with new "skills" they developed. Examples were added to the question.
After:	Q4: develop new skills (e.g., presentation, project management, software, etc.) based on the needs of the research team's goals?	
Before:	Q11: co-present at conferences with your sponsors or collaborators?	Most students were not co-presenting, only presenting. But many expressed that they did create presentations with their sponsor/collaborator, so the question was modified.
After:	Q11: co-create a presentation with your sponsors or collaborators?	
Before:	Q13: attend industry or government events (e.g., trade shows, exhibitions, etc.) as part of your research work?	Some students did not notice the "or" in the question. Some students thought that conferences counted as "events". This question did not perform well, and there were enough questions in this aspect, so it was removed.
After:	Q13: the question was eliminated.	
Before:	Q17: hold an internship or co-op during your graduate research studies?	Students understand the question, but had trouble scoring it. It was common for them to hold one internship, but they did not know how to score it. The question was changed to focus on interacting during internships/co-ops.
After:	Q17: interact with practicing engineers during internships or co-ops?	
Before:	Q21: utilize sophisticated engineering modeling or simulation tools to help solve a research problem?	For some students, the word "tools" was not the emphasis when asked about sophisticated. They focused on model sophistication. The question was reworded.
After:	Q21: utilize sophisticated tools to help solve an engineering modeling or simulation problem?	
Before:	Q26: plan how to use or deploy experimental equipment or instrumentation to gather valid data relevant to your research?	Some students not focused on the word "plan". They instead described use or deployment, not planning. The question was simplified to focus on planning.
After:	Q26: develop plans to use test equipment or instrumentation?	

Table 4.6: *Assessment Questions Changed For Clarification After Round 1 of Think-Alouds*

	Assessment Question
Before:	Q2: coordinate research tasks with other graduate students to accomplish research goals?
After:	Q2: coordinate research tasks with other graduate students?
Before:	Q3: share decision making responsibility with other graduate students to accomplish research goals?
After:	Q3: share decision making responsibility with other graduate students?
Before:	Q5: mutually depend on other graduate students to meet the desired research outcomes?
After:	Q5: mutually depend on other graduate students to meet the desired outcomes?
Before:	Q6: present your research results to your sponsors or collaborators (i.e., practicing professional engineers) who are involved in your research work?
After:	Q6: present your research results to your sponsors or collaborators (i.e., practicing engineers) who are involved in your research?
Before:	Q7: interact with your sponsors or collaborators (i.e., practicing professional engineers) at your institution who are involved in your research work?
After:	Q7: interact at your institution with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research?
Before:	Q8: correspond (e.g., email, phone, etc.) with your sponsors or collaborators (i.e., practicing professional engineers) who are involved in your research work?
After:	Q8: correspond (e.g., email, phone, etc.) with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research?
Before:	Q9: interact with your sponsors or collaborators at their place of work related to your research work?
After:	Q9: interact with your sponsors or collaborators at their place of work related to your research?
Before:	Q10: co-write journal or conference papers with your sponsors or collaborators?
After:	Q10: co-author journal or conference papers with your sponsors or collaborators?
Before:	Q12: develop professional relationships with working professionals (other than your sponsors or collaborators) through your research work?
After:	Q12: develop professional relationships with practicing engineers (other than your sponsors or collaborators) through your research?
Before:	Q14: participate in industry or government conferences as part of your research work?
After:	Q14: participate in industry or government conferences as part of your research?
Before:	Q15: participate in professional engineering societies (e.g., Institute of Electrical and Electronics Engineers, Society of Women Engineers, etc.) related to your graduate research studies?
After:	Q15: participate in professional engineering societies (e.g., Institute of Electrical and Electronics Engineers, Society of Women Engineers, etc.)?

Table 4.6 continued

	Assessment Question
Before:	Q16: present results of your research to professional engineers other than your sponsors or collaborators?
After:	Q16: present results of your research to practicing engineers (other than your sponsors or collaborators)?
Before:	Q18: interact with support professionals (e.g., project managers, building maintenance, outside vendors, etc.) to accomplish research objectives?
After:	Q18: interact with support professionals (e.g., project managers, building maintenance, outside vendors, etc.)?
Before:	Q19: develop or utilize a mathematical model to help solve a research problem?
After:	Q19: develop or utilize a mathematical model to help solve a problem?
Before:	Q20: specify constraints or assumptions in development of a mathematical model to help solve a research problem?
After:	Q20: develop or utilize a mathematical model to help solve a problem?
Before:	Q22: simulate the performance of a system to accomplish research goals?
After:	Q22: simulate the performance of a system to obtain results?
Before:	Q23: iterate on the development of a model or simulation to optimize research results?
After:	Q23: iterate on the development of a model or simulation to optimize results?
Before:	Q25: use physical equipment or instrumentation as an integral part of conducting your research?
After:	Q25: use test equipment or instrumentation as an integral part of conducting your research?
Before:	Q27: ensure the physical equipment or instrumentation is appropriately set-up (i.e., calibrated) before use?
After:	Q27: ensure the test equipment or instrumentation is appropriately set-up (i.e., calibrated) before use?
Before:	Q28: collect data from test equipment or physical apparatus using appropriate sensors or instrumentation?
After:	Q28: collect data from test equipment or apparatus using appropriate sensors or instrumentation?
Before:	Q29: interpret data gathered from physical equipment or apparatus?
After:	Q29: interpret data gathered from test equipment or apparatus?
Before:	Q30: troubleshoot or modify experimental equipment or instrumentation when it does not operate properly?
After:	Q30: troubleshoot or modify test equipment or instrumentation when it does not operate properly?

Minor changes were also made to six self-report and three demographic questions, including the addition of a demographic question after the first round of the think-alouds, summarized in Table 4.7 below. In addition, changes were made to the essence, conceptualization, and operational definition of the assessment based on the first round of think-alouds, shown in Table B.4 in Appendix B.

Table 4.7*: Self-Report/Demographic Questions Changed Made After Round 1 of Think-Alouds*

Self-Report/Demographic Question		Reason/Justification
Before:	SR-Q3: How is your research work organized?	"Ph.D." was added to ensure this was the experience referenced by students.
After:	SR-Q3: How is your Ph.D. research work organized?	
Before:	SR-Q4: What is your Ph.D. engineering major?	"Ph.D." was added to ensure this was the experience referenced by students.
After:	SR-Q4: What is your graduate engineering major?	
	Added a response category of 'other'	'Other' added in case engineering major is not listed.
Before:	SR-Q5: What type of research are you primarily working on?	"Ph.D." was added to ensure this was the experience referenced by students.
After:	SR-Q5: What type of Ph.D. research are you primarily working on?	
Before:	SR-Q6: What type of collaborators, either internal or external, do you work with primarily in your research?	"Ph.D." was added to ensure this was the experience referenced by students.
After:	SR-Q6: What type of collaborators, either internal or external, do you work with primarily in your Ph.D. research?	
Before:	SR-Q8: What type of equipment do you primarily use to conduct your research?	"Ph.D." was added to ensure this was the experience referenced by students.
After:	SR-Q8: What type of equipment do you primarily use to conduct your Ph.D. research?	Many students responded that the equipment used was a combination of responses 1 & 2, so this was added as an option.
	Added response "A combination of 1 & 2 above"	
Before:	SR-Q9: How is the work space for your research group organized?	"Ph.D." was added to ensure this was the experience referenced by students.
After:	SR-Q9: How is the work space for your Ph.D. research group organized?	From the think-aloud, it was clear this option was needed.
	Response added: "Housed in lab space that is shared with my research team only"	

Table 4.7 continued

Self-Report/Demographic Question		Reason/Justification
Before:	DM-Q3: Have you completed your department/school qualification exam?	Some students used the term area exam rather than a qualification exam, so this was added as an example.
After:	DM-Q3: Have you completed your department/school qualification exam (e.g., area exam)?	
Before:	DM-Q6: If you had an internship or co-op during graduate school, was it related to your research work?	"Ph.D." was added to ensure this was the experience referenced by students.
After:	DM-Q6: If you had an internship or co-op during graduate school, was it related to your Ph.D. research work?	
Before:	DM-Q7: Have you been a Teaching Assistant or Instructor during graduate school?	"Ph.D." was added to ensure this was the experience referenced by students.
After:	DM-Q7: Have you been a Teaching Assistant or Instructor during your Ph.D. research?	
Before:	DM-Q8: What is the primary source of funding for your research?	"Ph.D." was added to ensure this was the experience referenced by students.
After:	DM-Q8: What is the primary source of funding for your Ph.D. research?	
Before:	DM-Q9: not applicable	A question was added to understand students' intended destination after graduation.
After:	DM-Q9: Where do you see yourself working after graduation? Response Options: 1) government, 2) industry, 3) academia, 4) other.	

Twelve of the twenty-nine assessment questions were modified after the second round of think-alouds with five engineering Ph.D. students. There were no major cognitive issues encountered during the think-alouds, only cases where minor word clarifications made the assessment questions better. All of the changes made to the twelve assessment questions were made to clarify the assessment questions, in order to clarify a word, or the removal of a single word or phrase, summarized in Table 4.8 below.

Table 4.8: *Assessment Questions Changed For Clarification After Round 2 of Think-Alouds*

Assessment Question	
Before:	Q1: take on different roles or responsibilities within a research team?
After:	Q1: take on different roles or responsibilities within a research group?
Before:	Q4: develop new skills (e.g., presentation, project management, software, etc.) based on the needs of the research team's goals?
After:	Q4: develop new skills (e.g., presentation, project management, software, etc.) based on the needs of the research group's goals?
Before:	Q7: interact at your institution with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research?
After:	Q7: interact at your university with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research?
Before:	Q20: utilize sophisticated tools to help solve an engineering modeling or simulation problem?
After:	Q20: utilize sophisticated tools to help solve a modeling or simulation problem?
Before:	Q21: simulate the performance of a system to obtain results?
After:	Q21: simulate a system to obtain results?
Before:	Q23: verify a model or simulation against real-world data or actual results?
After:	Q23: verify a model or simulation based on real-world data or actual results?
Before:	Q24: use test equipment or instrumentation as an integral part of conducting your research?
After:	Q24: use testing equipment or instrumentation as an integral part of conducting your research?
Before:	Q25: develop plans to use test equipment or instrumentation?
After:	Q25: develop plans to use testing equipment or instrumentation?
Before:	Q26: ensure the test equipment or instrumentation is appropriately set-up (i.e., calibrated) before use?
After:	Q26: ensure testing equipment or instrumentation is appropriately set-up (i.e., calibrated) before use?
Before:	Q27: collect data from test equipment or apparatus using appropriate sensors or instrumentation?
After:	Q27: collect data from testing equipment or apparatus using appropriate sensors or instrumentation?
Before:	Q28: interpret data gathered from test equipment or apparatus?
After:	Q28: interpret data gathered from testing equipment or apparatus?
Before:	Q29: troubleshoot or modify test equipment or instrumentation when it does not operate properly?
After:	Q29: troubleshoot or modify testing equipment or instrumentation when it does not operate properly?

Minor changes were also made to three self-report questions and one demographic question after the second round of the think-alouds, summarized in Table 4.9 below.

Table 4.9*: Self-Report/Demographic Questions Changes Made After Round 1 of Think-Alouds*

Self-Report/Demographic Question		Reason/Justification
Before:	SR-Q1: Including yourself, approximately how many members are in your research group	Clarified that this question referred to graduate student members (not undergraduate students).
After:	SR-Q1: Including yourself, approximately how many graduate student members are in your research group?	
Before:	SR-Q6: What type of collaborators, either internal or external, do you work with primarily in your Ph.D. research?	The word "university" was added, as some students were confused about the type of research center.
After:	SR-Q6: Response clarified for "A strong emphasis on university research center collaborations"	
Before:	SR-Q9: How is the work space for your Ph.D. research group organized?	Added office.
After:	Response clarified for "Housed in lab space or office that is shared with my research group only"	
Before:	DM-Q1: What is your gender?	For clarification.
After:	Response modified from "other" to "non-binary"	

No changes were made to the essence, conceptualization, and operational definition of the assessment based on the second round of think-alouds. The final outcome of the second round of the think-alouds was a version of the assessment questions (shown in Appendix C) that was ready for Instrument Validation – Pilot Test 1.

4.3 Summary of Validity Evidence of Instrument Development

The primary purpose of the Instrument Development phase was to generate assessment questions and collect evidence of the content and substantive aspects of validity. As such,

Table 4.10 shows a summary of the validity evidence collected in the Instrument Development phase.

Table 4.10*: Summary of Validity Evidence Collected in the Instrument Development Phase*

Aspect of Validity	Types of Questions Asked	Evidence Collected	Results from Instrument Development Phase
Content	How well does the table of specifications match the intended purpose of the assessment?	Utilization of a theoretical framework, literature review, construct definitions	The utilization of a theoretical framework, literature review, and definitions of constructs resulted in an initial list of assessment questions, with a clear delineation of the bounds of measurement construct that match the intended purpose of the assessment.
	What is the level of alignment between test objectives and actual questions?	Review of assessment questions by experts	The review by 11 experts showed that none of the assessment questions were out of alignment. Experts review resulted in changes to the assessment questions and construct definitions that provided improved alignment between the objectives and the actual assessment questions.
Substantive	Is the group of interest interpreting the questions as intended? Are the cognitive processes the test is designed to measure being assessed?	Think-alouds with engineering Ph.D. students	Round 1 of the think-alouds indicated there were cognitive processes issues and clarifying issues, which resulted in changes to the assessment questions. These included major changes and minor word clarifications. Round 2 of the think-alouds indicated there were no cognitive processes issues, only clarifying issues, which resulted in changes to assessment questions. These included only minor word clarifications.

5. INSTRUMENT VALIDATION – PILOT TEST 1

The primary purpose of the Instrument Validation – Pilot Test 1 phase was to collect enough data to provide evidence of the internal consistency and structural aspect of validity. Internal consistency refers to the extent to which the assessment questions are measuring the same latent construct and have common variance, demonstrating reliability (Netemeyer et al., 2003). The structural aspect of validity refers to the extent to which the assessment questions and latent constructs form factor structures that are is in alignment with the theoretical structures (Messick, 1995). The purpose of this Chapter was accomplished by following the steps specified by Netemeyer et al. (2003) focused on exploring the assessment structure, specifically on removing assessment questions that were not dimensionally consistent, removing questions that were not internally consistent, and removing questions that did not fit the factor structure. As one of the main objectives of the pilot test was to perform an Exploratory Factor Analysis (EFA) to evaluate the instrument structure, a minimum sample size of 200 was targeted (Fabrigar, Wegener, MacCallum, & Strahan, 1999; Netemeyer et al., 2003).

5.1 Methods of Pilot Test 1

5.1.1 Procedure and Participants

The assessment was taken from its draft paper form (Appendix C) and put into an online electronic form using Qualtrics (2019) (an online survey tool) so that a survey link was provided to the research participants. Assessment questions 1 through 29 were entered in random order in Qualtrics so that the aspects would not be presented to respondents in order, while the self-assessment questions and demographic questions were kept in order. A filter question was added to the 29 assessment questions that asked a respondent to “if you are taking this survey, please select the response 'Never’ for this question” to identify respondents who were not paying attention to the questions. Potential respondents consisted of a convenience sample of 1988 engineering Ph.D. students from a large Midwestern University. Purdue IRB approval was received to conduct the study (see Appendix C) to contact each of the 1988 students by email via the University Registrar’s Office. An agreement with the University Registrar’s Office was obtained (see Appendix C, which includes the emails sent to the students), as the Registrar had better tools to send emails to each student. The emails sent to students included an IRB approved information sheet, which explains the study, as an email attachment (see Appendix C). Three emails were sent to each student: an initial email on 7/8/19; a reminder two weeks later on 7/22/19; and a final reminder two weeks later on 8/5/19. The Qualtrics survey was open from 7/8/2019 to 8/20/2019 for students to respond. Students who chose to participate in the study first had to click on the survey link in the email, then click 'Agree' to the question "I agree to be part of this study". If a student chose 'Disagree', the survey ended.

5.1.2 Analyses

Once data were collected from the online Qualtrics survey, several analyses were performed. All analyses (unless otherwise noted) were performed in 'R', v 3.6.1, which was the latest version of 'R' at the time analyses were conducted. The following analyses, as described, were processed in sequential order, with an explanation of why and how the analyses were completed.

Data cleaning and removal

The initial raw data from the Qualtrics survey was evaluated and cleaned to check for missing and incomplete data so it could be removed before further analyses. While incomplete was considered for use, the number of incomplete responses was small (less than 2%), therefore the incomplete data was removed per the procedure below. The evaluation and cleaning of data were accomplished by visual inspection and manipulation in Excel 2016. A row of data represented an individual respondent's data, and each row was individually evaluated to determine if the data were retained or discarded. A row of data was discarded if: 1) the respondent declined to participate in the study by selecting 'disagree' to be part of the study; 2) the respondent did not complete 100% of the survey; 3) the respondent did not answer the filter question correctly, by selecting 'Never' to the question "if you are taking this survey, please select the response 'Never' for this question". The remaining data were checked to ensure that all respondents were engineering students, and that all respondents were seeking a Ph.D. degree.

Data interpretation for 'Other'

After removing selected data, the remaining responses for the demographic and self-report data were checked for responses that indicated 'Other' rather one of the selected responses. If a response was 'Other' and the written response was obvious that it should be one of the selected responses, the response was changed to the appropriate selected response for that question.

Descriptive statistics and demographics

After cleaning the data, means, medians, standard deviations, and normality of scores were calculated to check for abnormalities in the data, such as elevated means or non-normality. Next, frequencies of demographic data and self-report data were tabulated to check for irregularities, such as unexpected values. Based on the results of the descriptive statistics analyses, analytical techniques were adjusted appropriately (discussed later, where relevant).

Question analysis

Inter-item Pearson correlations coefficients were calculated between questions to check for consistency of the construct as recommended by Spector (1992). Inter-item correlations were examined, and any low inter-item correlations of less than .30 were flagged as a potential question for removal (Spector, 1992).

Internal consistency

Cronbach's alpha is a common method used in psychometrics to provide a measure of the internal consistency, or evidence of the degree to which the assessment questions are measuring the same construct (Netemeyer et al., 2003). In this analysis, Cronbach's alpha was calculated (before questions were removed) to establish evidence of initial consistency. For newly developed scales, such as the REI, it is recommended that alpha values greater than .80 be used as a benchmark (Clark & Watson, 1995).

Exploratory Factor Analysis (EFA)

An EFA was conducted with a focus on providing evidence of the structural aspect of validity. The purpose of EFA is to reduce the data to a summary understanding by identifying the latent constructs (i.e., factors) that make up the larger measurement construct (Thompson, 2004). The EFA was conducted to identify assessment questions with common dimensionality (i.e., factors) and to understand the structure among the assessment questions (Fabrigar et al., 1999). Before conducting the EFA, the Kaiser-Meyer-Olkin (KMO) value was calculated to determine if the common variance among the assessment questions was adequate (Kaiser, 1974). Next, a parallel analysis was performed to determine how many factors to extract (Thompson, 2004). The parallel analysis utilized the EFA dataset to run a simulation where factors were extracted until the eigenvalues (i.e., the total amount of variance of the observed variables that a factor explains) of the EFA dataset are less than the corresponding eigenvalues of a randomly generated dataset where correlations among the variables are due to sampling error (Horn, 1965). A scree plot of eigenvalues vs. the number of factors to be extracted of both the simulated data and the EFA dataset was evaluated to determined how many factors to extract. Next, an initial EFA was conducted with the number of factors to extract based on the results of the parallel analysis. The factor rotation was set to an oblique promax rotation, which allows factors to be correlated, and was appropriate for educational research where some correlation between factors was expected (Fabrigar et al., 1999). A maximum likelihood (ML) estimation solution was utilized, as the results of the descriptive statistics indicated the scores were not normally distributed (Fabrigar et al., 1999). As recommended by Thompson (2004), both the pattern and structure coefficient were examined. Only assessment questions with a pattern coefficient (i.e., factor loadings) greater than .40 were retained as recommended by Costello and Osborne (2005) and Floyd and Widaman (1995). Also, pattern coefficients across assessment questions were examined (i.e., cross-loadings), and if an assessment question cross-loaded to another factor, it was removed (Fabrigar et al., 1999). Cronbach’s alpha was calculated to provide an initial internal consistency measure for each factor in the initial factor structure. After assessment questions were removed that had a pattern coefficients less than .40, the EFA was re-run with the remaining assessment questions to establish the structure of the remaining assessment questions, including the Cronbach’s alpha for each factor and an overall Cronbach’s alpha to establish the final internal consistency.

5.2 Results of Pilot Test 1

A total of 466 responses were collected from the Qualtrics survey emailed to 1988 engineering Ph.D. students from 07/08/2019 to 08/20/2019. The results that follow were completed in sequential order, and correspond to the description of the analyses provided in the previous section.

Data cleaning and removal

From the visual inspection of the initial raw data from the Qualtrics survey, the following data were manually discarded: 1) 7 of the 466 respondents declined to participate; 2) 190 of the 466 respondents did not complete 100% of the survey; 3) 13 of the 466 respondents incorrectly responded to the filter question. In total, 210 (7 + 190 + 13) responses were discarded, leaving a total of 236 (446 – 210) responses for analyses. All of the remaining 236 responses indicated that respondents had selected engineering as their discipline (i.e., major), and that all respondents were seeking a Ph.D. degree.

Data interpretation for 'Other'

The following written responses were changed in the demographic and self-report data, based on the rationale that it was obvious that the response should be one of the selected responses and not 'Other':

- For the self-report question Q1: Including yourself, approximately how many graduate student members are in your research group?, seven responses were changed; the response "~15", was changed to 15; the response "20ish", was changed to 20; the response "4 to 6" was changed to 5; the response "In the last year 0 others. Prior to that there were 4" was changed to 1; three responses were changed from 0 (which is not possible) to 1.
- For the self-report question Q2: How is your Ph.D. research group organized?, seven responses were changed; Six responses were changes from 'Other' to '(1) Research group is structured where the advisor sets most of the interactions, communication, and mentoring of students'; one response was changed from 'Other' to '(2) Research group is structured where much of the communication and mentoring is student-to-student, with the faculty advisor leading in a functional role'. An example of a changed response was "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'.

- For the self-report question Q3: How is your Ph.D. research work organized?, ten responses were changed; seven responses were changes from 'Other' to '(1) Most of the day-to-day work involves working by myself or with my advisor'; one response was changed from 'Other' to '(2) Most of the day-to-day work involves interaction with a broader team within the research group'. An example of a changed response was "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'.
- For the self-report question Q4: What is your engineering Ph.D. major?, one response was changed; the response 'Other –ECE & Statistics' was changed to '(7) ECE'.
- For the self-report question Q5: What type of Ph.D. research are you primarily working on?, two responses were changed; two responses were changes from 'Other' to '(2) Applied (research that has specific applications towards processes or products)'. An example of a changed response was "Applied social" was changed to '(2) Applied (research that has specific applications towards processes or products)'.
- For the self-report question Q6: What type of collaborators, either internal or external, do you work with primarily in your Ph.D. research?, eleven responses were changed; five responses were changes from 'Other' to '(1) A strong emphasis on government collaborations'; six response was changed from 'Other' to '(3) A strong emphasis on research center collaborations'. An example of a changed response was "National Labs" was changed to '(1) A strong emphasis on government collaborations'.
- For the self-report question Q7: What type of interactions do you have with the collaborators identified in the previous question?, five responses were changed; five responses were changes from 'Other' to '(1) Collaborations consist of infrequent contact, mostly written reports, resulting in a relationship with the collaborators that are not very deep'. An example of a changed response was "Collaboration consist 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'.

- For the self-report question Q9: How is the work space for your Ph.D. research group organized?, eight responses were changed; six responses were changes from 'Other' to '(1) Housed in a lab space or office where I work mostly alone or near a few others'; two response was changed from 'Other' to '(2) Housed in lab space or office that is shared with my research group only'. An example of a changed response was "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'.
- For the demographic question Q8: What is the primary source of funding for your Ph.D. research?, three responses were changed; two responses were changes from 'Other' to '(1) government (e.g., NSF, DOE, etc.)'; one response was changed from 'Other' to '(2) industry'. An example of a changed response was "Army, Navy and Air Force funded" was changed to '(1) government (e.g., NSF, DOE, etc.)'.
- For the demographic question Q9: Where do you see yourself working after graduation?, one response was changed; one response was changed from 'Other' to '(1) government'. The response "National Lab" was changed to '(1) government'.

Descriptive statistics and demographics

The descriptive statistics for the assessment questions for the 236 respondents are shown in Table C.1 in Appendix C. Eight of the twenty-nine assessment questions had elevated means (> 4.2 on a 6 point scale), the skewness ranged from −1.08 to 0.64, and kurtosis ranged from −1.34 to 2.35, indicating the data are not normally distributed, but met the respective thresholds of 3.0 and 10.0 established by Kline (2015) for EFA. The non-normality of the data was expected with the Likert-type scores used in the REI scale, which affects the type of analyses used in the EFA. Table C.2 in Appendix C shows the tabulated demographic information for the 236 respondents. Table C.3 and Table C.4, respectively, in Appendix C, show the tabulated self-report information for the 236 respondents. There were no noteworthy irregularities in the demographics or self-report information. Both data were utilized in the group analyses later in Chapter 7.

Question analysis

The inter-item correlation matrix, shown in Table C.5 in Appendix C, indicated that assessment questions Q4, Q14, and Q17 have correlation values less than .30 and are candidates for deletion. However, these assessment questions were included in the initial EFA for completeness.

Internal consistency

Cronbach's alpha was calculated as $\alpha = .90$ (before assessment question removal) to establish a measure of the initial internal consistency. This measure is greater than the recommended benchmark of .80 for new scale development (Clark & Watson, 1995).

EFA results

The Kaiser-Meyer-Olkin (KMO) value (.89) indicated that the common variance among the assessment questions was adequate (Kaiser, 1974). The results of the parallel analysis indicated that five factors should be extracted. This can also be seen in the results of the scree plot generated from the parallel analysis, shown in Figure 5.1. The scree plot shows a plot of eigenvalues vs. the number of factors to be extracted.

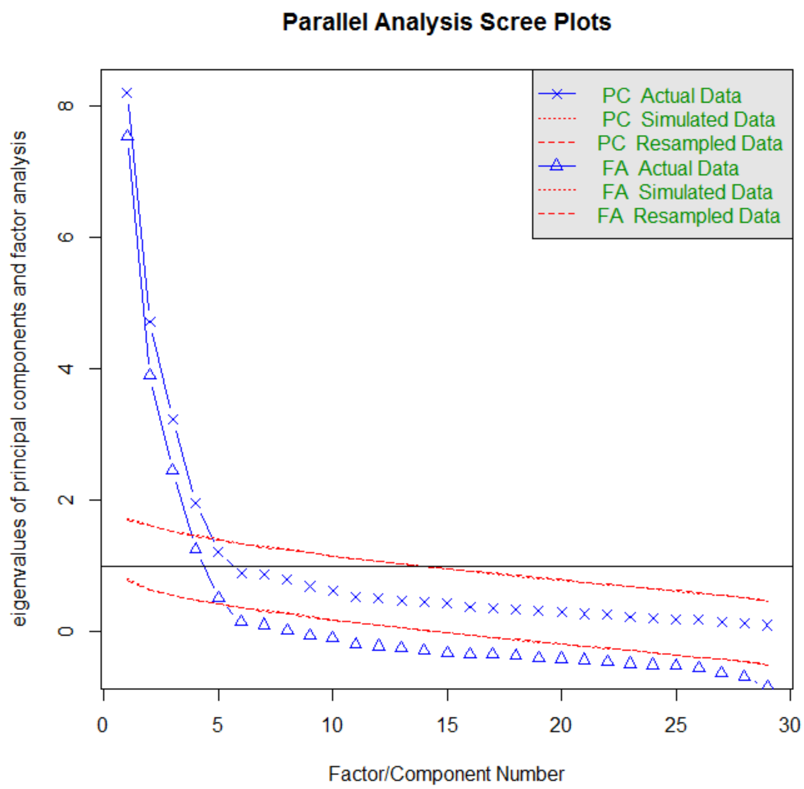

Figure 5.1: Scree Plot Summary from Parallel Analysis

Figure 5.1, as shown, indicates that the "parallel" plot (the red bottom line) intersects the factor analysis plot (FA Actual Data) at the point of 5 extracted factors, indicating again that five factors were to be extracted.

Table 5.1, shown below, summarizes the initial EFA results by indicating the factor structure before assessment question removal, the standardized pattern coefficients (i.e., factor loadings), and Cronbach's alpha for each factor. Pattern coefficients greater than .40 are in bold, coefficients less than .40, and that cross-load with other factors are indicated with a (*). Table C.6 in Appendix C summarizes the standardized structure coefficients, generated in SPSS version 26.

Table 5.1: *Initial Factor Structure (Pattern Coefficients and Cronbach's Alpha)*

Latent Construct	Assessment Questions	Standardized Pattern Coefficient F1	F2	F3	F4	F5
F1: Working as a team member (α = .84)	Q1: take on different roles or responsibilities within a research group	**.62**	.09	-.02	-.09	.12
	Q2: coordinate research tasks with other graduate students	**.91**	-.14	.12	-.02	-.05
	Q3: share decision making responsibility with other graduate students	**.87**	-.02	-.04	-.01	-.02
	Q4: develop new skills (e.g., presentation, project management, software, etc.) based on the needs of the research group's goals	.21*	.19	-.01	.20	.10
	Q5: mutually depend on other graduate students to meet the desired outcomes	**.88**	-.08	-.10	.06	-.05
F2: Exposure to collaborator's form of practice (α = .88)	Q6: present your research results to your sponsors or collaborators (i.e., practicing engineers) who are involved in your research	-.01	**.80**	-.04	.09	-.01
	Q7: interact at your university with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research	.06	**1.01**	-.32	-.05	.03
	Q8: correspond (e.g., email, phone, etc.) with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research	-.08	**.74**	.16	-.03	-.03
	Q9: interact with your sponsors or collaborators at their place of work related to your research	-.18	**.67**	.14	.02	.05
	Q10: co-author journal or conference papers with your sponsors or collaborators	-.11	**.64**	.22	-.09	-.10
	Q11: co-create a presentation with your sponsors or collaborators	.14	**.62**	.02	.04	-.01
F3: Exposure to relevant professional practice (α = .77)	Q12: develop professional relationships with practicing engineers (other than your sponsors or collaborators) through your research	-.03	.07	**.81**	-.10	.06
	Q13: participate in industry or government conferences as part of your research	-.01	.10	**.48**	.05	.05
	Q14: participate in professional engineering societies (e.g., Institute of Electrical and Electronics Engineers, Society of Women Engineers, etc.)	.21	.17	.20	-.14	-.10
	Q15: present results of your research to practicing engineers (other than your sponsors or collaborators)	-.12	.16	**.67**	.06	-.07

Table 5.1 continued

Latent Construct	Assessment Questions	Standardized Pattern Coefficient F1	F2	F3	F4	F5
	Q16: interact with practicing engineers during internships or co-ops	.07	-.04	**.54**	.13	-.04
	Q17: interact with support professionals (e.g., project managers, building maintenance, outside vendors, etc.)	.12	.03	.38*	-.01	.40*
F4: Modeling and simulation tasks (α = .90)	Q18: develop or utilize a mathematical model to help solve a problem	.05	-.09	.07	**.76**	-.10
	Q19: specify constraints or assumptions in development of a mathematical model to help solve a problem	-.06	.00	.04	**.87**	-.09
	Q20: utilize sophisticated tools to help solve a modeling or simulation problem	-.03	.15	-.09	**.76**	.04
	Q21: simulate a system to obtain results	.03	-.06	.02	**.72**	.00
	Q22: iterate on the development of a model or simulation to optimize results	-.05	-.03	.03	**.89**	-.08
	Q23: verify a model or simulation based on real-world data or actual results	.01	-.01	.04	**.67**	.10
F5: Practical skills (α = .95)	Q24: use testing equipment or instrumentation as an integral part of conducting your research	-.01	-.06	-.07	-.05	**.90**
	Q25: develop plans to use testing equipment or instrumentation	.00	.07	-.04	-.05	**.90**
	Q26: ensure testing equipment or instrumentation is appropriately set-up (i.e., calibrated) before use	-.04	-.06	.03	-.03	**.93**
	Q27: collect data from testing equipment or apparatus using appropriate sensors or instrumentation	-.03	-.01	-.07	.00	**.97**
	Q28: interpret data gathered from testing equipment or apparatus	.01	.03	.00	.07	**.79**
	Q29: troubleshoot or modify testing equipment or instrumentation when it does not operate properly	-.04	-.06	.10	-.06	**.86**

Based on the factor analysis in Table 5.1 above, the assessment questions Q4, Q14, and Q17 were removed. Table 5.2, shown below, provides a summary of the reasons these assessment questions were removed, with the justification. Q7 had a pattern coefficient of 1.01, which indicated a Heywood case (i.e., negative variance estimate) (Thompson, 2004), but Q7 was not removed because the pattern coefficient for Q7 was not an issue once Q4, Q14, and Q17 were removed in the subsequent analysis that followed.

Table 5.2: *Assessment Questions Removal Summary*

Assessment Question	Reason Removed	Construct Discussion
Q4: develop new skills (e.g., presentation, project management, software, etc.) based on the needs of the research group's goals	The pattern coefficient of .21 indicates it is too low to retain. The mean +/-SD of this question is 5.0 +/- 0.91, indicating most students score high on this question.	In hindsight, this is not a great question. Students are answering the first part (they developing new skills) but are not answering it related to doing it for their research team. If a question like this is to be asked in the future, it should be reworded. Since there were enough questions in this factor, this question was discarded.
Q14: participate in professional engineering societies (e.g., Institute of Electrical and Electronics Engineers, Society of Women Engineers, etc.)	The pattern coefficient of .20 indicates it is too low to retain.	This example appears to be too specific an example of professional practice experience. The other, more generic experiences performed much better. However, this experience (participating in professional engineering societies) is something important to capture, so it was moved to a self-report question.
Q17: interact with support professionals (e.g., project managers, building maintenance, outside vendors, etc.)	The pattern coefficient of .38 did not exceed the .40 threshold for retention. More importantly, this question cross-loads with factor 5 at .40.	Due to the cross-loading with Factor 5 (practical skills), the cross-loading is indicating that students who interact with support professionals are likely the ones working in testing environments, which makes sense. This question was removed, leaving four questions for factor 3.

After the removal of assessment questions Q4, Q14, and Q17, Cronbach's alpha was recalculated at $\alpha = .89$ to establish a final overall measure of the internal consistency. As with the initial measure, this value is greater than the recommended benchmark of .80 for new scale development (Clark & Watson, 1995).

The EFA results with assessment questions Q4, Q14, and Q17 removed are shown below in Table 5.3. Pattern coefficients greater than .40 are in bold. Table C.7 in Appendix C summarizes the structure coefficients, generated in SPSS version 26.

Table 5.3: *Factor Structure after Assessment Questions Removal (Pattern Coefficients and Cronbach's Alpha)*

Latent Construct	Assessment Question	Standardized Pattern Coefficient F1	F2	F3	F4	F5
F1: Working as a team member (α = .87)	Q1: take on different roles or responsibilities within a research group	**.60**	.12	.00	-.08	.12
	Q2: coordinate research tasks with other graduate students	**.86**	-.08	.15	-.02	-.05
	Q3: share decision making responsibility with other graduate students	**.83**	.03	-.01	-.01	-.02
	Q5: mutually depend on other graduate students to meet the desired outcomes	**.84**	-.04	-.05	.06	-.04
F2: Exposure to collaborator's form of practice (α = .88)	Q6: present your research results to your sponsors or collaborators (i.e., practicing engineers) who are involved in your research	.03	**.79**	-.04	.10	-.01
	Q7: interact at your university with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research	.08	**.97**	-.29	-.03	.02
	Q8: correspond (e.g., email, phone, etc.) with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research	-.03	**.73**	.15	-.03	-.03
	Q9: interact with your sponsors or collaborators at their place of work related to your research	-.14	**.65**	.13	.02	.05
	Q10: co-author journal or conference papers with your sponsors or collaborators	-.07	**.61**	.23	-.10	-.10
	Q11: co-create a presentation with your sponsors or collaborators	.16	**.59**	.06	.04	.00
F3: Exposure to relevant professional practice (α = .77)	Q12: develop professional relationships with practicing engineers (other than your sponsors or collaborators) through your research	.01	.10	**.77**	-.14	.07
	Q13: participate in industry or government conferences as part of your research	.02	.11	**.47**	.03	.06
	Q15: present results of your research to practicing engineers (other than your sponsors or collaborators)	-.07	.18	**.65**	.02	-.05
	Q16: interact with practicing engineers during internships or co-ops	.09	-.04	**.55**	.10	-.02
F4: Modeling and simulation tasks (α = .90)	Q18: develop or utilize a mathematical model to help solve a problem	.05	-.09	.07	**.76**	-.08
	Q19: specify constraints or assumptions in development of a mathematical model to help solve a problem	.06	.00	.02	**.87**	-.07

Table 5.3 continued

Latent Construct	Assessment Question	Standardized Pattern Coefficient F1	F2	F3	F4	F5
	Q20: utilize sophisticated tools to help solve a modeling or simulation problem	-.02	.16	-.11	**.77**	.05
	Q21: simulate a system to obtain results	.03	-.04	.01	**.72**	.01
	Q22: iterate on the development of a model or simulation to optimize results	-.05	-.01	.00	**.90**	-.05
	Q23: verify a model or simulation based on real-world data or actual results	.02	.00	.04	**.67**	.12
F5: Practical skills (α = .95)	Q24: use testing equipment or instrumentation as an integral part of conducting your research	.00	-.06	-.04	-.03	**.88**
	Q25: develop plans to use testing equipment or instrumentation	.02	.08	-.03	-.02	**.89**
	Q26: ensure testing equipment or instrumentation is appropriately set-up (i.e., calibrated) before use	-.03	-.05	.04	-.01	**.92**
	Q27: collect data from testing equipment or apparatus using appropriate sensors or instrumentation	-.02	.00	-.06	.02	**.96**
	Q28: interpret data gathered from testing equipment or apparatus	.02	.03	.03	.09	**.79**
	Q29: troubleshoot or modify testing equipment or instrumentation when it does not operate properly	-.02	-.05	.11	-.04	**.85**

Figure 5.2 and Table 5.4 below shows a summary of the factor structure with Q4, Q14, and Q17 removed, including the correlations among the factors.

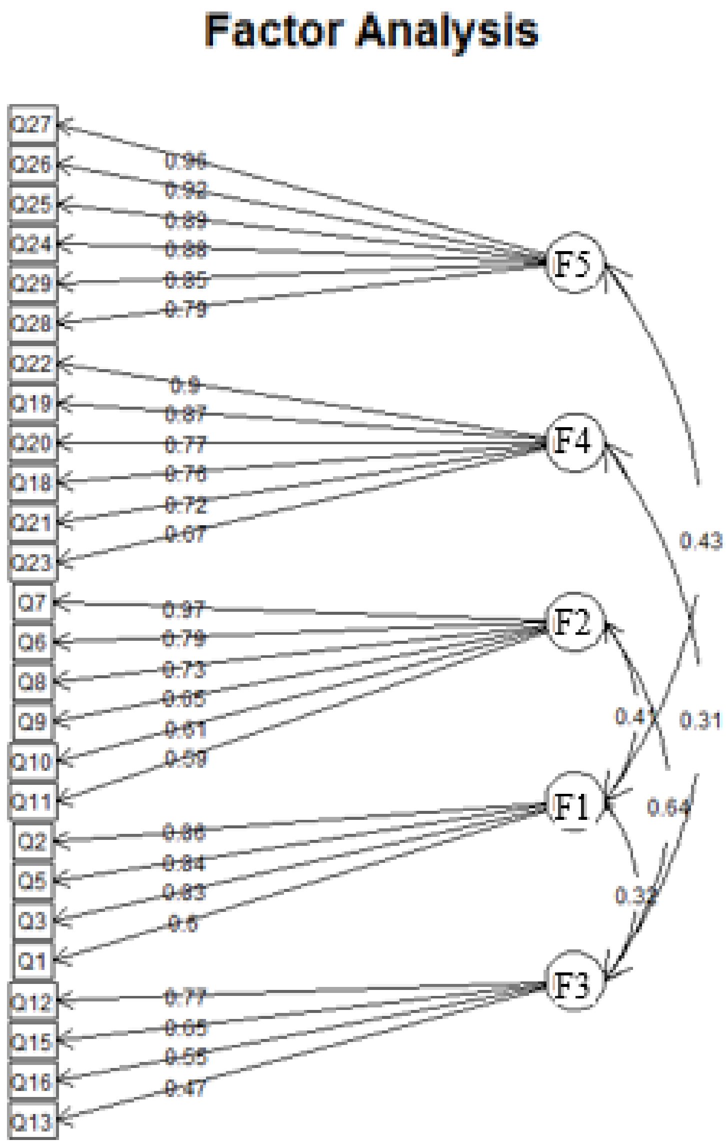

Figure 5.2: Final EFA Factor Solution (5- Factors)

Table 5.4: *Factor Correlations (Standardized)*

	F1	F2	F3	F4	F5
F1	1.00				
F2	.41	1.00			
F3	.32	.64	1.00		
F4	.03	.18	.31	1.00	
F5	.43	.28	.21	-.02	1.00

A 4-factor solution was also checked against a 5-factor solution due to the high correlation that F3 has with F2 (.64). The 4-factor solution does load with assessment questions Q6-Q16 loading into one factor with all pattern coefficients greater than .40. However, the model fit statistics (shown in Table 5.5) indicate that the 5-factor solution is a statistically better fit by both the Tucker Lewis Index (TLI) and the root mean square error of approximation (RMSEA).

Table 5.5: *Model Fit Comparison between 4-Factor and 5-Factor Solution*

Model Fit Statistic	4-Factor Solution	5-Factor Solution	Criteria
Tucker Lewis Index (TLI)	.913	. 944	Rule-of-thumb is that models with TLI > .95 fit the data well (Hu & Bentler, 1999)
Root mean square error of approximation (RMSEA)	.069	.057	Rule-of-thumb is that models with RMSEA ≤ .06 fit the data well (Hu & Bentler, 1999)

5.3 Summary of Validity Evidence of Pilot Test 1

The primary purpose of the Pilot Test 1 phase was to conduct a pilot test of the REI to collect enough data to provide evidence of the internal consistency and structural aspect of validity. As such, Table 5.6 shows a summary of the validity evidence collected in Pilot Test 1.

Table 5.6*: Summary of Validity Evidence Collected in Pilot Test 1*

Aspect of Validity	Types of Questions Asked	Evidence Collected	Result
Internal consistency (reliability)	What is the degree to which the assessment questions are measuring the same construct?	Initial Cronbach's alpha	$\alpha = .90$
		Final Cronbach's alpha	$\alpha = .89$ Both exceed the benchmark of .80
Structural	Is the internal structure of the instrument congruent with the structure of the construct domain?	Question analysis	Inter-item correlations indicated Q4, Q14, and Q17 were below .30
		Initial EFA	Q4, Q14, and Q17 were removed based on the pattern coefficient values being below .40
		Final EFA	Results indicated the 5-factor structure that corresponds to the theoretical structure proposed in Chapter 2.

6. INSTRUMENT VALIDATION – PILOT TEST 2

The primary purpose of the Instrument Validation – Pilot Test 2 phase was to collect additional data to provide evidence of the internal consistency and structural aspect of validity. Recall that internal consistency was assessed in Chapter 5, and refers to the extent to which the assessment questions are measuring the same latent construct and have common variance, demonstrating reliability (Netemeyer et al., 2003). Also, recall that the structural aspect of validity was assessed in Chapter 5 and refers to the extent to which the assessment questions and latent constructs form factor structures that are is in alignment with the theoretical structures (Messick, 1995). The purpose of this Chapter was accomplished by following the overall recommendations by Netemeyer et al. (2003) focused on confirming the theoretical factor structure of the REI instrument. This process involved specifically testing how well (or not) the data fit the theoretical factor structure detailed in Chapter 2, and iterating on the factor structure to find a better fit (Netemeyer et al., 2003). As one of the main objectives of the pilot test was to perform a Confirmatory Factor Analysis (CFA) to evaluate the REI factor structure as described, a minimum sample size of 200 was targeted (Floyd & Widaman, 1995); Netemeyer et al. (2003).

6.1 Methods of Pilot Test 2

6.1.1 Procedure and Participants

The REI assessment was modified based on the results from Chapter 5 – Pilot 1 Test and to capture additional demographic information. As summarized previously in Table 5.2 from the Pilot 1 test results, Q4 and Q17 were removed due to poor performance in the EFA, and Q14 was moved to the self-report questions. For the Pilot Test 2, two demographic questions were added to the REI to ask participants about their University name and location, as the Pilot Test 2 was intended to be a national survey with participation from multiple institutions (more details about participants below). Table 6.1 below details the two questions added to the REI assessment for Pilot Test 2.

Table 6.1*: Summary of Additions to Assessment for Pilot Test 2*

#	New Assessment Questions
1	Please indicate the name of your university (e.g., Example University): response is text enter
2	Please indicate the location of your university (city, state, country): response is text enter

The updated assessment (Appendix D) was put into an online electronic form using Qualtrics (2019) (an online survey tool) so that a survey link was provided to the research participants. Assessment questions 1 through 27 were entered in random order in Qualtrics so that the aspects would not be presented to respondents in order, while the self-assessment questions and demographic questions were kept in order. As with the Pilot Test 1, the same filter question was added to the 27 assessment questions that asked a respondent to "if you are taking this survey, please select the response 'Never' for this question" to identify respondents who were not paying attention to the questions. An additional filter question was added that asked, "Do you think you have taken this survey previously?", with options of 'yes', 'no', and 'other – explain' to check if respondents had previously taken the survey before.

Potential respondents consisted of a convenience sample of engineering Ph.D. students that were accessed through four ASEE listservs and generic private listservs at doctoral-granting U.S. universities and professional societies. Purdue IRB approval was received to utilize the four ASEE listservs (see Appendix D) and the generic private listservs at doctoral-granting U.S. universities and professional societies (see Appendix D). The listserv owners were contacted and requested that the owner sends out an IRB approved email (see Appendix D) seeking participants in the study, which contained a link to the Qualtrics survey. Listserv participants who were contacted and agreed to participate included the ASEE Educational Research and Methods (ERM) division; the ASEE Graduate Studies division; the ASEE Indiana/Illinois section; the ASEE Student Division; the engineering department at the University of Michigan; the engineering department at The Ohio State University; the engineering department at the University of Illinois at Urbana Champaign; The Qualtrics survey was open from 10/15/2019 to 1/13/2020 for students to respond. Students who chose to participate in the study first had to click on the Qualtrics link in the recruitment email. On the opening screen in Qualtrics, a link was provided to the Information Sheet (see Appendix

C) for potential participants to review, and next they had to click ‘Agree’ to the question “I agree to be part of this study”. If a potential participant chose ‘Disagree’, the survey ended.

6.1.2 Analyses

Once data were collected from the online Qualtrics survey, several analyses were performed. All analyses (unless otherwise noted) were performed in MPlus v8.4, which was the latest version of MPlus at the time analyses were conducted. The following analyses, as described, were processed in sequential order, with an explanation of why and how the analyses were completed.

Data cleaning and removal

This procedure is the same as was utilized in Pilot Test 1. The initial raw data from the Qualtrics survey was evaluated and cleaned to check for missing and incomplete data so it could be removed before further analyses. While incomplete was considered for use, the number of incomplete responses was small (less than 2.0%), therefore the incomplete data was removed per the procedure below. The evaluation and cleaning of data were accomplished by visual inspection and manipulation in Excel 2016. A row of data represented an individual respondent’s data, and each row was individually evaluated to determine if the data were retained or discarded. A row of data were discarded if: 1) the respondent declined to participate in the study by selecting ‘disagree’ to be part of the study; 2) the respondent did not complete 100% of the survey; 3) the respondent did not answer the filter question correctly, by selecting ‘Never’ to the question “if you are taking this survey, please select the response 'Never’ for this question”; 4) the respondent had taken the survey before. The remaining data were checked to ensure that all respondents were engineering students, that all respondents were seeking a Ph.D. degree, and that all respondents were at U.S. based Universities.

Data interpretation for ‘Other’

This procedure is the same as was utilized in Pilot Test 1. After removing selected data, the remaining responses for the demographic and self-report data were checked for responses that indicated ‘Other’ rather one of the selected responses. If a response was ‘Other’ and the written response was obvious that it should be one of the selected responses, the response was changed to the appropriate selected response for that question.

Descriptive statistics and demographics

This procedure is the same as was utilized in Pilot Test 1. After cleaning the data, means, medians, standard deviations, and normality of scores were calculated to check for abnormalities in the data, such as elevated means or non-normality. Next, frequencies of demographic data and self-report data were tabulated to check for irregularities, such as unexpected values. Based on the results of the descriptive statistics analyses, analytical techniques were adjusted appropriately (discussed later, where relevant).

Internal consistency

This procedure is the same as was utilized in Pilot 1 testing. Cronbach's alpha was calculated to establish evidence of initial consistency prior to conducting the CFA. For newly developed scales, such as the REI, it is recommended that alpha values greater than .80 be used as a benchmark (Clark & Watson, 1995).

Confirmatory Factor Analysis (CFA)

A CFA was conducted with a focus on providing additional evidence of the structural aspect of validity, beyond the similar evidence provided by the EFA performed in Pilot Test 1. Whereas the purpose of the EFA was to examine what factors were present in the Pilot Test 1 data, the purpose of the CFA was to examine if the data collected in Pilot Test 2 fit the theoretical model of the factor structure for the REI (Thompson, 2004). In conducting the CFA, the sequence of steps recommended by Brown (2015) was followed. These steps focused on 1) establish a first-order solution that provided a good fit and was valid to the theoretical model; 2) evaluate the correlations among the factors in the first-order solution; 3) theoretically and empirically fit the second-order model. For the purposes of the REI, the first-order model was intended to provide evidence of the theoretical factor structure, whereas the second-order model was intended to provide evidence that the first-order factors came together into one second-order latent factor, used later as an overall factor score when evaluating scores from the REI (discussed more in Chapter 7).

As Thompson (2004) explained, CFA should also include the testing of alternate models, therefore, as part of step 1 and step 3 above, alternate models were tested for fit for both the first-order and second-order models. One of the reasons MPlus was utilized to perform the CFA was the availability of a maximum likelihood (MLM) parameter estimates with standard errors and a mean-adjusted chi-square test statistic for the model fit that are robust to non-normality (Byrne, 2011). The MLM option in MPlus was utilized as the results of the descriptive statistics indicated the scores were not normally distributed (more details provided in the Results section). As MPlus outputs only pattern coefficients for factor loadings, only the standardized pattern coefficients were examined to evaluate factor loadings. Only assessment questions with a pattern coefficient greater than .40 were retained as recommended by Floyd and Widaman (1995). For every model that was evaluated in this process, MPlus generated called an output called "modification indices" that indicated potential misfitting parameters in the model, such as if an assessment question cross-loaded to another factor, if a covariance between residuals would improve fit, etc. This MPlus "modification indices" output was utilized to check for potential model fit improvements for each model.

As per by Brown (2015), a first-order solution was established by comparing the theoretical REI model to three alternate models using goodness-of-fit indices explained in the next section. The first-order solution was also compared to an "unstructured reference" model, as explained in the next section. Next, correlations among the factors in the first-order solutions were examined. Finally, a second-order solution was established that was theoretically and empirically consistent by comparing two second-order models using the same goodness-of-fit indices described below.

CFA model goodness-of-fit indices

In order to holistically evaluate the fit of the various models in the CFA across several different criteria, three categories of goodness-of-fit indices were utilized, per Brown (2015): 1) absolute, 2) comparative, and 3) parsimony. Brown (2015) also recommends using at least one index from each category when evaluating and reporting goodness-of-fit, and where possible, two for each category were reported in this study. Each of the three categories is briefly explained, along with the selected fit indices utilized in this study and "rules of thumb" for evaluation as recommended per Byrne (2011).

First, absolute fit indices assess the extent that the model being evaluated fits the sample data (Byrne, 2011). The first fit index used to evaluate the absolute fit was the commonly used chi-square statistic (χ^2), along with evaluating chi-square divided by the degrees of freedom (χ^2 / *df*), which provides a better overall indication of fit (lower χ^2 / *df* is better) due to χ^2 sensitivity to sample size (Byrne, 2011). The second fit index used to evaluate the absolute fit was the standardized root mean square residual fit index (SRMR). The SRMR indicates the difference between the measured and expected covariances, with good fitting models having a value of less than .05.

Second, comparative fit indices assess the extent that one model compares to another model, often a baseline model referred to as the "null" or "unstructured reference" model where there is no structure at all between the inputs (Brown, 2015). The first fit index used to evaluate the comparative fit was the comparative fit index (CFI). The CFI indicates a normalized measure of the proportion of incremental improvement of the fit of the theoretical model to the "unstructured reference" model, ranging from 0 to 1, where a value of above .95 is considered an excellent fit (Byrne, 2011). The second fit index used to evaluate the comparative fit was the Tucker-Lewis fit index (TLI). As with the CFI, the TLI indicates a measure of the proportion of incremental improvement of the fit of the theoretical model to the "unstructured reference" model, but the TLI is non-normalized, and the range can extend above 1 (Byrne, 2011). As with the CFI, TLI values above .95 are considered an excellent fit (Byrne, 2011).

Third, parsimony fit indices assess the extent of the model fit to the data as well as the extent of the complexity of the model and penalize overly complex models (Byrne, 2011). The first fit index used to evaluate the parsimony fit was the root mean square error of approximation (RMSEA) fit index. The RMSEA evaluates model fit and complexity by evaluating the discrepancy between how well the model would fit the population covariance matrix, and is sensitive to model complexity because it takes into account the degree of freedom (Byrne, 2011). As recommend per Byrne (2011), RMSEA value less than .05 indicates a good fit, between .05 to .08 indicates a reasonable fit, and above .08 indicate a poor fit, including 90% confidence intervals are reported. The second fit index used to evaluate the parsimony fit was the Bayesian information criterion (BIC). The BIC provides an indication of model parsimony by calculating an index based on the model fit and degrees of freedom (Byrne, 2011). This index then allows for comparison between models as to which model is more parsimonious, as indicated by the lower BIC value (Byrne, 2011).

6.2 Results of Pilot Test 2

A total of 439 responses were collected from the Qualtrics survey administered to an unknown number of engineering Ph.D. students from 10/15/2019 to 1/13/2020. The results that follow were completed in sequential order, and correspond to the description of the analyses provided in the previous section.

Data cleaning and removal

From the visual inspection of the initial raw data from the Qualtrics survey, the following data were manually discarded: 1) 4 of the 439 respondents declined to participate; 2) 214 of the 439 respondents did not complete 100% of the survey; 3) 3 of the 439 respondents incorrectly responded to the filter question; 4) 1 of the 439 respondents indicated they might have taken the survey before. In addition, 1 of the 439 respondents indicated they were a master's student, and 1 of the 439 respondents indicated they were not an engineering student. Both of these responses were removed. In total, 224 (4 + 214 + 3 + 1 + 1 + 1) responses were discarded, leaving a total of 215 (439 – 224) responses for analyses.

Data interpretation for 'Other'

The following written responses were changed in the demographic and self-report data based on the rationale that it was obvious that the response should be one of the selected responses and not 'Other':

- For the self-report question Q1: Including yourself, approximately how many graduate student members are in your research group?, seven responses were changed; the response "~15-20", was changed to 17; the response "2 but I also mentor 3 teams and 1 undergrad students", was changed to 2; five responses were changed from 0 (which is not possible) to 1.
- For the self-report question Q2: How is your Ph.D. research group organized?, five responses were changed; Four responses were changes from 'Other' to '(1) Research group

is structured where the advisor sets most of the interactions, communication, and mentoring of students'; one response was changed from 'Other' to '(2) Research group is structured where much of the communication and mentoring is student-to-student, with the faculty advisor leading in a functional role'. An example of a changed response was "there is just me and the advisor" was changed to '(1) Research group is structured where the advisor sets most of the interactions, communication, and mentoring of students'.

- For the self-report question Q3: How is your Ph.D. research work organized?, four responses were changed; Four responses were changes from 'Other' to '(1) Most of the day-to-day work involves working by myself or with my advisor'. An example of a changed response was "most of the day-to-day work involves working by myself or with another individual in the research group" was changed to '(1) Most of the day-to-day work involves working by myself or with my advisor'.
- For the self-report question Q4: What is your engineering Ph.D. major?, two responses were changed; the response '(14) Other - Aerospace' was changed to '(1) Aeronautics and Astronautics'; the response '(14) Other - Civil and Construction Engineering' was changed to '(5) Civil'.
- For the self-report question Q5: What type of Ph.D. research are you primarily working on?, two responses were changed; two responses were changes from 'Other' to '(1) Basic (fundamental research without specific applications towards processes or products in mind)'. An example of a changed response was "Purely computational and theoretical" was changed to '(1) Basic (fundamental research without specific applications towards processes or products in mind)'.
- For the self-report question Q6: What type of collaborators, either internal or external, do you work with primarily in your Ph.D. research?, six responses were changed; three responses were changes from 'Other' to '(1) A strong emphasis on government collaborations'; one response was changed from 'Other' to '(2) A strong emphasis on industry collaborations'; two responses were changed from 'Other' to '(3) A strong emphasis on research center collaborations'. An example of a changed response was "we mostly do government work but work with a lot of defense contractors as well" was changed to '(1) A strong emphasis on government collaborations'.

- For the self-report question Q7: What type of interactions do you have with the collaborators identified in the previous question?, three responses were changed; two responses were changes from ‘Other’ to ‘(1) Collaborations consist of infrequent contact, mostly written reports, resulting in a relationship with the collaborators that are not very deep’; one response was changed from ‘Other’ to ‘(2) Collaborations consist of frequent contact, including email and face-to-face interaction for reporting results, resulting in a deep relationship with the collaborators’. An example of a changed response was “communication with the member who is in industry is rarely through email and skype” was changed to ‘(1) Collaborations consist of infrequent contact, mostly written reports, resulting in a relationship with the collaborators that are not very deep’.
- For the self-report question Q8: What type of equipment do you primarily use to conduct your Ph.D. research?, one response was changed; one response was changed from ‘Other’ to ‘(1) The primary nature of the research work relies on modeling and simulation with sophisticated computer equipment and software tools’. The 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’.
- For the demographic question Q5: Please indicate the name of your university? This was a text enter question, and many respondents occasionally entered misspelled or partial names of their university, such as “Michigan Tech”. All University names were changed to the official name as needed for demographic purposes.
- For the demographic question Q10: What is the primary source of funding for your Ph.D. research?, five response was changed; five responses were changed from ‘Other’ to ‘(1) government (e.g., NSF, DOE, etc.)’. An example of a changed response was “My country government” was changed to ‘(1) government (e.g., NSF, DOE, etc.)’.

Descriptive statistics and demographics

The descriptive statistics for the assessment questions for the 215 respondents are shown in Table D.1 in Appendix D. Eight of the twenty-six assessment questions had elevated means (>4.2 on a 6 point scale), the skewness ranged from −1.32 to 0.62, and kurtosis ranged from −1.27

to 0.54, indicating the data were not normally distributed, but met the respective thresholds of 3.0 and 10.0 established by Kline (2015) for CFA. The non-normality of the data again was expected with the Likert-type scores used in the REI scale, which affected the type of analyses used in the CFA. Table D.2 in Appendix D shows the tabulated demographic information for the 215 respondents. Table D.3 and Table D.4, respectively, in Appendix D, show the tabulated self-report information for the 215 respondents, and Table D.5 in Appendix D shows the tabulated information for the respondent's University. There were no noteworthy irregularities in the demographics or self-report information. Both data were utilized in group analyses utilized later in Chapter 7.

Internal consistency

Cronbach's alpha was calculated as α = .88 prior to the CFA in order to establish a measure of the initial internal consistency. This measure is greater than the recommended benchmark of .80 for new scale development (Clark & Watson, 1995).

CFA results

Prior to conducting the CFA, inter-item correlations were checked to ensure that 26 assessment questions correlated correctly with the theoretical factor structure. All questions correlated as expected, so no assessment questions were removed prior to the CFA analysis.
To establish a baseline reference, the first CFA model fit that was evaluated was the "unstructured reference" model for a baseline comparison for other models, referred to as Solution 1. See Table 6.2 for a summary of all model fit comparisons, including Solution 1. Note that a CFI and TFI value was not produced for the "unstructured reference" Solution 1 model, and the fit was very poor for the Solution 1 model, as expected.

To establish a first-order solution, the next CFA model fit evaluated was the original theoretical model, referred to as Solution 2. This was the second CFA model fit that was evaluated and produced standardized pattern coefficients in acceptable ranges (.53 to .93) for all assessment questions, as shown in Table 6.1, and a good overall fit across all fit indices (see Table 6.2). The MPlus "modification indices" for Solution 2 indicated that the parameters most likely to improve the fit would be to allow the residuals for Q22 and Q21 to co-vary in the model. This suggestion

(Q22 and Q21 residuals to co-vary) was the third CFA model fit that was evaluated, referred to as Solution 3. Solution 3 altered the standardized pattern coefficients compared to Solution 2 by at most .01 across the range, and only marginally improved the fit (see Table 6.2 for Solution 3). The fourth CFA model fit evaluated was the original theoretical model again, but with the assumption that the data were categorical rather than continuous, referred to as Solution 4. Recall that while the collected Likert-type data were categorical, the data were treated as continuous because it was useful to do so to make sense of the data. However, it was possible the model fit may be improved by evaluating the data as categorical rather than continuous (Byrne, 2011). As can be seen from Table 6.2 for Solution 4, that is indeed the case, as the fit was improved, especially for CFI and TLI. In addition, Solution 4 improved standardized pattern coefficients across the range (.62 to .96).

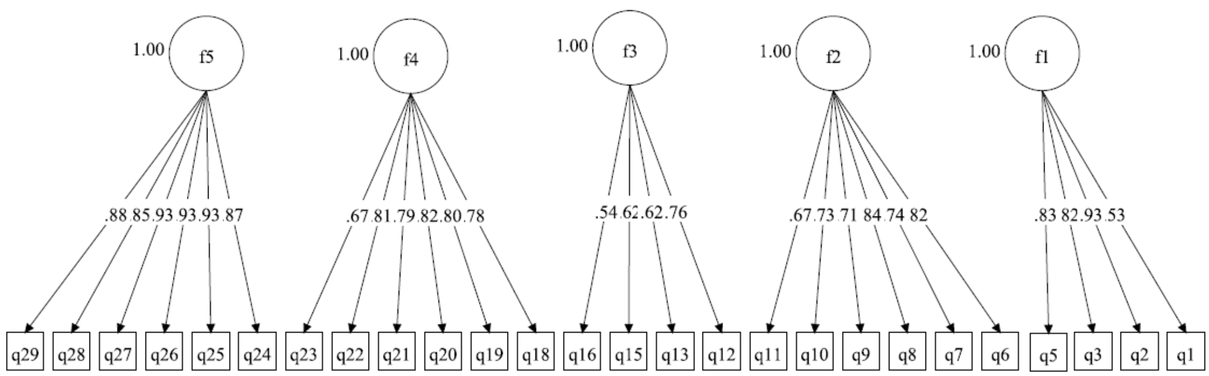

Figure 6.1: Solution 2 – Original Theoretical CFA Model for the REI with 5-Factors

Table 6.2: *CFA Goodness-of-Fit Comparison*

	Absolute Fit				Comparative Fit		Parsimony Fit	
Model	χ^2	*df*	χ^2 / *df*	SRMR	CFI	TLI	RMSEA 90% CI	BIC
NULL								
Solution 1 - Unstructured reference	3,782.2*	325	11.64	.29	**	**	.222 (.216, .229)	21,561
1st-order								
Solution 2 - Original - Theory	502.7*	289	1.74	.06	.94	.93	.059 (.050, .067)	18,136
Solution 3 - Q22-21 residuals co-vary	474.4*	288	1.65	.06	.95	.94	.055 (.046, .064)	18,110
Solution 4 - Original – Theory (Categorical)	503.9*	289	1.74	.06	.98	.98	.059 (.050, .067)	N/A
2nd-order								
Solution 5 – variance of 2nd-order fixed to 1.0	593.2*	295	2.01	.22	.91	.91	.069 (.061, .077)	18,206
Solution 6 - F2-F3 correlated; Residuals for F2-F3-F4 constrained equal	528.0*	295	1.79	.08	.93	.93	.061 (.052, .069)	18,128

*p < .001 (** not meaningful for the reference model)
SRMR = Standardized root mean square residual fit index; CFI = Comparative fit index;
TLI = Tucker-Lewis fit index, RMSEA = Root mean square error of approximation fit index;
BIC = Bayesian information criterion.

Solution 2 (the original theoretical model, continuous data) was selected as the first-order solution as it provided an overall good fit that is more parsimonious than Solution 3. In addition, Solution 4 further justifies using the original theoretical model, as it fits well across all fit indices. A further word of caution comes from MacCallum, Roznowski, and Necowitz (1992), who indicate that "when an initial model fits well, it is probably unwise to modify it to achieve even better fit because modifications may simply be fitting small idiosyncratic characteristics of the sample" from (1992, p. 501).

Next, the correlations among the factors in the first-order solution (Solution 2 - original theoretical model) were evaluated, as shown in Table 6.3 below. Two items to note in the correlations among the factors were the similar pattern of correlations among the factors found in the EFA (see Table 5.4) and the strong positive correlation between F2 (Exposure to collaborator's form of practice) and F3 (Exposure to relevant professional practice). This strong correlation between F2 and F3 was not surprising, as both factors were related to students working with collaborators (F2 to internal collaborators, F3 to external collaborators).

Table 6.3: *Factor Correlations (Standardized) for Solution 2*

	F1	F2	F3	F4	F5
F1	1.00				
F2	.21	1.00			
F3	.22	.82	1.00		
F4	.01	.20	.38	1.00	
F5	.28	.17	.20	-.07	1.00

Finally, in establishing a second-order solution for the REI, the second-order factor was understood to be the overall extent that the research experiences contributed to opportunities for students to practice being a professional (see Figure 1.1: Overview of Purpose of the Study in Chapter 1). This understanding fits the purpose of the REI and the theory established in Chapters 1 and 2. The next CFA model fit that evaluated was a simple second-order model where the variance of the second-order factor was fixed to 1.0, referred to as Solution 5. Solution 5 was the most parsimonious second-order factor to evaluate, as this solution allowed the five factors to freely correlate (rather than force correlations among the factors), and utilized the common practice of setting the second-order factor variance to 1.0 for standardization (Brown, 2015; Byrne, 2011). However, it was not expected that this solution would produce a better fit than the first-order model, as a second-order solution "cannot improve goodness-of-fit relative to the first-order solution where the factors are freely intercorrelated" (Brown, 2015, p. 332). This solution produced standardized factor loading for F1 through F5 ranging from .28 to .97, and standardized pattern coefficients for all assessment questions in the range of .59 to .96, as shown in Figure 6.2 and Table 6.4. As expected, the overall fit for this solution across all fit indices (see Table 6.2) was not as good as the Solution 2 (first-order original theory solution), but the fit was still acceptable.

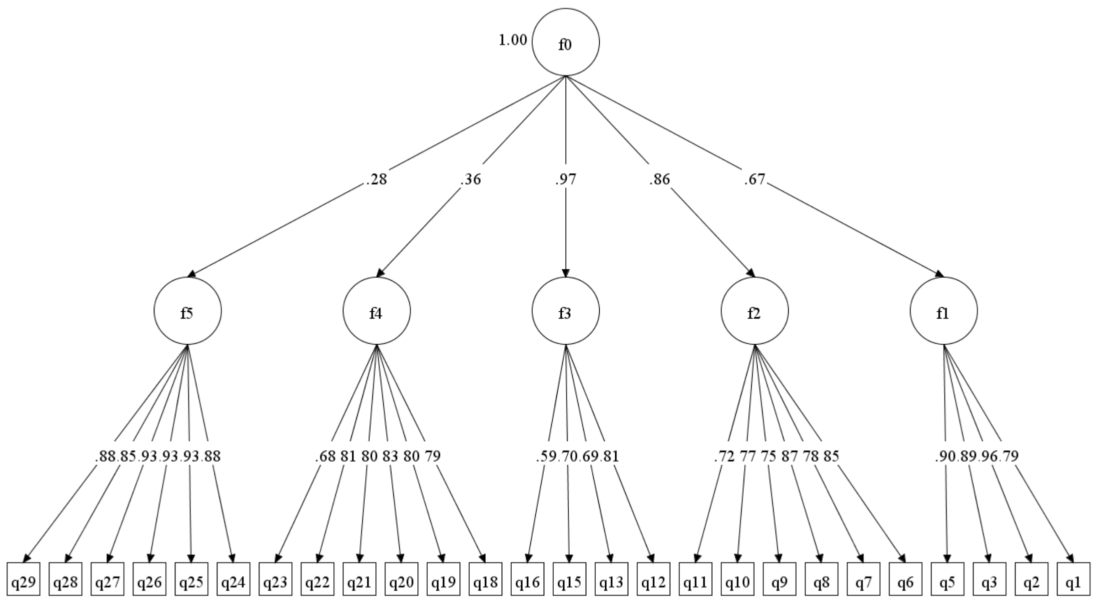

Figure 6.2: Solution 5 – Second-Order CFA Model for the REI with 5-Factors

Table 6.4: *Summary of Factor Loading for Solution 5 – Second-Order Model*

Factors	# of assessment questions	Factor Std. pattern coefficient	Range of std. assessment pattern coefficients
F1: Working as a team member	4	.67	.79 - .96
F2: Exposure to collaborator's form of practice	6	.86	.72 - .87
F3: Exposure to relevant professional practice	4	.97	.59 - .81
F4: Modeling and simulation tasks	6	.36	.68 - .83
F5: Practical skills	6	.28	.86 - .93

Various alternate second-order solutions were examined, and one of the better fitting solutions was to constrain factors F2 and F3 to be correlated (as there was a strong correlation seen in the data, see Table 6.3), and to constrain the residuals for F2, F3, and F4 to be equal, as that was observed in the data for Solution 2 (original theoretical model). This solution (F2-F3 correlated, F2, F3, F4 residuals constrained equal) was evaluated and referred to as Solution 6 in Table 6.2. Compared to Solution 5, Solution 6 decreased the standardized factor loading for F1 through F5, ranging from .11 to .56, and decreased the standardized pattern coefficients slightly for all assessment questions in the range of .53 to .94. However, this solution provided for better overall fit across the fit indices, approaching the well-fitting structure of the chosen first-order solution Solution 2.

Solution 5 (second-order factor variance set to 1.0, no correlation between factors) was selected as the second-order solution as it provided reasonable overall goodness-of-fit, and it was more parsimonious than Solution 6. As the goal of the second-order CFA was to evaluate if the first-order factors came together into one latent factor, this is evidenced by the maintenance of the overall goodness-of-fit of the second-order solutions.

6.3 Summary of Validity Evidence of Pilot Test 2

The primary purpose of the Instrument Validation – Pilot Test 2 phase was to collect additional data to provide evidence of the internal consistency and structural aspect of validity. As such, Table 6.5 shows a summary of the validity evidence collected in Pilot Test 2.

Table 6.5: *Summary of Validity Evidence Collected in Pilot Test 2*

Aspect of Validity	Types of Questions Asked	Evidence Collected	Result
Internal consistency (reliability)	What is the degree to which the assessment questions are measuring the same construct?	Cronbach's alpha	$\alpha = .88$ Exceeds the benchmark of .80
Structural	Is the internal structure of the instrument congruent with the structure of the construct domain?	First-order CFA model established	Results indicated the established first-order model supports the 5-factor structure that corresponds to the theoretical structure proposed in Chapter 2. All pattern coefficients values are in the acceptable range and goodness-of-fit indices that an acceptable fit.
		Second-order CFA model established	Results indicated established second-order model supports the theoretical second-order latent factor and the 5-factor structure that corresponds to the theoretical structure proposed in Chapter 2. Goodness-of-fit indices indicate an acceptable fit.

7. INSTRUMENT SCORING AND GROUP ANALYSIS

There were two primary purposes of the Instrument Scoring and Group Analysis phase, in support of the overall purpose and the Research Questions of this study. The first purpose of the Instrument Scoring and Group Analysis phase was to provide evidence of the external and generalizability aspects of validity. The external aspect of validity refers to the extent that assessment scores were both similar and different for hypothesized groups (Messick, 1995). For the REI, this aspect was assessed by understanding how scores were potentially the same and different among various groups, particularly demographic groups. The generalizability aspect of validity refers to the extent that the assessment score interpretations were broadly generalizable and not limited to the sample under evaluation (Messick, 1995). For the REI, the generalizability aspect of validity was assessed by understanding how scores differed among the various groups of different research experiences of students and how this aligned with previous literature. The second purpose of the Instrument Scoring and Group Analysis phase was to understand how the engineering Ph.D. research experiences of students grouped together from the collected data according to the Conceptual Framework in Chapter 2, so that once grouped, REI scores between the research experiences of students could be examined for differences, in support of the first purpose of the Instrument Scoring and Group Analysis phase.

Both purposes were accomplished by utilizing an integrative data analysis approach, which is an approach that combines data sets for simultaneous analysis (Curran & Hussong, 2009). This approach was used to combine the data from the Pilot Test 1 (n = 236) and the Pilot Test 2 (n = 215) into one large sample (n = 451), which was simultaneously analyzed per the recommendation of Curran and Hussong (2009). The combined sample was used in all aspects of the Instrument Scoring and Group Analysis phase, which involved four evaluation steps: 1) a scoring system for the REI was developed and validated through the use of the scores in steps 3 and 4; 2) the self-report data were evaluated to determine how students' research experiences compared relative to the Conceptual Framework in Chapter 2, and from this information, groups of research experiences were formed and defined based the Conceptual Framework in Chapter 2; 3) group means of the REI scores for all possible categorical data (demographic information, self-report information, and groups of research experiences) were calculated. Seventeen (17) groups were selected for statistical significance testing based on the size of the groups and if the REI scores indicated a potential difference in research experiences; 4) the 17 selected groups were tested for statistical significance between mean REI scores to understand the associations with what the different scores between groups indicated about their opportunities to practice becoming a professional in their research experiences.

7.1 Justification for Combining Pilot 1 Test and Pilot 2 Test Samples

As detailed by Curran and Hussong (2009), combining multiple data sets into one data set and analyzing that combined data set (referred to as integrative data analysis, or IDA) is a common practice and has many advantages when done correctly and for the right reasons (2009). Curran and Hussong (2009) detail the specific advantages of IDA, and relative to this study these included: 1) the potential to increase the statistical power, as sample size is increased; 2) the potential to increase sample heterogeneity, as "underrepresentation of potentially important subgroups in the population of interest" (2009, p. 86) may appear in the combined sample; 3) the potential to increase the estimation of reported base-rate behaviors, which in this study is related to students' research experiences; 4) broader psychometric assessment of the constructs, which in this study is across both the EFA and CFA constructs, and allows for validation of the REI scoring system.

As mentioned previously, care must be taken when determining if data sets can be combined. Curran and Hussong (2009) define five sources of between-study heterogeneity that must be considered before the data sets can be combined, as follows: 1) sampling, 2) geographic region, 3) history, 4) other design characteristics, and, 5) measurement. Each is briefly discussed relative to this study.

First, heterogeneity due to sampling refers to the targeted population in the sample, and could be an issue if the target populations are different (Curran & Hussong, 2009). Relative to this study, recall that the Pilot 1 Test sample was engineering Ph.D. students from a large Midwestern University, and the Pilot 2 Test sample was a sample of engineering Ph.D. students from U.S. doctoral-granting institutions. Combining the Pilot 1 Test and the Pilot 2 Test samples was a limitation, as the combined sample was over-represented with engineering Ph.D. students from the large Midwestern University. This limitation restricted the ability to compare responses between universities, as the sample size for other universities was not large enough.

Second, heterogeneity due to geographic region refers to studies conducted in multiple geographic regions, and could be an issue if the regions are different (Curran & Hussong, 2009).

Relative to this study, this issue is similar to the issues described above, with limitations with heterogeneity due to sampling. However, as the Pilot 2 Test sample was a national sample, the geographic regions needed to be diverse to sample the U.S. engineering Ph.D. population, so heterogeneity due to geographic region was not considered a limitation in this study.

Third, heterogeneity due to history refers to studies conducted at different points in time, which could be an issue if much time has passed (Curran & Hussong, 2009). Relative to this study, as the Pilot 1 Test and the Pilot 2 Test were only a few months apart, heterogeneity due to history was not considered a limitation.

Fourth, heterogeneity due to other design characteristics refers to issues that are unique to the design of a specific study that may cause issues and must be evaluated by the researcher (Curran & Hussong, 2009). Relative to this study, one unique aspect was the lack of incentives offered to potential participants. While the literature is mixed on the effects of incentives to increase participation (Dillman, Smyth, & Christian, 2014), the likelihood that an incentive would have increased participation, thereby increasing the sample size and the statistical power, cannot be discounted, especially when the target sample was university students. This unique aspect of the design was a limitation, but was overcome with the integrative data analysis approach used in this study.

Fifth, heterogeneity due to measurement refers to questions as to whether the data originated from the same measurement construct, and if there is evidence the data sets can be combined (Curran & Hussong, 2009). Relative to this study, the results presented in the previous two Chapters established that the data from the EFA and CFA originated from the same measurement constructs for the REI. Specifically, the EFA results in Chapter 5 and CFA results in Chapter 6 established the five factors in the REI and the assessment questions that made up each factor, providing evidence the data sets can be combined.

In summary, following the guidelines of Curran and Hussong (2009), the data from the Pilot Test 1 and the Pilot 2 Test were combined and used an integrative data analysis to evaluate the use of the REI for scoring and differences between groups. Specific details of the methods and results of combing the data set are provided below.

7.2 Methods of Instrument Scoring and Group Analysis

7.2.1 Participants

No new data were collected as part of the Instrument Scoring and Group Analysis phase. As previously stated, the data from Pilot Test 1 (n = 236) and Pilot Test 2 (n = 215) were combined into one large sample (n = 451), which is explained in detail below. From a participant standpoint, this combined the participant characteristics of the Pilot Test 1 sample and the Pilot Test 2 sample, which is detailed in the demographic information described below.

7.2.2 Analyses

As detailed at the beginning of this Chapter, there were five main analyses performed: 0) data from the Pilot 1 and the Pilot 2 were combined; 1) a scoring system for the REI was developed; 2) students' research experiences were compared relative to the Conceptual Framework; 3) group means of the REI scores were calculated and evaluated; 4) 17 selected groups were tested for statistical significance for differences in mean REI scores. The following analyses, as described, were processed in sequential order, with an explanation of why and how the analyses were completed.

Pilot 1 and Pilot 2 data combined

A combined data set was created by adding the final version of the validated EFA Pilot 1 Test data (responses to Q4 and Q17 were removed based on EFA results) to the validated CFA Pilot 2 Test data. Data were combined in Excel 2016, and included all 27 assessment questions, all self-report questions, and all demographic questions. Once the data were merged in Excel 2016, the data were checked that the original Pilot Test 1 data and Pilot Test 2 data calculated to the same descriptive statistics reported in the Appendix for the Pilot 1 and the Pilot 2 tests, respectively, to ensure no errors occurred in the merging process. The means, standard deviations, and normality of scores were calculated to check for abnormalities in the data, such as elevated means or non-normality. Next, the frequencies of combined demographic data and self-report data were tabulated to check for irregularities, such as unexpected values. The results of the descriptive statistical analyses were compared to the results of the descriptive statistics for the Pilot Test 1 data and the Pilot Test 2 data, respectively.

Scoring system for the REI

Chapter 1 established the intent for the REI scores to indicate the extent to which students' research experiences contributed to the opportunities to practice becoming a professional. In addition, the EFA results in Chapter 5 and CFA results in Chapter 6 established the five factors in the REI, and the assessment questions that make up each factor. Likewise, the CFA results in Chapter 6 established that the five first-order factors came together into one second-order latent factor. As such, this information was used to form a scoring system based on each factor for the REI. DiStefano, Zhu, and Mindrila (2009) suggest there are several options when considering a factor-based scoring system, such as summing and averaging assessment questions scores into an individual factor score, standardizing assessment question scores before summing and averaging, or weighting all assessment question scores by the factor loading before summing and averaging. As recommended by DiStefano et al. (2009), the simplest factor scoring solution was chosen for the REI, where an individual factor score for each participant was calculated by summing the scores for the assessment questions in that factor and then computing the mean. This method also had the advantage that each factor score remained on the original scale of the REI (i.e., 1 to 6).

Finally, an overall REI score was calculated for each participant by summing each of the individual factor scores together. This method put the overall REI score on a 5 to 30 scale. A detailed scoring instruction guide was developed for the REI, including the interpretation of the overall REI score. The REI scoring system was utilized to calculate the individual factor scores and the overall REI score for each participant. The means, standard deviations, and normality of the individual factor scores and the overall REI score were calculated to check for abnormalities in the data, and important characteristics of scores were identified and discussed.

Students' research experiences relative to the Conceptual Framework

Chapter 2 established a Conceptual Framework for measuring the engineering Ph.D. students' research experiences, summarized in a Concept Map (Figure 2.2 from Chapter 2). This framework was based on the social, historical, cultural, and material contexts of students' research experiences, and led to the creation of nine self-report questions about students' research experiences, detailed in Chapter 4. Based on students' responses to the nine self-report questions, two analyses were completed to understand how students' responses aligned to the Conceptual Framework.

In the first analysis, each of the individual nine self-report questions was examined separately. The Concept Map (Figure 2.2) from Chapter 2 was utilized to visualize percentages of respondents who choose each response for a particular self-report question, and the percentages between responses were compared for how well the comparisons aligned with the Conceptual Framework and the literature.

In the second analysis, the self-report questions were examined by clustering the self-report questions into groups according to their social, cultural, and material contexts. This clustering allowed for Figure 2.2 in Chapter 2 to be utilized again to visualize how the social, cultural, and material self-report questions clustered together. For a given context (social, cultural, or material), students' responses were sorted in Excel 2016, and the number of unique clusters of responses was tabulated and reported. As many different possible clusters existed based on possible students' responses, a threshold was established to define a group for consideration for further analysis. This group threshold was defined based on a statistical power analysis, with the significance criterion set to .05 (or 95% confidence interval), desired statistical power set to .80 (set to recommend minimum power per Cohen (1988)), and a medium effect size (.0625). In order to maintain statistical power of .80, when comparing 2 groups, the minimum group size used was ~64/group; when comparing 3 groups, the minimum group size used was ~53/group; when comparing 4 groups, the minimum group size used was ~45/group. These values were used as general guidelines when evaluating group sizes for both the cluster analysis and other group sizes used later in this Chapter. Once groups were defined for the social, cultural, and material contexts based on the established threshold per group, the Concept Map from Chapter 2 was utilized again to visualize the percentages of the groups, and the groups were defined and compared for how well these comparisons aligned with the Conceptual Framework and the literature.

Group means comparisons of the REI scores and group selection

Two types of analyses were conducted based on an initial comparison of group means. In the first analysis, group means and standard deviations for the individual factor scores and the overall REI scores were calculated in SPSS version 26 for all demographic groups, all self-report groups, and the selected social, cultural, and material groups. Scores between selected groups were compared that justified the overall REI scoring system. In the second analysis, the overall REI scores were compared between groups to determine if the scores indicated a potential difference in students' research experiences. If the overall REI scores indicated potential differences, then the previously established group size threshold for statistical power was checked (2 groups: ~64/group; 3 groups: ~53/group; 4 groups: ~45/group). Seventeen (17) groups were selected for statistical significance testing between mean scores based on the difference in overall REI scores and group size. The 17 groups included groups from the demographic groups, the self-report groups, and the social, cultural, and material groups.

Groups tested for significant differences between mean REI scores

The 17 selected groups were tested for statistical significance in the mean overall REI scores between groups to understand the associations in students' opportunities to practice becoming a professional in their research experiences. While the overall REI scores were normally distributed, the individual group distributions of overall REI scores were not. The non-normality of group scores required the use of nonparametric tests for the comparison of group means, as the assumptions of normality for ANOVA and MANOVA were violated (Rheinheimer & Penfield, 2001). Specifically, the nonparametric methods of the Mann-Whitney U test (for two groups) and the Kruskal-Wallis H test (for more than two groups) were utilized. Both of these nonparametric tests are ranked-based nonparametric tests, and convert the continuous dependent variable (in this case, the overall REI scores) to ranks, to compare mean ranks between groups (Upton & Cook, 2014). This comparison of mean ranks allowed for non-normality in the group data, and allowed for the distributions of the groups to be compared to determine if the distributions were statistically different between the groups (Upton & Cook, 2014). Both tests have as the null hypothesis that there are no differences in the distributions, so if the null was rejected, it indicated there were differences in the distributions of scores (Upton & Cook, 2014).

All statistical significance testing was performed in SPSS version 26, and followed the same overall procedure, as follows: 1) for groups that were compared, the group sizes were set to an equal group size, to the smallest group size of the group. For the larger group sizes in the group, a random sample of the group was taken by sampling in SPSS. After sampling, the means and standard deviations of the groups were checked to ensure that the values matched the original values within +/- 0.1; 2) a Mann-Whitney U test was utilized in SPSS for comparisons between two group distributions, with the significance level set at .05 and the confidence level set at 95%. The Mann-Whitney U test statistics were reported, along with a brief interpretation of the results; 3) a Kruskal-Wallis H test was utilized in SPSS for comparisons between three or more group distributions, with the significance level set at .05 and the confidence level set at 95%. If there was a significant difference in the distributions, SPSS automatically ran a pairwise comparison using Dunn's (1964) procedure with a Bonferroni correction for multiple comparisons. The Kruskal-Wallis H test statistics were reported, along with the mean rank and for any significant pairwise comparison, along with a brief interpretation of the results.

7.3 Results of Instrument Scoring and Group Analysis

The results that follow were completed in sequential order, and correspond to the description of the analyses provided in the previous section. As a reminder, no new data were collected for this Phase.

Pilot 1 and Pilot 2 data combined

The descriptive statistics for the assessment questions for the combined respondents are shown in Table E.1 in Appendix E. Six of the twenty-six assessment questions had elevated means (> 4.2 on a 6 point scale), the skewness ranged from -1.12 to 0.63, and kurtosis ranged from -1.22 to 0.83, indicating the data were not normally distributed. The non-normality of the combined data matched closely with the results from the Pilot 1 Test and Pilot 2 Test, as expected. Table E.2 shows the tabulated demographic information for all respondents. Table E.3 and Table E.4, respectively, show the tabulated self-report information, and Table E.5 shows the tabulated information regarding respondents' affiliated university. There were no noteworthy irregularities in the demographics or self-report information.

Scoring system for the REI

The detailed REI Scoring Instruction Guide that was developed for the REI is provided in Appendix E. To briefly summarize the most important points of the scoring system, when comparing group scores from the REI, the overall REI scores (which is the sum of the individual factor scores) should first be compared for which groups have higher and lower scores. Next, the individual factor scores (which are averaged scores of the assessment questions for that factor) should be examined for an indication of why the overall REI scores for the groups being compared are higher or lower.

The descriptive statistics for the five REI factor scores (‘F1: Working as a team member’, ‘F2: Exposure to collaborator’s form of practice’, ‘F3: Exposure to relevant professional practice’, ‘F4: Modeling and simulation tasks’, ‘F5: Practical skills’) and the overall REI scores are shown in Table E.6 in Appendix E. The means and standard deviations for the five REI factor scores and the overall REI scores are shown in Table 7.1 below. There were a few noteworthy points in the descriptive statistics information for these scores. First, the individual factor scores (‘F1’ through ‘F5’) remained non-normally distributed, as the skewness ranged from -0.75 to -0.02, and kurtosis ranged from -0.87 to -0.13. However, the overall REI score approached a normal distribution, as the skewness and kurtosis were -0.24 and -0.20, respectively. The non-normality of the factor scores was expected with the Likert-type scores used in the REI scale.

More importantly, as shown in Table 7.1 below, the mean factor scores provided the first indication of the extent to which students’ research experiences contributed to the opportunities to practice becoming a professional. Specifically, the two lowest mean factor scores were ‘F2: Exposure to collaborator’s form of practice’ (scored between ‘Rarely’ and ‘Occasionally’) and ‘F3: Exposure to relevant professional practice’ (scored ‘Rarely’), both related to students having opportunities for exposure to working professionals in their research experiences. In addition, the lowest mean factor score (‘F3: Exposure to relevant professional practice’) was approximately one standard deviation lower than scores for ‘F1: Working as a team member’, ‘F2: Exposure to collaborator’s form of practice’, and ‘F5: Practical skills’. This result was important because it showed a potential weakness in opportunities for students to engage with working professionals, and will be discussed in much greater detail in Chapter 8 – Discussion.

Table 7.1: *Respondent Factor Scores, Overall Score – Mean and Standard Deviations* (n = 451)

Factor	*M* (SD)	Score Interpretation
F1: Working as a team member	4.21 (1.12)	Occasionally
F2: Exposure to collaborator’s form of practice	3.63 (1.29)	Between Rarely and Occasionally
F3: Exposure to relevant professional practice	3.16 (1.17)	Rarely
F4: Modeling and simulation tasks	4.23 (1.31)	Occasionally
F5: Practical skills	4.15 (1.66)	Occasionally
Overall REI score:	19.38 (4.05)	Occasionally

Students’ research experiences relative to the Conceptual Framework

As a reminder, there were two main sets of results reported in this section of results. The first set of results (Students’ Self-Reported Research Experiences) utilized the Concept Map (Figure 2.2) from Chapter 2 to visualize the percentages of students’ who selected each category for a particular self-report question related to their research experiences. The percentages between categories were compared for how well the category selections aligned with the Conceptual Framework and the literature. The second set of results (Students’ Social, Cultural, Material Research Experiences) again utilized the Concept Map (Figure 2.2) from Chapter 2 to visualize how the social, cultural, and material aspects of students’ research experiences clustered together, and groups were defined based on a statistical power analysis and the Concept Map (Figure 2.2) from Chapter 2, previously explained.

Students’ Self-Reported Research Experiences

The cumulative results of the individual nine self-report questions are reported in Table E.3 and Table E.4, respectively, in Appendix E. In order to visualize the percentages of respondents who choose each response for a particular self-report question on the Concept Map (Figure 2.2) from Chapter 2, three of the self-report questions responses were converted to have the same categories as the Concept Map from Chapter 2 for the purposes of grouping, specifically Group Size, Equipment Type, and Work Space. Table 7.2 below shows the conversion of the categories Group Size, Equipment Type, and Work Space made for the Concept Map and categorization of groups.

Table 7.2: *Conversion of Group Size, Equipment, and Work Space Categories*

Reported Characteristic	Conversion	Concept Map Category	*n*	%
Response: # of graduate students in research group	Less than 5 students	Group Size: Small	151	33.5
	5 – 20 students	Group Size: Medium	290	64.3
	More than 20 students	Group Size: Large	10	2.2
Equipment Type: Primarily modeling	Not changed	Modeling	160	35.5
Equipment Type: Primarily testing or Combination of modeling and testing	Combined to one category	Physical	262	58.1
Equipment Type: Other	Not changed	Other	29	6.4
Work space: alone or with a few others	Not changed	Isolated	90	20.0
Work space: only with research group or shared with multiple research groups	Combined to one category	Shared	350	77.6
Work space: Other	Not changed	Other	11	2.4

Each of these conversions matches exactly the intent of the original Concept Map (Figure 2.2) from Chapter 2. The Group Size category conversion followed Crede and Borrego's (2012) established categorization of research group size discussed in Chapter 2 (small/medium/large group size). The Equipment Type category conversion followed the key finding from literature established in Chapter 2 that most engineering Ph.D. students utilized mathematical modeling and simulation at some point in their research experiences (Duka & Zeidmane, 2012), but only some students' were getting research experiences with testing. As such, any student who indicated research experience with testing was put in the "Physical" category for Equipment Type. Finally, the work space category conversion followed the key finding from literature established in Chapter 2 that students tended to work in either an isolated or shared work space (Crede & Borrego, 2012). As such, any student who indicated research experience in a shared type of work space was put in the "Shared" category for Work Space.

Figure 7.1 below shows the Concept Map from Chapter 2 with the reported percentages for each category (percentages are found in Table 7.2 above, and Table E.4 in Appendix E). The results for each category are briefly discussed relative to the original Concept Map proposed in Chapter 2. Each result is discussed in order of the social, cultural, and material contexts of the engineering Ph.D. student research experiences.

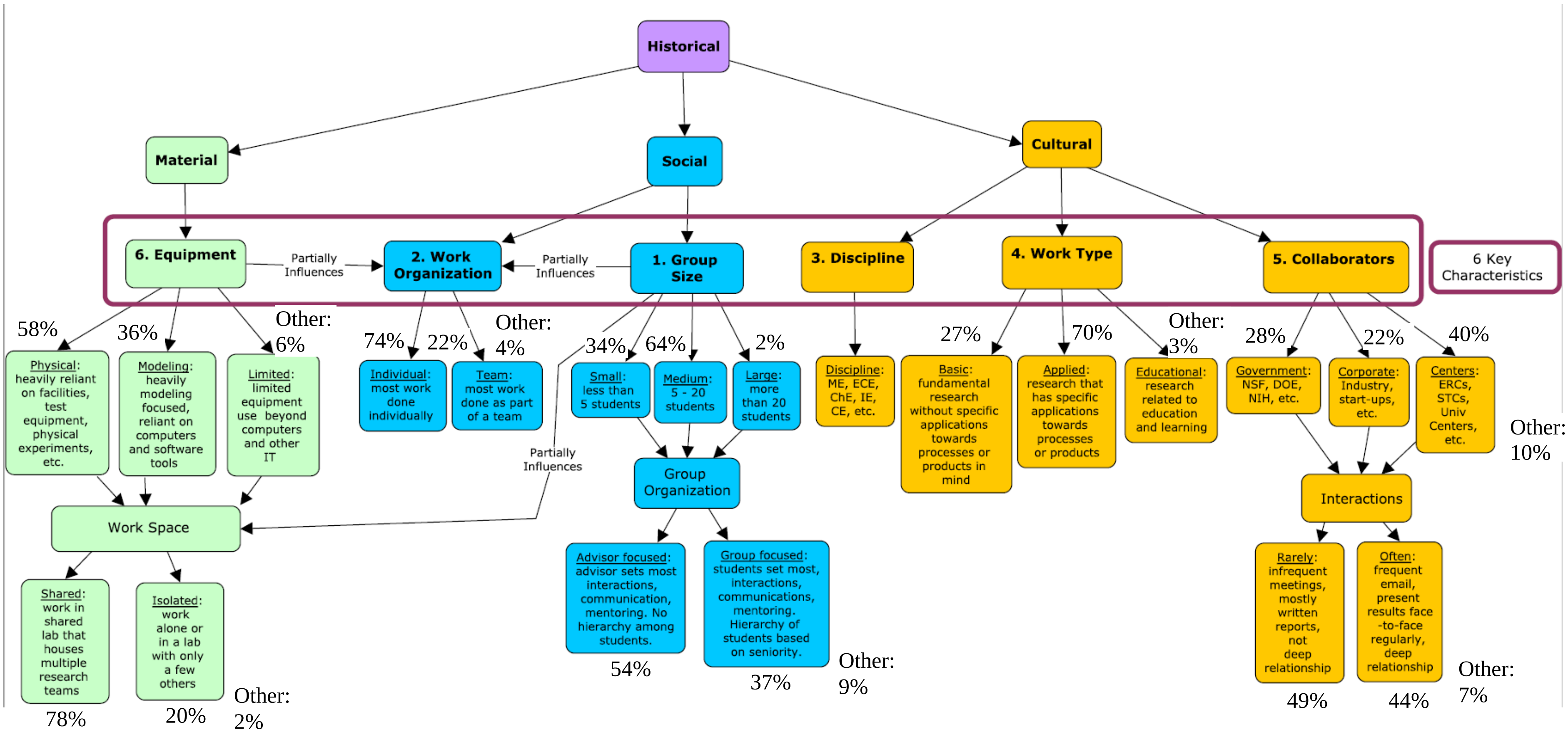

Figure 7.1: Concept Map of the Social, Historical, Cultural, and Material Contexts with Reported Percentages for Each Category

Social – Research Group Size

Almost twice as many students reported being in a medium size group (n = 290, 64%) as 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 (2012) for the same categories (small: 31%, medium 67%, large 3%).

Social – Work Organization

More than three times as many students reported working mostly individually or with their advisor (n = 332, 74%), as opposed to working mostly on a broader team (n = 99, 22%). Recall that work organization is influenced by the research group size (Crede & Borrego, 2012), where small groups tend to work more individually, and large groups more team-based. This result would suggest that students on medium size research groups also work mostly individually.

Social – Group Organization

Almost 1.5 times as many students reported working in an advisor dominated research group (n = 245, 54%), as opposed to working in a group-focused research group where the advisor takes a functional role (n = 165, 37%). Crede and Borrego (2012) 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 (2012) original findings explained above.

Cultural – Engineering Discipline

The percentage of engineering disciplines are reported in Table E.4 in Appendix E. The disciplines were evaluated later as a group in this Chapter when the mean factor scores were evaluated.

Cultural – Work Type

Almost 2.5 times as many students reported working on applied research (n = 314, 70%) as opposed to working on basic research (n = 123, 27%). The educational research option was not categorized in this study, as it was out of scope and not asked in the self-report questions. This result (applied vs. basic) aligned with what Behrens and Gray (2001) found that engineering graduate students rated their research as more applied than basic (mean of 3.29 on a 5 pt. scale, or 66%).

Cultural – 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 (2001) found that when engineering graduate students reported sponsorship (a proxy for collaborator), as 37% university research center, 34% government, 17% industry, and 12% other.

Cultural – Interactions

Slightly more students reported infrequently interacting with their collaborator (*n* = 222, 49%) vs. students who reported frequently interacting with their collaborator (*n* = 196, 44%). The literature summarized in Chapter 2 indicated the interactions were influenced by the type of collaborator, with government collaborators typically having less frequent interactions and industry collaborators more frequent. This result (that more students have infrequent interactions than frequent with their collaborators) is another important finding, as it provided the first indication a possible explanation for why the mean factor score for 'F2: Exposure to collaborator's form of practice', was lower than other factor scores, and is explored in much greater detail in Chapter 8 – Discussion.

Material – Equipment Type

Slightly more than 1.5 times as many students reported that they were involved with testing and physical experiments in their research experiences (*n* = 262, 58%) vs. those involved only with modeling and simulation (*n* = 160, 36%). The limited equipment type option was not categorized in this study, as it was out of scope and not asked in the self-report questions. These results further support the literature discussed in Chapter 2 that the traditional experiences of engineering Ph.D. students is work on physical experiments (Crede & Borrego, 2012). Yet many students (approaching 40%) were involved only in a modeling and simulation experience, which had implications on students' opportunities to practice being a professional when evaluated from the entire material aspect.

Material – Work Space

Almost four times as many students reported working in a shared work space (*n* = 350, 78%) as opposed to an isolated work space (*n* = 90, 20%). Crede and Borrego (2012) tracked a similar but slightly different metric for work space, and their metric also tracked at a ratio of 4:1 shared vs. isolated. The literature summarized in Chapter 2 (Crede & Borrego, 2012) indicated that students in an isolated work space have less access to equipment, which also suggests that students in an isolated work space might be missing out on opportunities to practice being a professional because they are isolated for others. This result became clearer when evaluated from the entire material aspect across their REI scores.

Students' Social, Cultural, Material Research Experiences

The cumulative results of the how the self-report questions were combined into clusters of responses from the social, cultural, and material contexts are reported in Table E.7, Table E.8, and Table E.9, respectively, in Appendix E. The social, cultural, and material clusters and the contexts of each were evaluated below.

Social Group Clusters

The social cluster grouped into twelve groups, including an 'other' groups that included any student who answered any of the individual self-report questions with the 'other" response. Four of the 12 groups were chosen for further evaluation, shown in Table 7.3 below, based on the previously established minimum group size of ~45/group to maintain statistical power of .80. Each group was further defined below.

Table 7.3: *Social Group Selections Evaluated*

Social Cluster Groups	*n*	%
4 – Medium / Advisor dominated / Individual	121	27
6 – Medium / Group focused / Individual	70	16
7 – Medium / Group focused / Team	42	9
8 – Small / Advisor dominated / Individual	82	18

Note: *n*, % refers to the values for each of the 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.

Social Group 4 was a medium research group size, in an advisor dominated group organization, where students work mostly individually. This cluster was the largest reported social group cluster at 27%. This results in not surprising given the results found earlier that most students worked in a medium size team (64%), were in an advisor dominated group (54%), and worked individually (74%).

Social Group 6 differed from Group 4 only in that students worked in a group focused group organization, where students mentor each other and the advisor is in a functional role, but the students still worked mostly individually. The main results here was that there were almost half as few students in Group 6 vs. Group 4 (16% vs. 27%), i.e., in the group focused group organization experience.

Social Group 7 was a medium research group size, in a group focused group organization, where students work mostly as a team. This group was the smallest reported social group cluster at only 9%. These students experienced both a teaming experience from their group organization and their work organization.

Social Group 8 is similar to Group 4, except that Group 8 was a small research group size. Group 8 was the second-largest reported social group cluster at 18%. Based on the literature established in Chapter 2, this result is exactly how a small research group tends to cluster, i.e., small research group size, in an advisor dominated group organization, where students work mostly individually (Crede & Borrego, 2012).

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%). This result would suggest that students' scores for 'F1: working as a team member' would be influenced by their group organization and work organization, which is explored in the next section of results.

Cultural Group Clusters

The cultural cluster grouped into thirteen groups, including an 'other' group that included any student who answered any of the individual self-report questions with the 'other' response. Four of the 12 groups were chosen for further evaluation, shown in Table 7.4 below, based on the previously established minimum group size of ~45/group to maintain statistical power of .80. Each group was further defined below.

Table 7.4: *Cultural Group Selections Evaluated*

Cultural Cluster Groups	*n*	%
1 – Applied / Research Center / Frequent	59	13
2 – Applied / Research Center / Infrequent	48	11
4 – Applied / Government / Infrequent	54	12
5 – Applied / Industry / Frequent	47	10

Note: *n*, % refers to the values for each of the 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 experience. Table E.8 in Appendix E indicated that with a slightly higher sample size, more cultural clusters would have been evaluated, and that in future studies, a larger sample size would help to understand the cultural impacts fully. Three other key points from the overall clustering were: 1) only applied work type research experiences generated clusters, as the basic research work type research experiences 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%).

Cultural Group 1 was an applied research work type, with university research center collaborators, where students frequently interacted with their collaborators. This cluster was the largest reported cultural cluster at 13%.

Cultural Group 2 differed from Group 1 only in the aspect that students *infrequently* interacted with their research center collaborators. Combing Group 1 and Group 2 indicated that at least 25% of students were in an applied research work type with research center collaborators, but only their interactions differed. As mentioned earlier, the mean factor score for 'F2: Exposure to collaborator's form of practice' is likely lower than other scores, affected by students' collaborator interactions, and the comparison of Group 1 vs. Group 2 provided a good case for examination of REI scores that were explored in the next section of results.

Cultural Group 4 was the only cluster where students had with government collaborators, and the students in this cluster infrequently interacted with their government collaborators. Based on the literature summarized in Chapter 2, this result was the expected clustering for government collaborators (i.e., infrequent) (Gemme & Gingras, 2012).

Cultural Group 5 was the only cluster where students had with industry collaborators (it was also the smallest cluster), and the students in this cluster frequently interacted with their industry collaborators. Based on the literature established in Chapter 2, this result was the expected clustering for industry collaborators (i.e., frequent) (Gemme & Gingras, 2012).

There were two main points to consider from the cultural clustering formed. First, the only clusters to form were the applied research work type, and the clusters that did occur were expected per the literature (government/infrequent and industry/frequent). Second, as previously mentioned, the research center clustering was interesting because it had both frequent and infrequent interactions, which provided for exploration of REI factor scores later in the results. But the research center clustering also suggested that there are different types of research center experiences, as the Chapter 2 literature established. This result points to the possibility of adding to the deeper categorization of the research center experiences in future research.

Material Group Clusters

The material cluster grouped into five groups, including an ‘other’ groups that included any student who answered any of the individual self-report questions with the ‘other’ response. Four of the five groups were chosen for further evaluation, shown in Table 7.5 below, based on the previously established minimum group size of ~45/group to maintain statistical power of .80. Each group was further defined below.

Table 7.5: *Material Group Selections Evaluated*

Material Cluster Groups	*n*	%
1 – Model / Isolated	43	10
2 – Model / Shared	113	25
3 – Physical / Isolated	40	9
4 – Physical / Shared	218	48

Note: *n*, % refers to the values for each of the 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.

Material Group 1 was defined by a modeling equipment type in an isolated work space where students tend to work alone or only with a few others. This cluster was a small reported cluster at only 10%. This result was surprising in one way and not in another. It was not surprising given the results found earlier that only 20% total of students were working in an isolated work space. But it was surprising in that it was only 10% for the students in the modeling equipment type and not higher, given the result for Group 3, discussed below.

Material Group 2 differed from Group 1 only in that students worked in a shared work space with others, as opposed to an isolated work space. The main result here was that there were about 2.5 times are many students in the shared work shape experience (25% vs. 10%). As will be evident when REI scores are compared later in the results of this Chapter, work space influenced students’ scores.

Material Group 3 was defined by a physical/testing equipment type in an isolated work space where students tend to work alone or only with a few others. Similar to group 1, this was a small reported cluster at only 9%. The somewhat surprising result here was that were enough students with this experience to form a cluster, which, while a few students would be expected in any survey, the literature indicated the need for equipment tended to be in shared work spaces (Crede & Borrego, 2012). However, as the literature also indicated, work space is also affected by research group size, with smaller teams likely being in isolated work spaces (Crede & Borrego, 2012), and the research group size was not included in the clustering information for the material group, and is left for future work.

Material Group 4 was defined by a physical/testing equipment type in a shared work space. This cluster was the largest material cluster by far (48%), almost twice as large as the next biggest (Group 2). Based on the literature established in Chapter 2, this result was the most common expected cluster, (i.e., a physical/testing equipment type in a shared work space) (Crede & Borrego, 2012).

Visualization of Social, Cultural, and Material Clusters

Figure 7.2 below shows the Concept Map from Chapter 2 with the reported percentages for each of the groups associated with the social, cultural, and material clusters. The percentages are found in Table 7.3, Table 7.4, and Table 7.5, respectively.

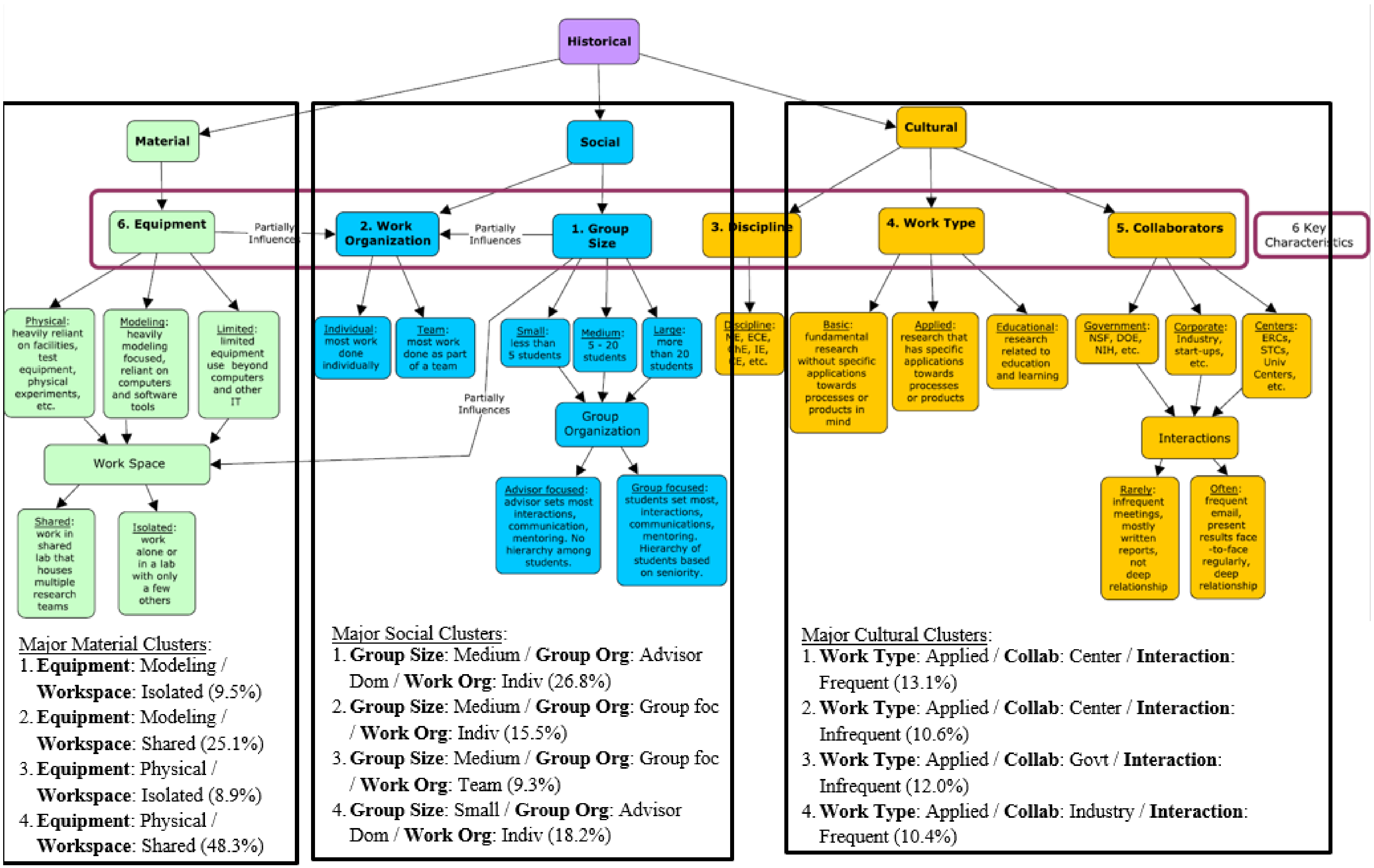

Figure 7.2: Concept Map of the Social, Historical, Cultural, and Material Clusters with Reported Percentages for Each Group

Group means of the REI scores and group selection

As a reminder, there were two main sets of results reported in this section. The first set of results (Gender and Ethnicity Score Comparison) compared the selected group means of the REI scores that justified the overall REI scoring system. The second set of results (Group Mean Score Comparison) selected 17 groups for statistical significance testing between mean scores by comparing the REI scores between groups and the group size threshold established previously.

Gender and Ethnicity Score Comparison

All of the group means of the individual factor scores, and the overall REI scores (and standard deviations for the overall REI scores) are reported in Appendix E. The group means for the demographic groups are shown in Table E.10. The group means for the ethnicity groups are shown in Table E.11. The group means for the discipline (i.e., major) groups are shown in Table E.12. The group means for all the self-report groups are shown in Table E.13. The group means for the selected social, cultural, and material groups are shown in Table E.14.

Table 7.6 below shows an example of two cases of REI scores that were used to justify the REI scoring system. Case 1 is an example where the REI scores were the same between gender groups (women and men). Note that the non-binary gender group was not large enough for group comparison. Case 2 is an example where REI scores were different between ethnicity groups (URM and non-URM) (URM is an abbreviation for unrepresented minorities). Table E.2 shows the ethnicity demographics used to tabulate the 51 URM students, comprised of those who identified as Black/African American, Hispanic or Latino, Native American, Pacific Islander, or a multiplicity of any of these. Non-URM students were comprised of White, Asian, Other, a multiplicity of any of these, and those that preferred not to respond.

Table 7.6: *Group Mean REI Scores Summary – Gender and Ethnicity* (n = 451)

Group	Values	*n*	%	Mean Scores F1: Work as a team member	F2: Exp. to collab form of pract	F3: Exp. to relev prof pract	F4: Model and sim tasks	F5: Practical skills	Overall score *M* (SD)
All		451	100	4.21	3.63	3.16	4.23	4.15	19.38 (4.05)
Case 1: Gender	Women	155	34.4	4.20	3.79	3.23	4.01	4.13	19.38 (4.17)
	Men	294	65.2	4.22	3.55	3.12	4.34	4.16	19.39 (3.99)
Case 2: Ethnicity	All URM	51	11.3	4.27	3.49	3.06	3.85	3.38	18.06 (4.50)
	Non-URM	400	88.7	4.21	3.65	3.17	4.28	4.24	19.55 (3.96)

In examining Case 1 (differences in scores – gender), the first item to note was the percentages of women (34.2%) and men (65.2%) in the sample. These percentages indicated the sample of women was slightly higher than the population, which is approximately 26.3% women and 73.7% men, per 2018 ASEE data for enrolled engineering Ph.D. students (Roy, 2018). NSF 2016 data for all enrolled graduate engineering students, not just engineering Ph.D. students, indicates a similar women/men percentages at 24.6% / 75.4% (National Science Foundation, 2016). The second item to note was that the overall REI score for women (*M* = 19.38; *SD* = 4.17) and men (*M* = 19.39; *SD* = 3.99). These scores had the same mean, with women having a larger standard deviation, and both women and men matched the overall sample mean (*M* = 19.38). This result indicated there were no differences, on average, between women and men in the opportunities to practice being a professional in their research experiences. This result was expected, as previous work (Borrego et al., 2017) on the research experiences of engineering Ph.D. students found no significant differences between women and men. The third item to note, especially important for the REI scoring system validation, was the individual factor scores between women and men did not differ substantially. This result was expected since the overall scores between women and men were the same.

In examining Case 2 (differences in scores – ethnicity), the first item to note was the percentage of URM (11.3%) and non-URM students (88.7%) in the sample. These percentages indicated the URM sample was slightly higher than the population, which is approximately 4.9% URM and 26.3% non-URM, per 2018 ASEE data for enrolled engineering Ph.D. students (Roy,

2018) (NSF 2016 data for all enrolled graduate engineering students is 6.5% URM and 93.5% non-URM) (National Science Foundation, 2016). However, the sample in this study also potentially included non-domestic students who identified as URM, whereas ASEE/NSF data only considers domestic students in their data. The second item to note was that the overall REI score and standard deviation of the URM students (M = 18.06; SD = 4.50) and non-URM students (M = 19.55; SD = 3.96) were different. The interpretation of the differences in overall mean scores between URM and non-URM students was that, on average, URM students had fewer opportunities to practice being a professional, typically "less occasionally" than non-URM students (URM students overall mean scores are only 1 point from being in the "rarely" category). This result was expected, as the report, *Doctoral Initiative on Minority Attrition and Completion* (Sowell, Allum, & Okahana, 2015) indicated minorities perceive to have fewer opportunities in their Ph.D. experiences. The third item to note, especially important for the REI scoring system validation, was the individual factor scores between URM and non-URM students. URM students had lower scores than non-URM students on all individual factor scores (except for 'F1: working as a team member', for which scores were essentially the same). The biggest individual factor score difference was 'F5: Practical Skills' (almost 1 point difference), which indicated, on average, URM students had fewer opportunities for testing/physical experiments in their research experiences as non-URM students.

These two examples, Case 1 (differences in scores – gender) and Case 2 (differences in scores – ethnicity), justified the scoring system of the REI as it showed how the overall REI score was predictive of and related to the individual factor scores. These examples also showed how to utilize the REI Scoring Instruction Guide by first examining the overall REI score for group comparison, and second examining the individual factor scores for why groups have higher or lower scores.

<u>Group Mean Score Comparison</u>

Table 7.7 below shows an abbreviated version of the 17 selected groups for statistical significance testing between the mean overall scores. Groups were chosen based on overall mean REI scores indicated a potential difference in research experiences, and the group sizes met the threshold for statistical power. The full version of this table, with all sub-groups shown for each group with groups means, is shown in Table E.17 in Appendix E. Also shown in Table 7.7 is the selected group size (n) for the statistical significance testing, which was the minimum group size in the group. For example, in Group 17, the smallest sub-group had a group size of 40, therefore for the statistical significance testing, the group size for all groups in Group 17 was set to 40.

Table 7.7: *Group Mean Comparison Selections (Abbreviated)*

Overall Group	Comparison Groups	*n*
Demographic Groups	Group 1: Internship or co-op	73
	Group 2: Source of funding	54
	Group 3: Participation in professional engineering societies	58
Ethnicity Groups	Group 4: Ethnic groups	159
	Group 5: URM	51
Discipline Group	Group 6: Major (i.e., Discipline)	50
Self-Report Groups	Group 7: Size of research group	151
	Group 8: Research group organization	165
	Group 9: Research work organization	99
	Group 10: Research work type	123
	Group 11: Collaborator Type	98
	Group 12: Collaborator Interactions	196
	Group 13: Equipment Type	160
	Group 14: Work Space	90
Social/Cultural/Material Groups	Group 15: Social Group	42
	Group 16: Cultural Group	47
	Group 17: Material Group	40

Note: *n* to the values for each of the comparison groups

Groups tested for significant differences between mean REI scores

The results of the statistical significance testing are shown in Appendix E. Specifically, Table E.18 shows the results for the Demographic Groups compared with the Kruskal-Wallis H Test (Groups 1 and 3). Table E.19 shows the results for the Demographic Groups compared with the Mann-Whitney U Test (Groups 2). Table E.20 shows the results for the Ethnicity Groups compared with the Mann-Whitney U Test (Groups 4 and 5). Table E.21 shows the results for the

Discipline Group compared with the Kruskal-Wallis H Test (Group 6). Table E.22 shows the results for the Self-Report Groups compared with the Mann-Whitney U Test (Groups 7, 8, 9, 10, 12, 13, and 14). Table E.23 shows the results for the Self-Report Group compared with the Kruskal-Wallis H Test (Group 11). Table E.24 shows the results for the Social, Cultural, Material Group compared with the Kruskal-Wallis H Test (Group 15, 16, and 17).

Table 7.8 below provides a summary of the results of the statistical significance testing for the selected groups, along with an interpretation of the results.

Table 7.8: *Summary of Result and Interpretations from Statistical Significance Testing*

Comparison Groups	Significance Test Results	Interpretations
<u>Demographic Groups</u>		
Group 1: Internship or co-op	Significant differences in scores between students who had an internship and those who did not.	For students who had an internship/co-op related to their research: - Their mean overall score was over 2 points higher than those that did not (21.31 vs. 18.76). - The mean 'F3: exposure to relevant practice' score was the highest for any sub-group (3.98), indicating they 'occasionally' had exposure to this, vs. those with no internship/co-op (2.84), i.e., 'rarely'.
Group 2: Source of funding	Significant differences in scores between government and industry funding.	For students who had industry funding: - Their mean overall score was almost 2 points higher than students with government funding (21.41 vs. 19.47). - The mean 'F2: exposure to collaborator's form of practice' score was ~0.6 points higher than the overall mean (and students with government funding), and 'F3' mean score was ~0.6 points higher than both, indicating students with industry funding are getting more opportunities for exposure to collaborators.
Group 3: Participation in professional engineering societies	Significant differences in scores between those who never participate at all with everyone else. Once some participation, scores are the same.	For students who never participate in prof engineering societies: - Their overall mean score was over two points lower than the overall mean (16.83 vs. 19.38). The overall mean score of ~17 was in the "rarely" category. - The mean 'F2: exposure to collaborator's form of practice' score was ~0.8 points lower than the overall mean, and 'F3' mean score was ~0.7 points lower than both, indicating students who never participate in prof engineering societies had fewer opportunities for exposure to collaborators. - Once students participate at a 'rarely' level with societies, their scores were statistically the same.

Table 7.8 continued

Comparison Groups	Significance Test Results	Interpretations
Ethnicity Groups		
Group 4: Ethnic groups	Significant differences in scores between Whites and Asians.	Asians' overall mean score was ~1 point higher than whites (20.17 vs. 19.21). Asians' mean individual factor scores were the same as Whites on factors 'F1' and 'F5', slightly higher on 'F2' and 'F3', and 0.5 pts higher on 'F4'. Overall, this would indicate that, on average, Asians had more opportunities for experiences in modeling and simulation.
Group 5: URM	Significant differences in scores between URM and non-URM.	For URM students: - Their overall mean score was ~1.5 points lower than non-URM students (18.06 vs. 19.55). - The two mean factor scores that differed were 'F4: modeling and simulation' and 'F5: practical skills', with 'F4' ~0.4 pts and 'F5' ~0.9 pts lower respectively. This result would indicate, on average, that URM students had fewer opportunities in these areas.
Discipline Group		
Group 6: Major (i.e., Discipline)	No differences between Chemical, ECE, Mechanical disciplines.	While no statistically significant differences were found, these results were likely due to sample size and the chosen groups (in other words, disciplines that had differences in scores did not have a large enough sample size for evaluation). As the author has master's degrees in both Engineering Education and Industrial Engineering, these two groups are singled out briefly. Both discipline groups have lower overall mean scores (ENE: 15.76, IE: 17.13), both in the "rarely" category. Both of these are driven by the individual mean factor scores for 'F5: practical skills' being low (ENE: 2.26, IE: 3.30). This result makes sense because physical experiments are not as much a part of these disciplines. Perhaps more concerning is the lower mean scores for ENE in 'F4: modeling and simulation' (2.34) and the lower mean score for IE in 'F1: work as a team member' (3.26), although the sample sizes are small.
Self-Report Groups		
Group 7: Size of research group	Significant differences in scores between medium and small group size.	For students who were in medium size groups: - The mean overall score was ~1 point higher than students in a small group (19.47 vs. 18.63). - The mean 'F1: work as a team member' and 'F5: practical skills' score both were about ~0.4 points higher than students on small teams, indicating student on medium size teams have more opportunities to work on a team and for physical testing. This result aligned with Crede and Borrego's (2012) previous work.
Group 8: Research group organization	No differences between Advisor dominated and group focused group organization.	While no statistically significant differences were found, the individual factor scores indicate that group focused students have higher mean 'F1: work as a team member' scores (4.58 vs. 3.95) while advisor dominated students have higher mean 'F4: modeling and simulation' scores (3.93 vs. 4.46). This result indicated that group focused students have more opportunities to work on a team, while

Table 7.8 continued

Comparison Groups	Significance Test Results	Interpretations
		advisor dominated students have more opportunities for modeling and simulation experiences.
Group 9: Research work organization	Significant differences in scores between individual and team work organization	For students who were in team work organization: - The mean overall score was ~2 points higher than students working individually (20.76 vs. 18.93). - The mean 'F1: work as a team member' and 'F5: practical skills' score both were about ~0.8 points higher than students working individually, indicating students working primarily on teams had more opportunities to work on a team and for physical testing. This result aligned with Crede and Borrego's (2012) previous work.
Group 10: Research work type	Significant differences in scores between basic and applied work type	For students who worked on applied research: - The mean overall score was ~2 points higher than students working individually (19.86 vs. 18.15). - All individual mean factor scores were higher, primarily the mean scores for 'F2: exposure to collaborator's form of practice' and 'F3: relevant professional practice' were both ~0.4 points higher, indicating students working on applied research were getting more opportunities for exposure to collaborators.
Group 11: Collaborator Type	Significant differences in scores between research center and industry	For students who worked with industry collaborators: - The mean overall score was ~2 points higher than students who work with research centers (20.72 vs. 18.93). Also ~1 point higher than students working with government collaborators, but not significant. - All individual mean factor scores were ~0.4 points higher, except 'F1: working as team member' was the same, indicating students working with industry collaborators were getting more opportunities almost all experiences (except their teaming) than students in a with research center collaborators.
Group 12: Collaborator Interactions	Significant differences in scores between frequent and infrequent interactions	For students who had frequent interactions with their collaborator: - The mean overall score was ~2 points higher than students had infrequent interactions (20.70 vs. 18.74). - The mean 'F2: exposure to collaborator's form of practice' score was about ~0.8 points higher than the overall mean, and ~1 point higher than students with infrequent interaction. The 'F3' mean score was ~0.5 points higher than students with infrequent interaction, indicating students who had frequent interaction with their collaborators, not surprisingly, had more opportunities for exposure to collaborators.
Group 13: Equipment Type	Significant differences in scores between modeling/simulation and testing/physical experiments	For students who had testing/physical experiments experiences: - The mean overall score was ~2 points higher than students had only modeling/simulation experiences (20.53 vs. 18.23). - The mean 'F1: work as a team member' score was ~0.5 points higher (4.42 vs. 3.86). The mean 'F4: modeling and simulation' score was ~0.9 points lower (4.01 vs. 4.91) and the mean 'F5: practical skills' score was ~2.5

Table 7.8 continued

Comparison Groups	Significance Test Results	Interpretations
		points higher (5.20 vs. 2.76). This result indicates that students who had testing/physical experiments experiences, as expected, still had experiences with modeling / simulation, but had more opportunities overall.
Group 14: Work Space	Significant differences in scores between shared and isolated work space	For students who worked in a shared work space, all of their scores were very close to the overall mean scores. For students who worked in an isolated work space, all of their mean scores (except 'F4: modeling and simulation tasks') were lower than the overall mean. Overall: ~2.0 pts lower; 'F1': 0.7 pts lower; 'F2': 0.6 pts lower; 'F3': 0.2 pts lower; 'F5': 0.6 pts lower; This indicates that students who worked in an isolated work space had many fewer opportunities overall, on average. This result aligned with Crede and Borrego's (2012) previous work.
<u>Social/Cultural/Material Groups</u>		
Group 15: Social Group (Group Size / Group Org / Work Org)	Significant differences in scores between (Group 7 – medium / group focused / team) and (Group 8 – small / advisor dominated /individual)	The main result for the social group showed the differences between the social order of the research group: one group (Group 7) was a medium research group size, in a group focused group organization, where students work mostly as a team. The other group (Group 8) was a small research group size, in an advisor dominated group organization, where students work mostly individually. Group 7 – these students had the highest mean overall score (20.60) in the social group, and their mean 'F1: working a team member' score was very high (5.02), and their mean 'F5: practical skill' was high (4.94). Group 8 – these students had the lowest mean overall score (18.04) in the social group, and their mean 'F1: working a team member' score was low (3.68), and their mean 'F5: practical skill' was low (3.65). This result indicated that Group 7, on average, had many more opportunities to work as a team and for testing/physical experiments. This result aligned with Crede and Borrego's (2012) previous work.
Group 16: Cultural Group (Work Type / Collaborator / Interaction)	Significant differences in scores between: (Group 1 – applied / center / frequent) and (Group 2 – applied / center / frequent) (Group 2 – applied / center / infrequent) and (Group 5 – applied / industry / frequent)	There were two key results for the cultural group: 1. Frequent vs. Infrequent Collaborator Interaction (Groups 1 vs. Group 2) - Both groups were students working with research center collaborators on applied research, where only the type of collaborator interaction differed (freq/infreq). For students with a frequent collaborator interaction: - The mean overall score was ~2 points higher than students had infrequent interactions (20.58 vs. 18.63). - The 'F2: exposure to collaborator's form of practice' score was about ~0.7 points higher, 'F3: relevant professional practice' were both ~0.4 points higher.

Table 7.8 continued

Comparison Groups	Significance Test Results	Interpretations
	(Group 4 – applied / govt / infrequent) and (Group 5 – applied / industry / frequent)	2. Industry collaborators vs. Other Collaborators (Group 5 vs. other groups) Group 5 – was defined as an applied research experience with industry collaborators with frequent interactions. - Students with this research experience had the highest mean overall score (22.07) in the cultural group, the highest for any sub-group. All of their mean individual factor scores were above the overall mean factors scores, especially 'F2' (4.65), 'F3' (3.83). Both results indicate that, on average, the frequency of interaction with collaborators (more frequent) and type of collaborator (industry) provided more opportunities for students.
Group 17: Material Group (Equipment Type / Work Space)	Significant differences in scores between: (Group 1 model / isolated) and (Group 3 – physical / isolated) (Group 1 model / isolated) and (Group 4 – physical / shared)	The main result for the material group showed how the isolated work space influenced opportunities: Group 1 was a modeling/simulation equipment type in an isolated work space. For students in this group: - The mean overall score was very low, ~3 points lower than the overall mean (16.62 vs. 19.38). The overall mean score of ~17 was in the "rarely" category. - The mean 'F1: work as a team member' score was ~1 point lower than the overall mean (3.26 vs. 4.21), 'F2: exposure to collaborator's form of practice' was ~ 0.5 points lower than the overall mean (3.07 vs. 3.63). 'F4' was higher, and 'F5' was lower, as expected. Group 4 was a physical/testing equipment type in a shared work space. For students in this group: - The mean overall score was ~4 points higher than the Group 1 (20.74 vs. 16.62). The overall mean score of ~17 was in the "rarely" category. - The mean 'F1: work as a team member' score was ~1.3 points higher than Group 1 (4.53 vs. 3.26), 'F2: exposure to collaborator's form of practice' was ~ 0.7 points higher than Group 1 (3.77 vs. 3.07). 'F4' was lower, and 'F5' was higher, as expected. These results indicate that, on average, working in an isolated work space can limit opportunities, especially to work on a team, to work with collaborators, and to work in testing environments. This result aligned with Crede and Borrego's (2012) previous work.

7.4 Summary of Validity Evidence of Instrument Scoring and Group Analysis

The primary purposes of the Instrument Scoring and Group Analysis phase were: 1) to provide evidence of the external and generalizability aspects of validity; and 2) to form groups of students' research experiences so that REI scores between research experiences could be examined for differences in support of the first purpose. As such, Table 7.9 shows a summary of the validity evidence collected in the Instrument Scoring and Group Analysis phase.

Table 7.9: *Summary of Validity Evidence Collected in Instrument Scoring and Group Analysis Phase*

Aspect of Validity	Types of Questions Asked	Evidence Collected	Result
External	Do the scores correlate with other variables as expected, either convergent or discriminant?	REI scores between two different demographic groups: Case 1 (gender)	Case 1 (gender): results indicated there were no differences, on average, in scores between women and men students. On average, the REI measured women and men as having the same opportunities in their research experiences.
		Case 2 (ethnicity)	Case 2 (ethnicity): results indicated there were statistically significant differences, on average, between in scores between non-URM and URM students. On average, the REI measured that URM students had fewer opportunities in their research experiences.
Generalizability	Can the scale be generalized to other situations under which it will be used?	Data from multiple universities that generalized across research experience from the literature	Several of the REI group scores compared for the various research experience (see Table 7.8) aligned with Concept Map from Chapter 2 and the literature, particularly Crede and Borrego's (2012) previous work.

8. DISCUSSION

This chapter discusses the major findings of the research with an emphasis on answering the four research questions presented in Chapter 1. Each research question is allocated a section in the first part of the chapter. In the second part of the chapter, the implications of these findings are discussed for the various stakeholders, including engineering Ph.D. students, faculty advisors, administrators, funding agencies, and instrument developers to assess the impact of the engineering Ph.D. experience on preparing students for practice. In the third part of the chapter, the results of the study are situated in the larger context of what an ontological approach would look like for engineering educators focused on engineering Ph.D. students' research experiences. In the final part of the chapter, the limitations of the study are discussed.

8.1 Research Questions Discussion

8.1.1 Research Question 1 (RQ1) Overview

Research Question 1 was a multi-part, instrument-level question: *To what degree does the REI measure engineering Ph.D. students' perceptions of the extent to which their engineering Ph.D. research experiences contributed to the opportunities to practice becoming a professional?* Specifically, the following sub-questions were addressed:

a. Which assessment questions demonstrate evidence of measuring engineering Ph.D. students' research experiences?
b. To what extent do the REI scale scores support the theoretical factor structure?
c. To what extent do the REI scale scores demonstrate evidence of reliability and validity based on the responses of engineering Ph.D. students?

Each sub-question is discussed separately, and then the overall RQ1 is re-visited.

Research Question 1a (RQ1a) – Assessment Questions

The original list of assessment questions after the Instrument Development phase, which included judging of the questions by experts and think-alouds with engineering Ph.D. students, consisted of twenty-nine assessment questions. The judging and the think-alouds indicated that the assessment questions were well-written and cognitively understood by students, and ready for pilot testing. These twenty-nine assessment questions were then tested in the Instrument Validation – Pilot Test 1 phase, where a sample of 236 engineering Ph.D. students was obtained for an Exploratory Factor Analysis (EFA). The EFA indicated that three assessment questions (Q4, Q14, and Q17) should be removed due to poor performance, in that these questions did not demonstrate evidence of measuring engineering Ph.D. students' research experiences. Accordingly, these questions were removed based on low inter-item correlations and low factor pattern coefficient values that indicated that these assessment questions were not measuring students' research experiences as intended. The EFA indicated the remaining twenty-six assessment questions were measuring engineering Ph.D. students' research experiences, as evidenced by the inter-item correlations and factor pattern coefficient values being in acceptable ranges. In addition, the 5-factor structure generated by the twenty-six remaining assessment questions corresponded to the theoretical factor structure proposed in Chapter 2.

Research Question 1b (RQ1b) – Theoretical Factor Structure

The remaining twenty-six assessment questions were tested in the Instrument Validation – Pilot Test 2 phase, focused on examining the theoretical factor structure. Based on a sample of 215 engineering Ph.D. students, the Confirmatory Factor Analysis (CFA) indicated that all twenty-six assessment questions supported the 5-factor structure that corresponds to the theoretical structure proposed in Chapter 2. Specifically, the CFA resulted in factor pattern coefficients values were in the acceptable range (.59-.96), and goodness of fit indices across a range of indices that indicated an acceptable fit (see Table 6.2). In addition, the CFA results established a second-order model that supported the theoretical second-order latent factor and the 5-factor structure that corresponded to the theoretical structure proposed in Chapter 2, also with acceptable model fit (see Table 6.2).

Research Question 1c (RQ1c) – Reliability and Validity of the REI

This study has utilized Messick's Unified Theory of Validity (Messick, 1995), in which all sources of validity evidence support the aspects of construct validity in an accumulation of evidence and subsequent justification of the evidence. In chapters 4 through 7, a table was presented at the end of each chapter that summarized the accumulated validity evidence from that chapter. Table 8.1 below combines all of the evidence from those four chapters so that a discussion of the accumulated validity evidence is facilitated, or as Messick said: "a compelling argument that the available evidence justifies the test interpretation and use" (Messick, 1995, p. 774) can be facilitated. Each aspect of validity is discussed, including the collected evidence, and what it means.

Table 8.1: *Summary of All Validity Evidence Collected*

Aspect of Validity	Types of Questions Asked	Evidence Collected	Result
		Instrument Development Phase	
Content	How well does the table of specifications match the intended purpose of the assessment?	Utilization of a theoretical framework, literature review, construct definitions	The utilization of a theoretical framework, literature review, and definitions of constructs resulted in an initial list of assessment questions, with a clear delineation of the bounds of measurement construct that match the intended purpose of the assessment.
	What is the level of alignment between test objectives and actual questions?	Review of assessment questions by experts	The review by 11 experts showed that none of the assessment questions were out of alignment. Experts review resulted in changes to the assessment questions and construct definitions that provided improved alignment between the objectives and the actual assessment questions.
Substantive	Is the group of interest interpreting the questions as intended? Are the cognitive processes the test is designed to measure being assessed?	Think-alouds with engineering Ph.D. students	Round 1 of the think-alouds indicated there were cognitive processes issues and clarifying issues, which resulted in changes to the assessment questions. These included major changes and minor word clarifications. Round 2 of the think-alouds indicated there were no cognitive processes issues, only clarifying issues, which resulted in changes to assessment questions. These included only minor word clarifications.

Table 8.1 continued

Aspect of Validity	Types of Questions Asked	Evidence Collected	Result
		Instrument Validation – Pilot Test 1	
Internal consistency (reliability)	What is the degree to which the assessment questions are measuring the same construct?	Initial Cronbach's alpha	α = .90
		Final Cronbach's alpha	α = .89
			Both exceed the benchmark of .80
Structural	Is the internal structure of the instrument congruent with the structure of the construct domain?	Question analysis	Inter-item correlations indicated Q4, Q14, and Q17 were below .30
		Initial EFA	Q4, Q14, and Q17 were removed based on the pattern coefficient values being below .40
		Final EFA	Results indicated the 5-factor structure that corresponds to the theoretical structure proposed in Chapter 2.
		Instrument Validation – Pilot Test 2	
Internal consistency (reliability)	What is the degree to which the assessment questions are measuring the same construct?	Cronbach's alpha	α = .88
			Exceeds the benchmark of .80
Structural	Is the internal structure of the instrument congruent with the structure of the construct domain?	First-order CFA model established	Results indicated the established first-order model supports the 5-factor structure that corresponds to the theoretical structure proposed in Chapter 2. All pattern coefficients values are in the acceptable range and goodness-of-fit indices that an acceptable fit.
		Second-order CFA model established	Results indicated established second-order model supports the theoretical second-order latent factor and the 5-factor structure that corresponds to the theoretical structure proposed in Chapter 2. Goodness-of-fit indices indicate an acceptable fit.

Table 8.1 continued

Aspect of Validity	Types of Questions Asked	Evidence Collected	Result
		Instrument Use Phase	
External	Do the scores correlate with other variables as expected, either convergent or discriminant?	REI scores between two different demographic groups: Case 1 (gender) Case 2 (ethnicity)	Case 1 (gender): results indicated there were no differences, on average, in scores between women and men students. On average, the REI measured women and men as having the same opportunities in their research experiences. Case 2 (ethnicity): results indicated there were statistically significant differences, on average, between in scores between non-URM and URM students. On average, the REI measured that URM students had fewer opportunities in their research experiences.
Generalizability	Can the scale be generalized to other situations under which it will be used?	Data from multiple universities that generalized across research experience from the literature	Several of the REI group scores compared for the various research experience (see Table 37) aligned with Concept Map from Chapter 2 and the literature, particularly Crede and Borrego's (2012) previous work.
		Discussion – Chapter 8	
Consequential	What is the evidence that the consequences of the test scores are justifiable? Who will determine the usage of the test scores?	Discussion presented in Chapter 8 below.	The purpose, intended use, and inferences to be made with the REI are clear, explicit, and readily accessible. The unintended consequences of low score misuse are minimal.

Content Aspect of Validity

Evidence of the content aspect of validity, related to the technical quality of the measurement constructs of the REI, was provided in the Instrument Development phase of this study through two different results. First, evidence of the overall technical quality, relevance, and content representativeness of the REI is evidenced by utilizing a theoretical framework, a thorough literature review, and concise definitions of the constructs for the REI provided in Chapter 2. The result was an initial list of twenty-nine assessment questions, with a clear delineation of the bounds of measurement constructs that matched the intended purpose of the assessment. Second, evidence of the alignment between the assessment objectives and the actual assessment questions was provided by the review of the questions by eleven experts. The result was that all of the assessment questions were well aligned with the objectives of the assessment. Feedback from the experts' review resulted in minor changes to the assessment questions and construct definitions that provided improved alignment between the objectives and the actual assessment questions.

Substantive Aspect of Validity

Evidence of the substantive aspect of validity, related to how respondents engaged with the assessment questions of the REI as intended, was provided in the Instrument Development phase of this study. This evidence was provided by ensuring that engineering Ph.D. students were cognitively processing the assessment questions through the utilization of two rounds of think-alouds with engineering Ph.D. students. Round 1 of the think-alouds indicated there were cognitive processing issues and clarifying issues with some of the assessment questions, which resulted in changes to the assessment questions. These included major changes and minor word clarifications. Round 2 of the think-alouds indicated there were no cognitive process issues, only clarifying issues, which resulted in only minor word clarification changes to assessment questions.

Internal Consistency (i.e., Reliability) Aspect of Validity

Evidence of the internal consistency (i.e., reliability) aspect of validity, related to the extent to which the REI assessment questions were measuring the same latent construct, was provided in both the Instrument Validation – Pilot Test 1 and Pilot Test 2 phases. Evidence of internal consistency was provided through the calculation of Cronbach's alpha, which provided a measure of the degree to which the REI assessment questions were measuring the same construct. Cronbach's alpha for the REI was measured at $\alpha = .89$ in Pilot Test 1, and was measured at $\alpha = .88$ in Pilot Test 2. Both results exceed the benchmark of .80 established for new scales.

Structural Aspect of Validity

The structural aspect of validity, related to the extent to which the REI assessment questions and latent constructs form factor structures that were in alignment with the theoretical structures, was provided through the EFA conducted in Instrument Validation – Pilot Test 1 and the CFA conducted in Instrument Validation – Pilot Test 2. The results, along with the validity evidence collected, were addressed in RQ1a and RQ1b, respectively.

The combined evidence collected (i.e., the result of the EFA and CFA) for the structural aspect of validity indicated that, for the intended use and purpose of the REI, the REI assessment questions formed factor structures and latent constructs in alignment with the theoretical structures. Specifically, the REI consisted of 26 assessment questions with five first-order factors that were found to empirically support the 5-factor structure that corresponded to the theoretical structure proposed in Chapter 2. Additionally, structural evidence was provided in the CFA results of a second-order latent factor for which the five factors came together and were labeled as a single, second-order construct, also as proposed in Chapter 2.

External Aspect of Validity

Evidence of the external aspect of validity, related to the extent that the REI assessment scores were both similar and different for hypothesized groups, was provided in the Instrument Scoring and Group Analysis phase of this study (Chapter 7) through two different results. First, evidence that the REI scores converged, or were similar, was provided by a gender group comparison of women and men. The results indicated that, on average, the REI measured women and men as having the same opportunities in their research experiences, which was the expected results based on previous research (Borrego et al., 2017). Second, evidence that the REI scores diverged, or were different, was provided by an ethnicity group comparison of URM and non-URM students. The result indicated statistically significant differences between URM and non-URM students, and on average, the REI measured URM students as having fewer opportunities in their research experiences. This outcome was the expected result based on prior work (Sowell et al., 2015).

Generalizability Aspect of Validity

Evidence of the generalizability aspect of validity, related to the extent that the REI assessment score interpretations are broadly generalizable and not limited to the sample under evaluation, and was provided in the Instrument Scoring and Group Analysis phase of this study by two key results. First, the combined data sample used in the Instrument Scoring and Group Analysis phase (n = 451) was composed of a multi-university sample, of which 53% (n = 241) was from a single university, and 47% (n = 210) was from thirty other universities. Second, the results from the group comparison of mean REI scores between students' research experiences indicated alignment with Concept Map from Chapter 2 and the literature, particularly Crede and Borrego's (2012) previous work. Specific examples (see Table 7.8 for all examples) of previous work included: 1) size of the research group, where students' on medium size research teams were found to have significantly more opportunities than students on small research teams; 2) work space organization, where students who work in a shared work space have were found to have significantly more opportunities than students who work in isolated work spaces.

In summary, the combined evidence of the multi-university sample and examples of results that relate to previous generalizable research findings, suggests the new results found for the REI can be generalized to other situations for the intended use and purpose of the REI.

Consequential Aspect of Validity

The consequential aspect of validity has yet to be addressed, and refers to how the REI assessment scores are used and interpreted, especially if there are any unintended consequences of individuals or groups based on low scores (Messick, 1995). This aspect has been addressed in several ways with the design and implementation of the REI. First, the purpose, intended use, and inferences to be made with the REI have been made explicit from the beginning of the design, and used consistently throughout the development and implementation process. Second, the REI Scoring Instruction Guide (in Appendix E), which is one of the main interaction points with the users of the REI, reiterates these points clearly and succinctly. Finally, the focus of the REI, and this study, and the conclusions that follow in the next chapter, have been on *opportunities* for engineering Ph.D. students to practice being a professional. Low scores on the REI do not indicate anything is wrong with students' research experiences. Low scores indicate the possibilities for improving students' opportunities to practice being a professional, and the REI provides a diagnostic for identifying which opportunities might be lacking students' research experience. In summary, the consequential aspect of validity has been addressed by making the purpose, intended use, and inferences to be made with the REI clear, explicit, and readily accessible. In addition, unintended consequences of low score misuse are minimal.

8.1.1.1 Research Question 1 (RQ1) – Overall Effectiveness of the REI

In this study, validity evidence was provided for the use of the Research Experiences Instrument (REI) to assess engineering Ph.D. students' opportunities to practice being a professional in their research experiences. The evidence was gathered by evaluating the factor structure of student responses and scores across groups of students from multiple universities. The REI was designed based on an ontological framework built upon published research that focused on potential aspects missing from students' research experiences that were important to professional practice development. Based on this ontological framework, a Conceptual Framework of students' research experiences was developed, and five ontological aspects (or factors) were identified in students' research experiences that could be present or missing that were important to professional practice development: *Working as a team member*, *Exposure to collaborator's form of practice*, *Exposure to relevant professional practice*, *Modeling and simulation tasks*, *Practical skills*.

Operational definitions and assessment questions were developed for each factor, resulting in twenty-nine initial questions on a 6-point scale. The assessment questions went through iterations with expert judges, and think-alouds with engineering Ph.D. students to understand their cognitive thought processes. The twenty-nine assessment questions were utilized in an initial, single-university pilot study focused on Exploratory Factor Analysis (EFA). The EFA resulted in the elimination of three assessment questions due to poor performance, but the remaining twenty-six assessment questions supported the theoretical five-factor REI structure.

The twenty-six assessment questions were utilized in a second, multi-university pilot study focused on Confirmatory Factor Analysis (CFA). A second-order *Opportunities to Practice Being a Professional* factor was supported through CFA, with evidence that the other five factors are distinct first-order factors in students' opportunities to practice being a professional, in support of the theoretical REI structure.

The evaluation of REI scores across gender and ethnic groups suggest the REI may be used to assess those groups appropriately. The evaluation of generalizability of the REI structure, by utilization of multi-university data, and through results that aligned with previous research about engineering Ph.D. students' research experiences (Crede & Borrego, 2012), suggests that the REI is generalizable for its intended use and purpose.

In summary, the collected validity evidence shows the REI can be used for its intended purpose (to assess engineering Ph.D. students opportunities to practice becoming a professional) with the proper inferences to be made (scores from the REI are to be interpreted such that higher scores indicated more opportunities to practice becoming a professional while lower scores indicated fewer opportunities to practice becoming a professional). Specifically, the evidence has shown the overall REI scores indicate the overall opportunities to practice becoming a professional, while the individual factor scores provide an indication of why the overall REI scores for peer groups are higher or lower, comparatively.

8.1.2 Research Question 2 (RQ2) – Most Common Research Experiences

Research Question 2 was a study-level question: *What are the most common types of engineering Ph.D. research experiences based on the data, and how do the results align with the identification and characterization of those experiences from the literature?*

This question is answered in three ways as follows: 1) the evidence provided of students' reported research experiences; 2) the evidence provided of the how the social, cultural, and material aspects of students' research experiences clustered together; 3) a discussion of proposed changes and future work to the Conceptual Framework from Chapter 2.

Students' Reported Research Experiences

Evidence of how students' reported their research experiences was provided in Chapter 7, both in a visualization using the Concept Map from Chapter 2, and in table format. Table 8.2 summarizes the main points of the most common types of students' research experiences and the alignment with the Concept Map from Chapter 2 and the literature.

Table 8.2: *Most Commonly Reported Student Research Experiences*

Reported Characteristic	Most common types of students' research experiences	Alignment with Chapter 2 Concept Map/Literature
Social - Research Group Size	Most students on a medium size team; twice as many as small (64% vs. 34%). Almost none in large (2%).	Aligned with Concept Map and literature (Crede & Borrego, 2012).
Social - 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.
Social - Group Organization	More than half of students work on advisor dominated group; 1.5 times as many as group-focused (54% vs. 37%)	Aligned with Concept Map and literature (Crede & Borrego, 2012).
Cultural - Work Type	Most students on applied research; 2.5 times as many as basic (70% vs. 27%).	Aligned with Concept Map and literature (Behrens & Gray, 2001).
Cultural - Collaborators	Diverse experiences 40% research center 28% government 22% industry	Aligned with Concept Map and literature (Behrens & Gray, 2001).
Cultural - Interactions	Roughly even distribution 49% infrequent 44% frequent	Not specified in Concept Map. New finding not previously reported in literature.
Material - Equipment Type	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 (Crede & Borrego, 2012).
Material - Work Space	Most students work in a shared work space; almost four times as many as isolated (78% vs. 20%).	Aligned with Concept Map and literature (Crede & Borrego, 2012).

In summary, the evidence of students' reported research experiences indicated alignment with the Concept Map from Chapter 2 and the literature on six aspects (Behrens & Gray, 2001; Crede & Borrego, 2012; Gemme & Gingras, 2012), and new findings on two aspects that have not been reported in the literature to date.

Social, Cultural, and Material Clusters of Students' Research Experiences

Evidence of how the social, cultural, and material aspects of students' research experiences clustered together was provided in Chapter 7, both in a visualization using the Concept Map from Chapter 2, and in table format. Table 8.3 below summarizes the main points of how the social, cultural, and material aspects of students' research experiences clustered together and aligned with the Concept Map from Chapter 2 and the literature.

Table 8.3: *Summary of Social, Cultural, and Material Clusters of Students' Research Experiences*

Cluster Groups	Most common types of students' research experiences	Alignment with Chapter 2 Concept Map/Literature
Social Group (Group Size / Group Org / Work Org)	Four (4) 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 (Crede & Borrego, 2012). New findings presented with social clustering statistics.
Cultural Group (Work Type / Collaborator / Interaction)	Four (4) groups were formed in the cultural cluster, for which the groups accounted for 46% of respondents. All 4 groups were roughly the same size (~11%), and all were applied research work type. The most common type were two groups of research center collaborators, one with frequent interactions and without.	While there was overall alignment with Concept Map and literature (Gemme & Gingras, 2012), the low clustering percentage (46%) and the dual clusters for research centers indicate that future work is needed to obtain a larger sample size for the cultural cluster, and to provide a deeper categorization of the research center experiences. New findings presented with cultural clustering statistics.
Material Group (Equipment Type / Work Space)	Four (4) 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 work space, which was the expected result.	Overall alignment with Concept Map and the literature (Crede & Borrego, 2012). New findings presented with material clustering statistics.

In summary, the evidence of how the social, cultural, and material aspects of students' research experiences clustered together suggest alignment with the Concept Map from Chapter 2 and the literature for the Social and Material aspects (Crede & Borrego, 2012). New findings for the Social and Material aspects show how each aspect clustered together in groups, with relative percentages that have not been reported in the literature to date. The evidence from the Cultural cluster also suggests alignment with the Concept Map from Chapter 2 and the literature (Gemme & Gingras, 2012), from the standpoint that the Cultural aspect has the correct characteristics (i.e., work type, collaborators, and interactions). However, the results also suggest that the Cultural aspect is more diverse than the Social and Material aspects. The data suggests that with a larger sample size, and deeper categorization of the research center experiences aspects, additional clustering would appear in the data, further defining the Cultural aspects.

Proposed Changes and Future Work to the Conceptual Framework from Chapter 2

The Conceptual Framework from Chapter 2 utilized a social, cultural, and material (and historical) lens (Sandberg & Dall'Alba, 2009) for examining students' research experiences related to important aspects for professional practice preparation. The evidence presented suggests that this lens was very effective for this purpose, as the social and material aspects captured a very large percentage of respondents (70% and 92%, respectively), and the cultural aspect captured the diversity of experiences within the cultural aspect. The evidence suggests the Conceptual Framework from Chapter 2 is valid, as many results found were similar to previous research results (Behrens & Gray, 2001; Crede & Borrego, 2012; Gemme & Gingras, 2012). This result is expected, because the Conceptual Framework was built upon the literature of previous work. But the alignment with the literature also suggests that new results from this study, based on the Conceptual Framework presented in Chapter 2, are valid for the research experiences of engineering Ph.D. students.

In summary, no changes are proposed to the Conceptual Framework from Chapter 2 based on the evidence presented. Future work is recommended on the Conceptual Framework, previously identified. Specifically, future work is recommended on the Cultural aspects, to obtain a larger sample size, and deeper categorization of the research center experiences.

Summary of RQ2: Most Common Research Experiences

In conclusion, the collected evidence has both visually and in table form displayed the most common types of engineering Ph.D. research experiences across the social, cultural, and materials of engineering Ph.D. students' research experiences. These results both aligned with the Conceptual Framework from Chapter 2 and previous literature (Behrens & Gray, 2001; Crede & Borrego, 2012; Gemme & Gingras, 2012), while bringing new research findings to the literature. The Conceptual Framework from Chapter 2 is an effective way to evaluate engineering Ph.D. research experiences related to important aspects for professional practice preparation.

8.1.3 Research Question 3 (RQ3) – Difference between Research Experiences

Research Question 3 was a study-level question: *Are there significant differences in the mean REI scores between research experiences that indicate certain research experiences contribute more or fewer opportunities to practice becoming a professional?*

From the analyses in Chapter 7, there were eleven (11) groups analyzed for significant differences in the mean REI scores between research experiences that indicated certain research experiences contributed more or fewer opportunities to practice becoming a professional. Ten (10) of the 11 groups resulted in significant differences in the mean REI scores between research experiences, which indicated that students in those experiences had more or fewer opportunities to practice becoming a professional. A summary of the ten groups of research experiences and how the scores indicated the research experiences contributed more or fewer opportunities to practice becoming a professional is provided below in Table 8.4.

Table 8.4: *Significant Differences Between Research Experiences*

Research Experience Characteristic	Summary of Mean REI Score Indication Contributing More or Fewer Opportunities
Social - Research Group Size	Scores indicated that students on medium size research groups had more opportunities than students on a small size research groups; specifically, more opportunities to work on teams and for practical skills from testing environments. This result was as expected based on the Concept Map from Chapter 2 and the literature (Crede & Borrego, 2012).

Table 8.4 continued

Research Experience Characteristic	Summary of Mean REI Score Indication Contributing More or Fewer Opportunities
Social - Work Organization	Scores indicated that students who did most of their work on a team had more opportunities than students who worked mostly individually; specifically, more opportunities to work on teams. While this is obvious in one way, nevertheless, it is important to note because students who worked in a team in testing environments also gained more practical skills. This result was as expected based on the Concept Map from Chapter 2 and the literature (Crede & Borrego, 2012).
Cultural - Work Type	Scores indicated that students who worked on applied research had more opportunities than students who worked on basic research; specifically, more opportunities to work with both their direct collaborator and the wider community of practice. While this result might have been expected at least in part, the REI provides clear empirical evidence for it.
Cultural - Collaborators	Scores indicated that students who worked with industry collaborators had more opportunities than students who worked with research center collaborators; specifically, more opportunities for all aspects (except to work on teams, which was the same for both). While it is known that industry collaborators typically provide more opportunities for interactions (Parker, 1997; Thune, 2010), the REI provides clear empirical evidence of the nature of industry's impact on opportunities.
Cultural - Interactions	Scores indicated that students who frequently worked with their collaborators had more opportunities than students who infrequently worked with their collaborators; specifically, more opportunities to work with both their direct collaborator and the wider community of practice. While this result might have been expected at least in part, the REI provides clear empirical evidence for it.
Material - Equipment Type	Scores indicated that students who worked on testing/physical experiments had more opportunities overall than students who worked only on modeling and simulation; specifically, more opportunities to work on teams, and more opportunities for practical skills from testing environments. Students who worked only on modeling and simulation had more opportunities to work on modeling and simulation tasks. These results were as expected based on the Concept Map from Chapter 2 and the published literature, as Thune (2010) indicated students who work on testing/physical experiments were more likely to work on teams.

Table 8.4 continued

Research Experience Characteristic	Summary of Mean REI Score Indication Contributing More or Fewer Opportunities
Material - Work Space	Scores indicated that students who worked in a shared work space had more opportunities than students who worked in isolated work spaces; specifically, more opportunities in all aspects except modeling and simulation tasks. This might have been expected based on the Concept Map from Chapter 2, and the literature from the work space effects (Crede & Borrego, 2012). However, the REI provides valuable new empirical evidence for all of the aspects influenced by work space.
Social Group (Group Size / Group Org / Work Org)	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, more opportunities to work on teams (highest team score for any group) and for practical skills from testing environments. This might have been expected based on the Concept Map from Chapter 2, and the literature (Crede & Borrego, 2012). However, the REI provides valuable new empirical evidence for it.
Cultural Group (Work Type / Collaborator / Interaction)	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 students who had infrequent interactions with their research center collaborators working on applied research; specifically, more opportunities to work with both their direct collaborator and the wider community of practice. 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, more opportunities to work on a team, and for work with both their direct collaborator and the wider community of practice. The overall 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.

Table 8.4 continued

Research Experience Characteristic	Summary of Mean REI Score Indication Contributing More or Fewer Opportunities
Material Group (Equipment Type / Work Space)	Scores indicated that students who worked on testing/physical experiments in a shared work space had more opportunities than students who worked on modeling and simulation in isolated work space; specifically, more opportunities in all aspects except modeling and simulation tasks. The material group combination of a modeling and simulation work in an isolated work space particularly was impactful on students' scores (i.e., opportunities) in that scores from the REI indicates that these students had many fewer opportunities, especially to work on a team, and to work with both their direct collaborator and the wider community of practice. This might have been expected based on the Concept Map from Chapter 2, and the literature from the work space effects (Crede & Borrego, 2012). However, the REI provides valuable new empirical evidence for it.

Overall, there are four main takeaways from these results about the differences between research experiences and what those results indicate. First, and most importantly, the evidence indicated that there are indeed differences between research experiences, where some research experiences contributed more, and some contributed fewer opportunities for students to practice becoming a professional. Second, the evidence indicated which *characteristics* of the research experiences contributed more or fewer opportunities for students to practice becoming a professional. For example, in some cases, the characteristics identified were the size of the research group, or type of work space, etc. This result is also important as a diagnostic, as it allows for consideration of possible ways to provide more opportunities for students to practice becoming a professional, and is discussed further in Section 8.2 (Implications). Third, the evidence indicated which *aspects* of the research experiences students had more or fewer opportunities to practice becoming a professional. For example, in some cases, the opportunity identified was to work on a team. In other cases, the opportunity identified was to work with their collaborators, etc. This result is also important as a diagnostic, as it allows for consideration of possible ways to provide more opportunities for students to practice becoming a professional, and is discussed further in Section 8.2 (Implications). Fourth, the evidence indicated alignment with the Concept Map from Chapter 2 and with previous literature (Behrens & Gray, 2001; Crede & Borrego, 2012; Gemme & Gingras, 2012; Parker, 1997; Thune, 2010), while also presenting new findings. As evidence has been provided previously suggests the Conceptual Framework from Chapter 2 is valid, the results here suggest that new findings presented here fit within that Conceptual Framework as well.

Another major finding was the comparison of mean factor scores of all the students (not in groups, but the entire sample, which can be considered one large group). These scores (i.e., opportunities) indicated that, on average, students had fewer opportunities in their research experiences on two aspects (as compared to other aspects): to work with both their direct collaborators and the wider community of practice. When these results are put in the context of the ontological framework discussed in Chapter 2, these two aspects are the most ontological of the factors because they provide students' opportunities to work with professionals (i.e., take on others' forms of practice). Dall'Alba pointed out this lack of focus on the ontological aspect of becoming a profession in higher education (Dall'Alba & Sandberg, 2010), and the evidence suggests the REI measured this lack of focus on the ontological aspect in students' research experiences via the mean REI scores. The implications of this result are discussed further in Section 8.2 (Implications).

In summary, the evidence presented indicated that there are significant differences in engineering Ph.D. students' research experiences, as shown by the mean REI scores. This result indicated that ten groups of research experiences contributed more or fewer opportunities for students to practice being a professional. The evidence indicates the REI can be a diagnostic tool to identify which *characteristics* of the research experiences contributed more or fewer opportunities for students and which *aspects* of the research experiences students had more or fewer opportunities to practice becoming a professional. These results both aligned with the Conceptual Framework from Chapter 2 and previous literature (Behrens & Gray, 2001; Crede & Borrego, 2012; Gemme & Gingras, 2012; Parker, 1997; Thune, 2010), while bringing new research findings to the literature. Finally, the mean REI scores indicate, on average, an overall lack of focus on the ontological aspects of becoming a profession in engineering Ph.D. students' research experiences.

8.1.4 Research Question 4 (RQ4) – Demographic Differences

Research Question 4 was a study-level question: *Are there significant differences in the mean REI scores between demographic groups (discipline, gender, ethnicity, etc.) that indicate certain group's research experiences contribute more or fewer opportunities to practice becoming a professional?*

From the analyses in Chapter 7, there were seven (7) groups analyzed for significant differences in the mean REI scores between demographic groups that indicated certain groups' experiences contributed more or fewer opportunities to practice becoming a professional. Five (5) of the seven groups resulted in statistically significant differences in the mean REI scores between research experiences, which indicated that students in those experiences had more or fewer opportunities to practice becoming a professional. A summary of the five demographic groups and how the scores indicated their research experiences contributed more or fewer opportunities to practice becoming a professional is provided below in Table 8.5.

Table 8.5: *Differences Between the Research Experiences by Demographic Groups*

Demographic Group	Summary of Mean REI Score Indication Contributing More or Fewer Opportunities
Internship or co-op	Scores indicated that students who had an internship or co-op related to their research experiences had more opportunities than students who did not; specifically, more opportunities with the wider community of practice. This group of students (who had an internship/co-op) had the highest score on this aspect, which overall was low (fewer opportunities) than the sample overall. While this result might have been expected at least in part, the REI provides clear empirical evidence for it.
Source of funding	Scores indicated that students who had industry funding had more opportunities than students with government funding; specifically, more opportunities for work with both their direct collaborator and the wider community of practice. While it is known that industry funding typically positively influences students' attitudes (Ponomariov, 2009), the REI provides clear empirical evidence of the nature of industry's impact on opportunities in their research experiences.
Participation in professional engineering societies	Scores indicated that students who never participated in professional engineering societies had fewer opportunities than students who participated "rarely"; specifically, fewer opportunities for work with both their direct collaborator and the wider community of practice. With this result, the REI provides clear empirical evidence for possible ways to improve students' opportunities to practice being a profession.
Gender	Scores indicated no differences in the opportunities between women and men. This result was as expected based on published literature (Borrego et al., 2017).
Ethnic groups	Scores indicated that Asian students had more opportunities than White students; specifically, more opportunities in modeling and simulation tasks. The REI provides clear empirical evidence of being able to distinguish differences between groups.

Table 8.5 continued

Demographic Group	Summary of Mean REI Score Indication Contributing More or Fewer Opportunities
URM	Scores indicated that non-URM students had more opportunities than URM students; specifically, more opportunities in modeling and simulation tasks and for practical skills from testing environments. This result was as expected based on published literature (Sowell et al., 2015).
Discipline	Scores indicated no differences in the opportunities between Chemical, Electrical and Computer, and Mechanical engineering disciplines. These were the only disciplines tested based on the sample size available. Based on scores of other disciplines with a smaller sample size, in future studies with a larger sample size, the evidence would suggest differences in disciplines would likely be detected.

Overall, there are four main takeaways from the results of the difference between demographic groups and what the results mean. First, and most importantly, the evidence indicates that there are indeed significant differences between demographic groups, where some demographic groups had research experiences that contributed more opportunities and some contributed fewer opportunities for students to practice becoming a professional. Second, the evidence indicates which *characteristics* of the demographic groups had more or fewer opportunities in their research experiences for students to practice becoming a professional. For example, the evidence shows that when students participated in engineering professional societies at the level of "rarely", then on average, students would have more opportunities in their research experiences to practice being a professional. This result is also important as a means for suggesting ways to provide more opportunities for students to practice becoming a professional, and is discussed further in Section 8.2 (Implications). Third, the evidence indicates which *aspects* of the research experiences afforded students either more or fewer opportunities to practice becoming a professional for a particular demographic group. For example, for URM students, the evidence suggests that URM students had fewer opportunities in modeling and simulation tasks and for practical skills from testing environments. This result is also important as a diagnostic, as it allows for consideration of possible ways to provide more opportunities for students to practice becoming a professional, and is discussed further in Section 8.2 (Implications). Fourth, two aspects related to the Conceptual Framework from Chapter 2 for future work should be considered based on the evidence. First, the discipline aspect is part of the cultural aspect of the Conceptual Framework from Chapter 2. While no differences were found between the disciplines compared, the evidence suggested this was likely due to the sample size in this study. The evidence would suggest there are differences in opportunities between some disciplines, but a larger sample size is needed to detect it. Second, for future work, the Conceptual Framework from Chapter 2 could be expanded to include new aspects that have been identified to influence students' scores (i.e., opportunities), such as funding sources, internship opportunities, etc. The challenging aspect for this task will be to determine where those aspects fit within the social, cultural, and material framework.

In summary, based on the REI scores, there are significant differences in engineering Ph.D. students' research experiences based on demographic groups. This result indicated that five demographic groups had research experiences that contributed more or fewer opportunities for students to practice being a professional. The REI can identify which *characteristic* of the demographic groups had more or fewer opportunities in their research experiences and which *aspects* of the research experiences students had more or fewer opportunities to practice becoming a professional. In future work, the Conceptual Framework from Chapter 2 has the possibility for expansion based on the identified aspects shown to influence students' opportunities to practice being a professional in their research experiences.

8.2 Implications of the Study

The results of this study suggest the potential for new ways of understanding the engineering Ph.D. research experiences, with possible improvements in ways to measure students' research experiences, possible ways to diagnose areas for providing more opportunities for students' to become professionals, and indications at ways to provide those opportunities for students. The results are applicable for different stakeholders depending on their perspectives, and as Chapter 1 identified three focus areas with different perspectives of stakeholders for each area, as follows: 1) <u>engineering educational practice</u>, centered around faculty and students understanding more about research experiences to make decisions about practice; in this discussion, two other practitioners are added who are potentially impacted; other researchers, and REI users; 2) <u>organizational arrangements</u>, centered around higher education administrators in engineering to assist students in providing more opportunities; 3) <u>national policy</u>, centered on program managers at NSF and similar organizations, where a better understanding of students' research experience could help decisionmakers. Implications for each of the six stakeholders are discussed separately, although there is some overlap between the areas.

8.2.1 Practice: Other Researchers

One helpful way to understand the potential impact of this study is to understand how it adds to the literature, from the standpoint of filling identified gaps in the literature, augmenting and complementing previous work, and adding new findings.

From the standpoint of filling identified gaps in the literature, two specific literature gaps were identified in the needs of this study in Chapter 1. First, there was the need to identify and characterize the most important aspects of the engineering Ph.D. student research experiences related to professional practice that can be derived from a broad review of the literature. Second, there was a need to understand what aspects of the engineering Ph.D. student research experiences were the most important opportunities for students to practice becoming a professional. Both of these needs were met by the development of the new Conceptual Framework for measuring the engineering Ph.D. research experience from Chapter 2. Not only did this framework serve as the backbone of this study, but it greatly simplified the heterogeneity of the engineering Ph.D. research experience, especially from the standpoint of professional practice. As this framework was used in the development of the REI, and later validated with results that aligned from previous work, this new Conceptual Framework is something other researchers can use to simplify the understanding of engineering Ph.D. research experiences.

From the standpoint of augmenting and complementing previous work, this study has further validated the results of others, while building on those results and expanding the knowledge in several areas. For example, this study further validated the work of Crede and Borrego (2012) about the effects of isolated and shared work spaces for students, and augmented these results by measuring the ontological aspect of an isolated work space. In other words, this study added to the understanding that work space isolation could diminish students' opportunities to practice being a professional, especially team work and collaborator opportunities. In another example, this study complemented Dall'Alba's previous work when she pointed out this higher education's lack of focus on the ontological aspect of becoming a profession (Dall'Alba & Barnacle, 2007) as the results of measuring engineering Ph.D. research experiences indicated the same thing: students' on average were not getting as many opportunities to with professionals to understand what it means to be and become a professional as they were in other their other research experiences. This result suggests why some students have difficultly translating their knowledge to practice.

The new findings from this study emanated from the purposes of the study that were identified in Chapter 1. First, the primary purpose was to develop and validate the use of a psychometrically sound engineering-specific Research Experiences Instrument (REI) that measures engineering Ph.D. students' research experience. The secondary purpose was to identify and group the engineering Ph.D. students by their research experiences and other demographic data to indicate the extent to which their research experiences contributed to the opportunities to practice becoming a professional. Both of these purposes were met, and the results of this study add to the literature through two key sets of results. First, the accumulation of validity evidence for the REI suggests the REI can be used for its intended purpose and inferences, providing a new instrument for researchers and others. Second, the results of the research experience group analysis begin to provide examples as to which research experiences and demographic groups have more or fewer opportunities to practice being a professional, providing researchers new prospects for viewing engineering Ph.D. student professional development.

8.2.2 Practice: Instrument Users

Users of the REI have been identified as higher-education administrators, faculty, and researchers. Although each group may use the REI with different objectives in mind, there are implications from this study that affect all users globally. These global implications include using the REI as a diagnostic tool, the potential to add or modify the REI, and the potential to use only certain factors in the REI.

First, the evidence from this study has shown that the REI can be used as a diagnostic tool to help identify which *characteristics* of the research experiences contributed more or fewer opportunities for students and which *aspects* of the research experiences students had more or fewer opportunities to practice becoming a professional. For example, this study identified that, on average, students who have more frequent interactions with their collaborator (i.e., which *characteristic*) had more opportunities to engage with working professionals in their research experiences (i.e., which *aspect*). The evidence from this study has shown that the REI can be used as a diagnostic tool to help identify which *characteristics* of the demographic groups had more or fewer opportunities in their research experiences, while also being able to identify which *aspects* of the research experiences students had more or fewer opportunities to practice becoming a professional. Both of these capabilities provide a powerful tool for potential REI users.

If REI users wanted to add or modify the REI, the simplest place to do would be the demographic questions. Users could somewhat easily add their own demographic questions without issue, and analyze those groups as needed. It is not recommended that users modify the nine self-report questions related to the research experiences without serious consultation with the literature. However, the nine questions could be removed from a survey entirely if those aspects of the research experiences are not of interest.

If REI users wanted to only use certain factors in the REI, the following are suggestions to try for pilot studies: 1) never remove factors 'F2: Exposure to collaborator's form of practice' or 'F3: Exposure to relevant professional practice', as these are most important theoretical factors in the REI, as these measure students' interactions with collaborators; 2) it would only make sense to remove 'F4: Modeling and simulation tasks' and 'F5: Practical skills' together. In other words, remove both factors. These factors are both from the Material – Equipment aspect, and are slightly negatively correlated; 3) factor 'F1: Working as a team member' also should not be removed. It has a medium correlation with all factors except 'F4: Modeling and simulation tasks', indicating it needs to remain in the factor structure.

8.2.3 Practice: Engineering Ph.D. Students

The context of this study is about engineering Ph.D. students' professional practice preparation through their research experiences. Ideally, students would be a direct beneficiary of the results of this study. Yet, students are likely to only be indirect beneficiaries in that students would benefit from any changes that others (faculty, administrators, and national program managers) would implement to provide more opportunities. It is possible for students that can do some things on their own seek more opportunities to practice being a professional in their research experiences, and advocate for those opportunities. Both implications are discussed.

Engineering faculty, administrators, and national program managers can and do have profound effects on engineering Ph.D. students' research experiences, and hence students' opportunities to practice being a professional. We know that many Ph.D. students struggle to apply and translate their knowledge based on the multiple reports from Chapter 1. The results from this study begin to shed light on why: that Ph.D. students, on average, are not getting enough opportunities to practice being a professional in their research experiences, especially to understand others ways or practice through work with professional. Suggestions for faculty, administrators, and national program managers based on the results of this study are explored separately.

Engineering Ph.D. students can also do some things on their own seek more opportunities to practice being a professional in their research experiences based on the results of this study. For example, students who work in an isolated work space could consider advocating to their advisors to move to a more collaborative work space with others if such spaces are available in order to get more of a team work experience. Students could also 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 different types of research projects that have different experiences. The results from this study suggest that students should also pursue some opportunities on their own, such a joining and becoming active in professional engineering societies. However, other opportunities could be pursued as well, as long as those opportunities bring students closer to understating what it means *to be and become a professional*. For students, this means being on the lookout for opportunities to interact and be with other professionals. Most Ph.D. students receive many email notices about professional development opportunities, from myriad sources, including their university, graduate school, engineering college, engineering college, and home department (i.e., discipline), and the number of opportunities can sometimes be overwhelming. Again, this study would suggest students focus on opportunities *to be and become a professional* when they come along. These opportunities will provide students the chance to take on others' forms of practice, which is what most students appear to be missing. Students who are not getting much teamwork experience can also work on those skills on their own. Eswara (2019) has excellent suggestions for students working mostly by themselves or with their advisors, such as serving on committees, among others. One last thing for engineering Ph.D. students to consider: consider the Engineering lens on the Vitae Researcher Development Framework (RDF) (Vitae, 2014) at https://www.vitae.ac.uk/vitae-publications/rdf-related/engineering-lens-on-the-vitae-researcher-development-framework-rdf-2012.pdf. Recall the RDF's 12 subdomains and 63 descriptors for engineering researchers, but remember, the RDF is epistemological in nature. Users should apply it to their own engineering discipline (in other words, what does it mean to be a mechanical engineering researcher, etc.?). Students can use the

RDF to help understand which knowledge and skills they may be missing as they progress in their professional development.

8.2.4 Practice: Engineering Faculty

The engineering Ph.D. students' advisor did not play a large *direct role* in the Conceptual Framework from Chapter 2. The only aspect where students' advisor was a factor was the Social – Group Organization (either advisor dominated or group focused), and that aspect was not found to be statistically significant. This result is not surprising, because ontologically speaking, students generally do not take on their advisors' form of practice, but get that experience from other professionals, likely due to what Dall'Alba referred to as *Openness with resistance* (2009) and the power dynamics with students' advisors.

However, engineering faculty clearly have a large direct role in students' academic development and success (Barnes & Austin, 2009; Nettles & Millett, 2006), and an indirect role in every aspect in the Conceptual Framework from Chapter 2. For some of these aspects, faculty could help students with opportunities to practice being a professional.

Before looking at what engineering faculty can do to help students with their opportunities to practice being a professional, it is also important to acknowledge what faculty should not consider based on the results of this study. For example, faculty should not consider moving away from basic research to applied research, as basic research is critical to fundamental knowledge (Proctor & Zandt, 2018). But this study does inform faculty that their students performing basic research might be missing out on opportunities to practice being a professional. Faculty should also not consider changing their collaborators they prefer working with, as this is a personal choice. But again, this study does inform faculty that their students with a research center or government collaborators may be missing out on opportunities to practice being a professional. Faculty can also not change their group size easily without additional funding, but this study provides insight that students in a small research group may be missing out on opportunities to practice being a professional.

Table 8.6 below provides a summary of what engineering faculty might do based on the results of this study do to help their students with their opportunities to practice being a professional. Table 8.6 also includes a category called 'Other Ways' for which faculty can help their students, including allowing/encouraging students to go on co-ops and internships, encouraging participation in professional engineering societies and other ways to get mentoring from professionals, and utilizing the Vitae RDF with students to develop and evaluate their skills.

Table 8.6: *Summary of Engineering Faculty Recommendations for Possible Ways to Help Students*

Research Experience Characteristic	Suggestions for Faculty Based on Results of This Study
Social - Research Group Size	Faculty who have small size research groups can help students find opportunities to work as team members.
Social - Work Organization	Faculty who have students that mostly work alone or with their advisors can help students find opportunities to work as team members.
Cultural - Work Type	Faculty who have students that work on basic research can help students by involving them with their direct collaborators and the wider community of practice.
Cultural - Collaborators	Faculty who have students that work with research center or government collaborators can help students by involving them with their direct collaborators and the wider community of practice.
Cultural - Interactions	Faculty who have students that infrequently worked with their collaborators can help students by involving them with their direct collaborators and the wider community of practice.
Material - Equipment Type	Faculty who have students that work on only modeling and simulation can help students find opportunities to work as team members.
Material - Work Space	Faculty who have students that work in isolated work spaces can help students find opportunities to work as team members and by involving them with their direct collaborators.
Social Group (Group Size / Group Org / Work Org)	Faculty who have students on small size research groups, with a group organization that is advisor dominated, and a work organization that is individual-based can help students find opportunities to work as team members.
Cultural Group (Work Type / Collaborator / Interaction)	Faculty who have students working with government or research center collaborators who had infrequent interactions can help students find opportunities to work as team members and by involving them with their direct collaborators and the wider community of practice.
Material Group (Equipment Type / Work Space)	Faculty who have students that work on modeling and simulation in an isolated work space particularly can help students find opportunities to work as team members and by involving them with their direct collaborators and the wider community of practice.

Table 8.6 continued

Research Experience Characteristic	Suggestions for Faculty Based on Results of This Study
Other Ways	Allows students to go on co-ops/internships Encourage participation in professional engineering societies and other ways to get mentoring from professionals Utilize the Vitae RDF with students to develop and evaluate their skills

The three general themes that emerge from Table 8.6 are 1) to help students find opportunities to work as team members; 2) involving students with their direct collaborators; 3) and involving students with opportunities with the wider community of practice. Each is briefly considered.

Some options for faculty to consider to help engineering Ph.D. students with teamwork opportunities include getting students involved in collaborative research opportunities, which tend to involve teams of faculty and students across disciplines and boundaries (Shneiderman, 2016). Other options include having undergraduate students involved in the research, as undergraduates are both relatively inexpensive and provide mentoring (i.e., team work) opportunities for Ph.D. students (Ahn & Cox, 2016). In other words, adding undergraduates can be an easy way to build the size of the team and provide the students needed team work experiences. Faculty can also encourage students to seek team work opportunities on their own, such as those previously mentioned by Eswara (2019). If students work in an isolated work space, faculty can consider if students could be moved to collaborative locations with others, preferably with their groupmates, so that they can have more team interactions. Sometimes faculty will have the ability to move students on their own, and sometimes faculty will have to advocate upper administration for help.

Some options for faculty to consider to help engineering Ph.D. students with direct collaborator opportunities include being more purposeful about letting students participate with collaborators rather than the faculty always taking the lead with the collaborators. For example, letting students present to the collaborators, letting students take the lead in meetings with collaborators, etc. provides more opportunities for students to interact with collaborators and understand what it means to be a professional. This option (where students take more of the lead with collaborators) *does require more mentoring* from the faculty member for students, in that often, faculty will have to review presentations, possibly review sensitive emails before being sent by students, etc. However, the experience for students with collaborators is so valuable to understand what it means to be a professional from others (besides their advisor). For students who work with collaborators that are mostly from research center or government, with infrequent student interactions, faculty can consider allowing students to work on multiple projects with different opportunities with various collaborators. Faculty can also consider asking their current collaborators to find more opportunities for the students to 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 (Loeb, 2020).

Faculty can have an even larger impact on involving students with opportunities with the wider community of practice. For example, faculty can be more flexible in letting students take an internship at some point in their Ph.D. studies. Students are often afraid to approach their advisors about an internship for fear that they will be seen as unserious (Wood, 2018), and faculty may be hesitant to let students participate in an internship due to research progress. However, this study shows the effect that an internship can have on students' professional development. The best option for an internship for students is often with students' collaborators for which they are already working, but if that option is not available, students often need help in finding an internship because they are competing with others for a short term opportunity. Students often do not know how to discuss their current research in an applicable way with companies or others that make it applicable for an internship, and sometimes it is likely their current research might not *directly* apply to an internship, but students have other skills and abilities that do apply to an internship, but students do not understand how to discuss those with potential employers because students are so focused on their research. In other words, many students need more mentoring and guidance when it comes to internships, as they struggle to find opportunities and then relate their experiences in a relevant way to potential employers. Faculty can also encourage students to get involved with the wider community of practice, especially opportunities for students to engage with working professionals. These opportunities can include options where students can present their research to working professionals, such as research symposiums, poster shows, conferences, etc. Other options can include encouraging students to get involved with professional engineering societies, which often have student divisions that provide opportunities for student leadership. Faculty can also encourage students to get involved in graduate entrepreneurship opportunities. Most universities offer entrepreneurship programs and certificates (Center for Entrepreneurship, 2018), which have been shown to increase students' access to working professionals (Wilson, Holloway, Gandhi, Cox, & Goldstein, 2014).

In summary, it should be acknowledged that faculty mentoring of Ph.D. students is not easy, and there are many aspects to it (University of Nebraska–Lincoln, 2020). The message to faculty is not to inundate them with more to do. The message instead is to encourage faculty to think a little differently about professional development opportunities for their Ph.D. students within the context of activities that already happen in their research community and university. If their students need more opportunities to work as team members, or to work with their direct collaborators, or to work wider community of practice, this study has provided some practical advice of how to bring those to opportunities to help students be and become better professionals.

8.2.5 Organizational: Engineering Administrators

This study helps shed light on how higher education administrators in engineering can help engineering Ph.D. students with their opportunities to become a professional through two different means: 1) by helping students directly with opportunities; 2) by helping faculty support students with opportunities.

Engineering administrators and graduate schools have taken the calls for graduate professional development (Wendler et al., 2010) seriously, as there are now multiple opportunities for different kinds of professional development opportunities for graduate students (Denecke, Feaster, & Stone, 2017). The recent report *Professional Development: Shaping Effective Programs for STEM Graduate Students by the Council of Graduate Schools* (Denecke et al., 2017), specifically targeted to higher education administrators that are involved in graduate professional training, provides a useful signpost on the path to better professional development training for graduate students, and this study has addressed some of the recommendations from that report. This report "cited a lack of evidence about what forms of professional development are most effective and most worthy of investment" (Denecke et al., 2017, p. 9). This study would suggest professional development that focuses on what it means to be and become a professional, by students having the opportunity to work and be with other professionals. This report also recommended that "more evidence and more accessible information about the effectiveness of different models for delivering engaging and relevant professional development programs to graduate students" (Denecke et al., 2017, p. 9). This study provided insight on which research expereinces, and why those research experiences, provided more opportunites to students to become professionals. This infomration can be used by engineering admnistrators and graduate schools to provide more opportunites to students to become professionals.

Regarding specific things that engineering administrators can do to help students, the same general themes that were identified for faculty earlier to help students with opportunities apply. Namely helping to provide opportunities for students to work as team members, work with direct collaborators, and with the wider community of practice. The most likely aspect that engineering administrators can help students *directly* is with the wider community of practice. Possible ways include arranging internships for Ph.D. students, encouraging and promoting involvement with professional engineering societies, research poster shows with industry or others where students get to interact with professionals. The theme here is obvious: students need more interaction with professionals than they are getting.

Engineering administrators can *indirectly* support Ph.D. students by helping faculty support students with opportunities to practice being a professional, namely opportunities to work as team members and to work with direct collaborators. One way to help Ph.D. students with opportunities to work as team members, previously discussed for both students and faculty, is to facilitate undergraduate students being involved in the research. The benefits of this for Ph.D. students have already been discussed, but administrators can help facilitate it by providing funding to faculty, by providing summer programs for undergraduate research opportunities, etc. Another way for administrators to help Ph.D. students with opportunities to work as team members, previously discussed, is to support faculty who need assistance moving students from an isolated work space to a shared (more collaborative) work space. This study has shown how being in an isolated wok space limits students' opportunities to work on a team and for equipment, which aligned with previous work (Crede & Borrego, 2012). Shared work spaces should also be considered in new buildings, especially for student research spaces, so that students have more opportunities to work as a team member. Administrators for research can also help faculty find opportunities for students to work with direct collaborators. Many faculty express a desire for more collaborations, but are unsure of how to go about it (Bozeman, Fay, & Slade, 2013). Some universities provide formal training for faculty for how to successfully engage with industry (Kansas State University, 2018), but most do not. Administrators for research can help faculty expand into new areas by providing small start-up grants in new areas, especially for collaborative team research. They can help by providing training for faculty for working with industry or other types of collaborators, and when appropriate, providing cost share opportunities for research experiences that are make efforts to increase opportunities for students to practice being a professional.

Of course, engineering administrators can use the central outcome of this study. They can use the REI to assess students at their institution to understand which research experiences are providing more and fewer opportunities to be a professional in order to determine where possible changes at their institution could be implemented.

In summary, higher education administrators in engineering can utilize the results from this study to implement positive change for engineering Ph.D. students. The key focus should be on finding and providing more opportunities for students to be and become a professional, likely in the areas of working as team members, working with direct collaborators, and working with the wider community of practice. These opportunities can be provided by directly helping students with opportunities to work with the wider community of practice, and indirectly by helping faculty with opportunities for students to work as team members and work with direct collaborators.

8.2.6 National Policy: National Program Managers

Suggestions for ways that National Program Managers at NSF and similar organizations can utilize the results from this study center around two aspects: 1) utilization of the REI as an assessment tool; and 2) utilization of results from the REI to make decisions about programs. Both are discussed.

The REI provides a tool that National Program Managers can use or recommend for use by others for assessment of various graduate or Ph.D. student initiatives. For example, the REI could be utilized to assess ERC experiences of graduates students, which in theory should provide more opportunities to be a professional based on the design of ERC experiences (National Academy of Engineering, 2017b). In theory, students involved in ARPA-E experiences should also provide more opportunities to be a professional (National Academy of Engineering, 2017a). But in both cases, it likely will depend on how much industry involvement is present, what type of research is being performed, etc. In other words, even though the ERC and ARPA-E experiences should provide more opportunities to be a professional, it is likely there will be differences between the research experiences at various sites based on the Conceptual Framework in Chapter 2. Those differences can be measured, understood, and potentially improved for the benefit of students.

As mentioned in Chapter 1, National Program Managers could use the results from this study to decide which programs to fund, which initiatives to pursue that will improve opportunities to practice becoming a professional, or what initiatives could incentivize providing more opportunities for students to practice becoming a professional. These options should be considered very carefully, especially regarding funding. The option most likely to have the greatest impact is to incentivize providing more opportunities for students to practice becoming a professional, as this option is not punitive. This option is focused on the central point of this study, which is that students are not getting enough opportunities to practice being a professional, centered on not enough opportunities for students to work with professionals. National Program Managers can be on the lookout for supporting proposals that provide opportunities for students to practice becoming a professional and helping weak proposals find ways to invest in more opportunities for students to practice becoming a professional.

8.2.7 Summary of Implications, and Understanding the Context

The implications of this study provide suggestions for those involved in engineering educational practice, such as researcher, REI users, engineering Ph.D. students, and faculty. Suggestions are provided for each stakeholder for helping students getting more opportunities to practice being a professional, especially in the identified weak areas of work as a team member and with working professionals. Similarly, suggestions are provided for those involved in organizational arrangements, such as higher education administrators in engineering, for how to provide students more opportunity to practice being a professional. These suggestions for engineering administrators centered on *direct* assistance to student opportunities, and *indirect* assistance by helping faculty provide more opportunities to students. Finally, suggestions are provided for those involved in national policy, such as program managers at NSF and similar organizations, for ways to utilize the REI in assessment and ways to incentivize initiatives to focus on providing more opportunities to students to practice being a professional.

Despite the suggestions provided here, the suggestions should be understood in the context that Ph.D. students are frequently under immense stress (Evans, Bira, Beltran-Gastelum, Weiss, & Vanderford, 2017; Levecque, Anseel, De Beuckelaer, Van der Heyden, & Gisle, 2017; Woolston, 2019). Often this stress is caused by students' concerns about their professional development and job prospects (Woolston, 2019). This stress leads to mental health issues (Evans et al., 2017; Levecque et al., 2017; Woolston, 2019), higher divorce rates (Wedemeyer-Strombel, 2018), and attrition (Berdanier, Whitehair, Kirn, & Satterfield, 2020). From the standpoint of Ph.D. student stress, the results and suggestions of this study should be used to *focus and direct* engineering Ph.D. professional development opportunities, not necessarily to add to an already overwhelming time for many Ph.D. students. Perhaps with more focused and better professional development opportunities that help Ph.D. students with opportunities to practice being a professional, they might feel less stressed about their professional development and job prospects.

8.3 An Ontological Approach for Engineering Ph.D. Students' Research Experiences

The results of this study suggest that the Cultural Group, defined as an applied research experience where students worked with an industry collaborator with frequent interactions, had the "best" ontological experience, as defined as most opportunities to practice being a professional. Students in this Cultural Group, on average, had the highest overall REI score, because their scores for 'F1: Working as a team member', 'F2: exposure to collaborator's form of practice' and 'F3: relevant professional practice' were all much higher than mean scores. It can be argued that from an ontological standpoint, or from students getting exposure to being a professional, it is not the necessarily the fact that this group had an industry collaborator *per se*. But that the collaborator provided frequent interactions and provided students the opportunities to take on their ways of being as professionals. Industry's motivations for having a deeper relationship than other collaborators are well understood and were discussed in Chapter 2.

The takeaway from this is *not* that all students should have an industry research experience to improve their opportunities to practice becoming a professional. The takeaway is that students overall need more opportunities to work with professionals, and one way to do that is to adopt more of an ontological approach for engineering Ph.D. students' research experiences. But what would an ontological approach look like?

8.3.1 Applications from the Literature

Dall'Alba provides direction for what an ontological approach would look like, but this approach is very *discipline-specific*, and *job-specific* (Dall'Alba & Barnacle, 2007). For example, in the case of engineering Ph.D. students, students have *both* a discipline area (such as mechanical engineering), and students are future researchers, so they are becoming *both*. The challenge is to help students become both, which requires focusing on providing opportunities for students to integrate their knowledge and skills in what it means to be, for example, a professional mechanical engineering researcher (Dall'Alba & Barnacle, 2007). The first step is defining what it means to be a professional mechanical engineering researcher (where something similar to the Vitae RDF could assist). The second step is to provide opportunities for students to integrate their knowledge and skills in what it means to be a professional. Medical schools have been adopting the ontological approach (Dall'alba, 2002, 2009; Mol, 2002), where the experience of becoming a doctor in their clinical rotations (with other doctors) is so vital to the experience of becoming a professional doctor (Dall'Alba, 2009). But this approach is more difficult in engineering, where Ph.D. students are trained more to be "stewards of the discipline" (Golde & Walker, 2006) rather than practitioners of the discipline. How can this be accomplished in engineering?

8.3.2 Trends and Examples in Engineering

One positive trend that is happening at U.S. Universities, especially with engineering and science schools, is that universities are becoming hubs of innovation (Heaton, Siegel, & Teece, 2019), and industry and government are setting up shop on campus (Curvelo Magdaniel, 2019). This trend provides more opportunities for students to interact with working professionals.

For example, at the University of Illinois at Urbana-Champaign (UIUC), the John Deere Technology Innovation Center houses John Deere personnel working with UIUC students, faculty, and staff to further John Deere technology (University of Illinois at Urbana-Champaign, 2020). At Purdue University, Sandia National Labs established a presence on campus for collaborative research initiatives between the two institutions (Purdue University, 2020). Examples such as these start to envision the possibilities of involving industry and government collaborators on campus with students. Taking this a step further are two examples, one at Stanford University and one in

Australia. Both of these examples show how having a more ontological focus can help students in their efforts to become a professional.

At Stanford University, the Biodesign Innovation "is a fast-paced, project-based course for graduate and post-graduate students with a passion for entrepreneurship and a commitment to improving healthcare for patients around the world through technology innovation" (Stanford Byers Center for Biodesign, 2020a). The Biodesign Innovation is a multi-disciplinary set of courses that occur over two quarters. Students work on teams of six and the courses require them to "validate real-world medical needs, invent new health technology products to address them, and plan for their implementation into patient care" (Stanford Byers Center for Biodesign, 2020a). Students also work with faculty, staff, and industry, and receiving mentoring and coaching. Students' comments on their experiences ranged from "you get the *opportunity to work in a team* alongside doctors, business students, and engineers" (Stanford Byers Center for Biodesign, 2020b) to "an approach to solving problems that translates to any industry" (Stanford Byers Center for Biodesign, 2020b).

In Australia, the Australian Research Council (ARC), which is the equivalent of NSF, has implemented a program called the Industrial Transformation Training Centres. This program is focused on providing Ph.D. student experiences where students are "gaining real-world practical skills and experience through placement in industry" (The Australian Research Council, 2020). One specific example is the Bioreactor ARC Training Centre in Biodevices at Swinburne University of Technology in Melbourne (Thongpravati, Maritz, & Stoddart, 2016). This program is focused on medical devices, and the key parts of the student experience include spending at least one-third of their time working in industrial work places. Industry are fully ingrained partners in the educational process of the students (Thongpravati et al., 2016). The key aspect of this type of training for students was that it "*creates an opportunity* (and challenge) for the students to transfer their knowledge to company employees, as well as sharing the technical capabilities that they are exposed to in the University environment" (Thongpravati et al., 2016, p. 1232).

8.3.3 Vision for New U.S. Engineering Ph.D. Research Experiences

In the report *A New Vision for Center-Based Engineering Research* (National Academy of Engineering, 2017b), the NAE issued seven high-level recommendations for the vision and future of NSF-funded Engineering Research Centers. One of those recommendations focused specifically on the engineering education of students, as follows:

RECOMMENDATION 3-3a: Centers should offer students opportunities to exercise design and entrepreneurship skills obtained through their departmental coursework by providing experiences such as internships, exposure to industrial and public sector expertise through collaborations, workshops, seminars, personnel exchanges, and opportunities to discuss the ethical dimensions of their work. (National Academy of Engineering, 2017b, p. 5).

This report fundamentally echoes the same recommendations provided earlier to the six potential stakeholders of this study. The fundamental issue with national programs such as ERCs and APRA-E, from an engineering education standpoint, is that these programs, while impactful for the students in these programs, the impacts are distributed to only a few students, relatively. As an example, from 2013-2017, ERCs averaged 258 graduate student degrees awarded per year (103 master's, 155 Ph.D.) (National Science Foundation, 2018a). In that same time frame, approximately 60,000 graduate student degrees were awarded per year in engineering in the U.S. (~50,000 master's, ~10,000 Ph.D.) (National Science Foundation, 2019). The ERC experiences likely provide a better ontological experience for students, but more students need experiences like this to improve students' preparation for professional practice.

What is needed is not a new vision for center-based research, but a vision for new U.S. engineering Ph.D. research experiences for *all* students. We already know what students need in their research experiences. The recommendation mentioned above from the NAE sums it up very well. The challenge for the engineering education community to bring those types of opportunities for all students, not just the chosen or fortunate few.

8.3.4 Summary of an Ontological Approach

Many universities, funding agencies, and industries have recognized the value of an ontological approach to students' education and the process of becoming a professional, as shown in the examples provided. Yet incorporating this approach for engineering Ph.D. students is not straightforward because it requires the process of defining what it means to be a professional for each discipline as well as a researcher. In addition, it requires the participation of working professionals, which requires collaborations and funding. Fortunately, as universities become a hub of innovation, the trend is for more working professionals from industry and government to be located on campus, and that is an opportunity to take advantage of for students' professional development. While organizations such as NSF-funded ERCs and DOE-funded APRA-E likely provide a better ontological experience for students, the challenge for the engineering education community is how to provide those types of opportunities for all students in the future.

8.4 Limitations

The main limitation of this study is that the sample size ideally would have been larger for the group analyses that were completed. Even so, as the main goal of this study is an instrument development and validation study, the sample sizes obtained for Pilot Test 1 and Pilot Test 2 are adequate for those objectives. Yet in an ideal scenario, the Pilot Test 2 (the multi-university data) would have yielded an adequate sample size on its own for the group analyses. The combining of the Pilot Test 1 data and the Pilot Test 2 data, while valid for the reasons explained in Chapter 7, also caused limitations. Specifically, the combined sample is over-represented with students from one large Midwestern University. This limitation restricted the ability to compare responses between universities, as the sample sizes for other universities are not large enough. Another limitation due to sample size was identified during the group analysis Chapter 7. Specifically, a larger sample size is needed to capture the diverse nature of the cultural aspect of the engineering Ph.D. students' research experiences. Finally, it can be argued that the results of the group analyses can be generalized across the overall population of engineering Ph.D. students with the inclusion of multi-university data. This argument is strengthened as so much of the self-report results about students' research experiences aligned statistically with previous results from the literature. However, as mentioned previously, in an ideal scenario, the multi-university data collection would have yielded an adequate sample size on its own for the group analyses. As previously stated in Chapter 7, no incentive was offered to students for participation, and this or may not have limited participation, and hence sample size.

Another limitation is that this study excludes engineering master's students in the population that was studied. However, this study was originally designed to encompass *all* engineering graduate students, as is evidenced by the original stem of the assessment question (i.e., How often in your graduate research experience did you…). As discussed in Table 4.5, the stem was changed during the think-aloud process, as some students had different master's and Ph.D. research experiences, and students were not sure which experience to use when answering the assessment questions. The Conceptual Framework from Chapter 2 was developed for *all* graduate engineering students, not only engineering Ph.D. students. The REI assessment questions were developed for *all* graduate engineering students as well. In order to use the REI with master's engineering students, the REI stem would need to be changed to: How often in your master's research experience did you…, and the assessment would need to be validated for the use case with engineering master's students. However, just as ERCs and ARPA-E and other experiences apply to all graduate students, the recommendations in this study also apply to *all* graduate engineering students as well.

A final potential limitation is the issues that are sometimes expressed about measuring people's perceptions and the validity of self-reporting in literature. Chan (2009) summarizes the validity of self-reporting in literature and indicates that self-report studies are often discounted for four main problems: construct-related evidence for validity, correlation interpretation, social desirability, and the value of the data collected. In this study, careful consideration was taken to limit the known problems with self-report items identified by Chan through the following considerations: 1) providing strong content-related evidence of the aspect of construct validity by using a sound theoretical framework (the Chapter 2 Conceptual Framework and the Vitae Research Development Framework (Vitae, 2011)) and the evidence provided of the aspects of construct validity; 2) the REI is not designed to have students self-assess their own research skills, as there is evidence that will lead to inflated scores (Gilmore & Feldon, 2010). Rather, the REI is designed to have students self-report how their research experience contributed to their opportunities to practice becoming a professional. Because the REI is not a self-assessment of the individual, a student's tendency to inflate a score should be lower. Instructions were included with the REI to ensure that students who take the survey understood the distinction (i.e., that the REI is not a self-assessment of their research skills).

9. CONCLUSIONS

The final chapter focuses on what can be taken away and acted on from this study in context of the problem identified in Chapter 1, namely, to better prepare U.S. engineering Ph.D. students for professional practice. In addition, future work emanating from this study, which was previously identified, is briefly discussed.

9.1 Overall Conclusions

In this study, evidence is provided to justify the intended use of the REI as a research and program evaluation survey to assess engineering Ph.D. students' research experiences for opportunities to practice being a professional. The REI is a tool for national program officers, researchers, engineering administrators, and engineering faculty to use as a diagnostic tool. It can help them identify which characteristics of students' research experiences contributed more or fewer opportunities and which aspects of the research experiences had more or fewer opportunities to practice becoming a professional. Likewise, the REI can be used with demographic information to determine which aspects of the research experiences had more or fewer opportunities to practice becoming a professional for demographic groups.

The REI was developed with an ontological perspective, focused on what it means to be a professional. This ontological perspective was utilized to characterize the social, cultural, and material aspects of engineering Ph.D. students' research experiences, based on the literature, into a new Conceptual Framework. This new Conceptual Framework was validated based on the results of self-report data, and provides for a new understanding of how students' research experiences prepare them for professional practice. When engineering Ph.D. students' research experiences were assessed with the REI with this ontological perspective, the results suggest that, on average, students had fewer opportunities to work with professionals (i.e., take on others' forms of practice) in their research experiences. This result, along with the validity evidence of the REI, is the key finding for this study, and suggest a possible reason why engineering Ph.D. students' struggle to apply their knowledge and skill in the work place. The evidence suggests engineering Ph.D. students are not getting enough opportunities to work with professionals in their research experiences.

Additional testing between groups, both groups of students' research experiences and demographic groups, confirmed that, as expected, there are significant differences in opportunities for students to practice being a professional. Some groups have more opportunities than others, and some groups have fewer opportunities than others to practice being a professional. This result is not unexpected (i.e., that different research experiences provide different opportunities to students). On a global scale, this result has been observed in the literature (Crede & Borrego, 2012), and by those observing engineering Ph.D. students at work. What makes the results of this study unique is the clarity it helps to bring around the professional practice standpoint of the engineering Ph.D. students' research experiences. Analyzing the engineering Ph.D. students' research experiences from the professional practice standpoint helped bring simplicity to the heterogeneity of the students' research experiences. Analyzing the research experiences from a professional practice standpoint helped bring transparency to what students' are most likely struggling with in their educational process: the ontological process of becoming a professional.

Most importantly, analyzing the engineering Ph.D. students' research experiences from a professional practice standpoint allowed for a focus on the actual problems in students' professional practice development. Specifically, one problem is the global concerns expressed about Ph.D. students' preparedness for professional practice, especially their ability to translate knowledge and skills in a work setting. And the second problem is the lack of understanding of how the engineering Ph.D. students' research experiences are influencing students' preparedness for professional practice. The development of the REI as an assessment of engineering Ph.D. students' research experiences for opportunities to practice being a professional focused on both of these problems. The REI brings some resolution to these problems through the ability to assess students and determine how their research experiences are influencing their preparedness for professional practice.

The use of the REI indicates students are not getting enough opportunities across all five aspects of professional practice opportunities measured by the REI for certain research groups and demographic groups. In other words, depending on the specific research experiences or demographic group, students are not getting enough opportunities to practice being a professional. Specific recommendations for stakeholders (faculty, students, administrators, etc.) were provided in Chapter 8, Section 8.2. In summary, there are four short take-home points regarding the lack of students' opportunities:

1) Team work: some students, especially those in small teams, isolated work spaces, who work on modeling and simulation, often need more opportunities to work on a team.
2) Exposure to collaborators: many students do not have enough opportunities for interactions with their direct collaborators in order to take on their collaborator's form of practice. In particular, those students working on basic research, with research centers or government collaborators, or those who have infrequent interactions with their collaborators.
3) Exposure to the wider community of practice: most students do not have enough opportunities for interactions with the wider community of practice (i.e., other working professionals). Almost all students need more opportunities for interaction with the wider community.
4) Practical skills: some students, especially those in small teams, working in isolated work spaces, who work on modeling and simulation, often need more opportunities to work on testing/physical experiments, where appropriate.

This study set out with the goal of developing a deeper understanding of engineering Ph.D. students' research experiences and how those experiences are providing opportunities for students to practice becoming a professional. With the development and evidence of the REI as a tool for understanding these experiences, this study added to the knowledge of engineering Ph.D. students' research experiences. More work remains in the process of continuing to understand engineering Ph.D. students' research experiences, and what is in students' best interests for professional practice development. Dall'Alba's words about becoming a professional can help think about the future: "Becoming [a professional] is, by definition, never complete" (Dall'Alba & Barnacle, 2007, p. 687).

9.2 Future Research

There are three directions for future research emanating from this study. First, future research across more institutions with a larger sample size would allow for additional studies, such as examining if there is an institutional or advisor level of effect. Future studies, with expanded sample size, can provide a deeper categorization of the research center experiences, and potentially find differences between engineering disciplines.

Second, future research with a focus on master's level engineering students could lead to a better understanding of how to prepare them for professional careers more effectively. While the REI was designed to assess Ph.D. students, future research could modify the REI to target master's level students and conduct validation studies on the new instrument. While not all master's engineering students have a research experience, as some complete a non-thesis master's, there are generally more master's students than Ph.D. students in engineering, so it is important to understand their experiences as well.

Finally, future research with a focus on changes to the Conceptual Framework to include Cultural characterization of students' research experiences would provide a deeper categorization of the research center experiences. Along with this change to the Conceptual Framework, future research could include the research group size in the clustering information for the Material aspect characterization, and doing so might provide additional information about the Material aspect. Additionally, future researchers might consider how to expand the Conceptual Framework to include new aspects that have been identified to influence students' REI scores (i.e., opportunities), such as funding sources, internship opportunities, etc.

Global reports for the past 30 years have echoed concerns about how engineering Ph.D. students are being prepared for professional practice (Borrell-Damian et al., 2015; Edge & Munro, 2015; McGagh et al., 2016; National Academies of Sciences, 2018; National Academy of Engineering, 2017b). This study responds to these calls by providing a conceptual framework to theoretically guide how to assess engineering Ph.D. students' research experiences and interpret results. In addition, this study found that contextual factors related to a students' research group were significantly related to the type of experiences they reported and, thus, their professional preparation. It is understood that engineering faculty will differ in how they manage research teams and the types of research in which they engage. However, understanding how these contextual factors affect students' career preparation can inform faculty and graduate programs about how to provide students more opportunities to practice being a professional so that they are better prepared. These students are our future faculty, our future researchers, our future inventors, and the key to maintaining the competitive advantage for U.S. technical innovations. We owe it to the students to help them be as prepared for professional practice as possible.

APPENDIX A. THEORETICAL FRAMEWORK

Table A.1: *Summary of Vitae RDF Domains, Subdomains, and Descriptors* (Vitae, 2011, 2014)

Vitae Domain	Vitae Subdomains	Vitae Descriptors
Domain A: Knowledge and intellectual abilities Definition: The knowledge, intellectual abilities and techniques to do research.	A1: Knowledge base	1. Subject knowledge 2. Research methods: theoretical knowledge 3. Research methods: practical application 4. Information seeking 5. Information literacy and management 6. Languages 7. Academic literacy and numeracy
	A2: Cognitive abilities	8. Analyzing 9. Synthesizing 10. Critical thinking 11. Evaluating 12. Problem solving
	A3: Creativity	13. Inquiring mind 14. Intellectual insight 15. Innovation 16. Argument construction 17. Intellectual risk
Domain B: Personal Effectiveness Definition: The personal qualities and approach to be an effective researcher.	B1: Personal qualities	18. Enthusiasm 19. Perseverance 20. Integrity 21. Self-confidence 22. Self-reflection 23. Responsibility
	B2: Self-management	24. Preparation and prioritization 25. Commitment to research 26. Time management

Vitae Domain	Vitae Subdomains	Vitae Descriptors
		27. Responsiveness to change 28. Work-life balance
	B3: Professional and career development	29. Career management 30. Continuing professional development 31. Responsiveness to opportunities 32. Networking 33. Reputation and esteem
Domain C: Research governance and organization Definition: The knowledge of the standards, requirements, and professionalism to do research	C1: Professional conduct	34. Health and safety 35. Ethics, principles, and sustainability 36. Legal requirements 37. IPR and copyright 38. Respect and confidentiality 39. Attribution and co-authorship 40. Appropriate practice
	C2: Research management	41. Research strategy 42. Project planning and delivery 43. Risk management
	C3: Finance, funding, and resources	44. Income and funding generation 45. Financial management 46. Infrastructure and resources
Domain D: Engagement, influence and impact Definition: The knowledge and skills to work with others and ensure the wider impact of research.	D1: Working with others	47. Collegiality 48. Team working 49. People management 50. Supervision 51. Mentoring 52. Influence and leadership 53. Collaboration 54. Equality and diversity
	D2: Communication and dissemination	55. Communication methods 56. Communication media

Vitae Domain	Vitae Subdomains	Vitae Descriptors
		57. Publication
	D3: Engagement and impact	58. Teaching
		59. Public engagement
		60. Enterprise
		61. Policy
		62. Society and culture
		63. Global citizenship

APPENDIX B. INSTRUMENT DEVELOPMENT

INITIAL ASSESSMENT DEVELOPMENT ASPECTS

Table B.1: *Initial List of Assessment Questions Developed*

Ontological Aspect	1. Work as a team member
What is the essence of this?	Students' experiences being a team member working on research – experiences where students do the types of working in a team that practicing professionals do.
Conceptualization:	This aspect is conceptualized as what it means for graduate engineering students to be a member of a research team 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.
Definition:	Two or more graduate engineering students who share a commitment to common research goals that are part of a larger research group in which members have differentiated skill sets, roles, and responsibilities in which they make decisions and coordinate tasks to accomplish research goals while exhibiting interdependencies with respect to workflow, goals, and outcomes (adapted from Fernandez, Kozlowski, Shapiro, and Salas (2008)).
Stem:	How often in your graduate research experience did you
Q1:	take on different roles or responsibilities within a research team?
Q2:	coordinate research tasks with other graduate students to accomplish research goals?
Q3:	share decision making responsibility with other graduate students to accomplish research goals?
Q4:	develop different skill sets to complement the needs of the research team's goals?
Q5:	depend on other graduate students to meet the desired research outcomes?
Ontological Aspect	2. Exposure to collaborator's form of practice
	Exhibit professional actions and behaviors through exposure to collaborator's form of practice (i.e., practicing professional engineers)
What is the essence of this?	Students' experiences being engaged with professional engineers involved in the students' research – experiences where students exhibit professional behavior through interactions with professionals.
Conceptualization:	This aspect is conceptualized as what it means for graduate engineering students to exhibit professional actions and behaviors by working with practicing professional engineers who are the students' main collaborator in their research work. This opportunity to exhibit professional actions and behaviors typically occurs with regular interaction through email, face-to-face meetings, presenting of results, etc. where students exhibit professional actions and behaviors by emulating other professionals.

Definition:	A graduate engineering student exhibiting professional actions and behaviors with practicing professional engineers in the act of working in close collaboration together on research through regular interaction (adapted from Aldridge (1994)).
Q6:	present your research results to your sponsors or collaborators (i.e., practicing professional engineers) who are involved in your research work?
Q7:	meet at your institution with your sponsors or collaborators (i.e., practicing professional engineers) who are involved in your research work?
Q8:	correspond (e.g., email, phone, etc.) with your sponsors or collaborators (i.e., practicing professional engineers) who are involved in your research work?
Q9:	meet with your sponsors or collaborators at their place of work to discuss your research or results?
Q10:	co-write journal or conference papers with your sponsors or collaborators?
Q11:	co-present at conferences with your sponsors or collaborators?
Ontological Aspect	3. Exposure to relevant professional practice Exhibit professional actions and behaviors through exposure to professional engineers
What is the essence of this?:	The students' wider experiences being engaged with professional engineers (conferences, internships, professional societies, etc.) – experiences where students exhibit professional behavior through interactions with professionals through their wider research experiences.
Conceptualization:	This aspect is conceptualized as what it means for graduate engineering students to exhibit professional actions and behaviors by working with practicing professional engineers related to their wider research experiences, such as conferences, internships, professional societies, etc.
Definition:	A graduate engineering student exhibiting professional actions and behaviors with practicing professional engineers through to their wider research experiences (adapted from Aldridge (1994)).
Q12:	develop professional relationships with working engineers through your research work?
Q13:	attend industry or government trade shows as part of your research work?
Q14:	participate in industry or government conferences as part of your research work?
Q15:	participate in professional engineering societies (e.g., Institute of Electrical and Electronics Engineers, Society of Women Engineers, etc.) related to your graduate research studies?
Q16:	present results of your research to professional engineers other than your sponsors or collaborators?
Q17:	hold an internship or co-op during your graduate research studies?
Q18:	interact with support professionals (e.g., project managers, building maintenance, outside vendors, etc.) to accomplish research objectives?

Ontological Aspect	4. Modeling and simulation tasks
What is the essence of this?:	Students' experiences being engaged with modeling and simulation tasks as a signification part of their research work – experiences where students do the types of modeling and simulation work that practicing professionals do.
Conceptualization:	This aspect is conceptualized as what it means for graduate engineering students to utilize to the computational thinking, methods, and techniques that practicing engineers use to solve research problems. It is expected that most students will have some exposure to this in their research experiences.
Definition:	The process of graduate engineering students identifying engineering problems, specifying constraints and assumptions in order to design and develop a mathematical model, often utilizing complex engineering tools. The process continues with the verification and optimization of the model by evaluating the simulated performance of the system in an iterative process that utilizes refinement of the constraints, assumptions, and the model itself, facilitated by knowledge and discovery (adapted from (Magana & Coutinho, 2017); Radcliffe (2014)).
Q19:	develop or utilize a mathematical model to help solve a research problem?
Q20:	utilize complex engineering modeling or simulation tools to help solve a research problem?
Q21:	simulate the performance of a system to accomplish research goals?
Q22:	iterate on the development of a model or simulation to optimize research results?
Q23:	verify a model or simulation against real-world data or actual results?
Ontological Aspect	5. Practical Skills
What is the essence of this?:	Students' experiences being engaged with practical skills that translate to a real-world setting as a significant part of their research work – experiences where students do work that involves physical experiments, equipment set-up, and troubleshooting, and collect data from physical phenomena and have to interpret and translate results.
Conceptualization:	This aspect is conceptualized as what it means for graduate engineering students to be exposed to research experiences that involve experiments that require students to engage with complex physical experiments that require machinery, instrumentation, etc. and require them to be a part of the installation, operation, and maintenance of the experiment and the machinery. This work often requires troubleshooting of broken equipment and interaction with the larger research enterprise, such as support staff, building maintenance, and outside vendors.
Definition:	Engineering research tasks in which graduate engineering students interact with materials to observe phenomena typically requiring the use of higher-order thinking, such as problem-solving and other cognitive tasks. These tasks include working with machinery and equipment, troubleshooting and repair, and teamwork and leadership (adapted from Lumpe and Oliver (1991); (Rivera-Reyes & Boyles, 2013)).
Q24:	use physical equipment or instrumentation as an integral part of conducting your research?

Q25:	plan how to use or deploy experimental equipment or instrumentation to gather valid data relevant to your research?
Q26:	ensure the physical equipment or instrumentation is appropriately set-up (i.e., calibrated) before use?
Q27:	collect data from test equipment or physical apparatus using appropriate sensors or instrumentation?
Q28:	interpret data gathered from physical equipment or apparatus?
Q29:	troubleshoot or modify experimental equipment or instrumentation when it does not operate properly?

Responses:

1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

IRB APPROVAL FOR THINK-ALOUDS

PURDUE
UNIVERSITY

HUMAN RESEARCH PROTECTION PROGRAM
INSTITUTIONAL REVIEW BOARDS

To:	KERRIE DOUGLAS ARMS
From:	JEANNIE DICLEMENTI, Chair Social Science IRB
Date:	01/11/2019
Committee Action:	**Expedited Approval** - **Category**(7)
IRB Approval Date	01/11/2019
IRB Protocol #	1810021221
Study Title	REI assessment of construct validity
Expiration Date	01/09/2022
Subjects Approved:	50

The above-referenced protocol has been approved by the Purdue IRB. This approval permits the recruitment of subjects up to the number indicated on the application and the conduct of the research as it is approved.

The IRB approved and dated consent, assent, and information form(s) for this protocol are in the Attachments section of this protocol in CoeusLite. Subjects who sign a consent form must be given a signed copy to take home with them. Information forms should not be signed.

Record Keeping: The PI is responsible for keeping all regulated documents, including IRB correspondence such as this letter, approved study documents, and signed consent forms for at least three (3) years following protocol closure for audit purposes. Documents regulated by HIPAA, such as Authorizations, must be maintained for six (6) years. If the PI leaves Purdue during this time, a copy of the regulatory file must be left with a designated records custodian, and the identity of this custodian must be communicated to the IRB.

Change of Institutions: If the PI leaves Purdue, the study must be closed or the PI must be replaced on the study through the Amendment process. If the PI wants to transfer the study to another institution, please contact the IRB to make arrangements for the transfer.

Changes to the approved protocol: A change to any aspect of this protocol must be approved by the IRB before it is implemented, except when necessary to eliminate apparent immediate hazards to the subject. In such situations, the IRB should be notified immediately. To request a change, submit an Amendment to the IRB through CoeusLite.

Continuing Review/Study Closure: No human subject research may be conducted without IRB approval. IRB approval for this study expires on the expiration date set out above. The study must be close or re-reviewed (aka continuing review) and approved by the IRB before the expiration date passes. Both Continuing Review and Closure may be requested through CoeusLite.

Unanticipated Problems/Adverse Events: Unanticipated problems involving risks to subjects or others, serious adverse events, and serious noncompliance with the approved protocol must be reported to the IRB immediately through CoeusLite. All other adverse events and minor protocol deviations should be reported at the time of Continuing Review.

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THINK-ALOUD PROTOCOL

Appendix B

Cognitive Interview for Assessment of the Research Experience Instrument (REI)
Semi-Structured Protocol

PART 1 - Prior to the Interview

[1] Instructions for interviewer: The purpose of this exercise is to examine the extent to which survey items are understood and interpreted correctly by engineering graduates students. Please study the REI and prepare to ask detailed follow-up questions in the context of the survey items. Be prepared to take notes on what questions students struggle to understand or must read twice.

PART 2 - Pre-Interview (Do not need to record audio for this portion)

[2] Read to Interviewee: *The purpose of this interview is to evaluate an assessment developed to measure engineering graduate students' perceptions of about how often in their graduate research experiences they utilized skills relevant to professional practice. Please read each item out loud and select the response that most accurately describes your opinion.* ***Please answer the questions as best you can and any response is okay. We are interested in how you interpret the items and select your response, as there are no correct or incorrect responses. Ultimately, we are evaluating the instrument, not you.*** *If you need time to think, let me know and I will give you time. Participation in this study is voluntary and you may stop at any time. We have an informed consent form for you to review. If you agree to participate in this study, please sign the form and let me know when you are ready to proceed.*

[3] Instructions for interviewer: Allow time for participant to read and sign informed consent agreement.

[4] Read to Interviewee: *I will give you time to review the survey instructions then respond to a series of survey items. While you are responding to the survey items, you will need to speak out loud what you are thinking until you have selected a response and are ready to proceed to the next item. During the interview I will not be able to answer any questions regarding the content of the survey items. If you have any questions about the survey items, voice them and continue to talk aloud as you decide how to proceed.*

Do you have any questions about the interview before we begin?

Read the instruction for the survey. Take your time, there is no rush. Let me know when you are ready to proceed to the first survey item.

Appendix B

PART 3 - During the Interview (begin recording)

[5] Instructions for interviewer: Allow the participant to read the instructions for survey.

[6] Read to Interviewee: *Read and respond to item 1. Once you have selected a response for Item 1, wait for my cue before moving on to Item 2.* [Read this before Item 1, only repeat if participant is not following instructions.] *As a reminder, please speak out loud what you are thinking. I will not be able to answer any questions regarding the content or meaning of the survey items. If you have any questions, voice them and continue to talk aloud as you decide which option to select.*

[7] Instructions for interviewer: Allow time for participant to read and respond to Item 1. Do not interrupt the think-aloud portion of the interview.

- If the participant asks you any question regarding the survey item, remind them you are not able to answer the question and they should talk aloud as they decide how to select a response with what they know.
- If the participant asks a question about the interview procedures, answer the question as parsimoniously as possible, and try to avoid engaging in a discussion.
- If the participant is quiet for more than 5 seconds, gently remind them to speak their thoughts out loud.

While the participant is talking, listen for evidence of the following:

- How did the participant interpret the item/what did they think the question was asking?
- What responses did they consider?
- What evidence did they use to make a selection?
- Did they identify any part of the instructions, survey item, or item choices as being difficult or unclear?

Once the participant has made a selection, ask one to three follow-up questions. Consider the following:

- If the participant was unsure of selection:
  - *I noticed you did not seem confident of your selection for this item, can you tell me what made it difficult?*
- If the participant arrived at a response very quickly, or said very little:
  - *In your own words, can you restate what this item was asking?*
  - *Which of the options did you consider selecting as the correct one?*
- If the participant is struggling to find any response that is appropriate (e.g., doesn't think any of the six are correct):
  - *In your own words, what do you think the correct response should be?*
- If the participant is struggling to find only one response that is appropriate (e.g., doesn't think any of the six are correct):
  - *I noticed you seemed to be struggling between two (or more) of the responses, what about these selections made them seem plausible?*

[8] Instructions for the interviewer: Repeat steps [6] and [7] for the remaining items.

[9] Instructions for the interviewer: After all items or approximately 30 minutes have elapsed, whichever comes first, end the interview and thank the participant for their time and value added to the study.

PART 4 - After the Interview

[10] Instructions for the interviewer: Save the instrument used by the student, the informed consent agreement, and any of your interview notes.

ASSESSMENT QUESTIONS USED FOR THINK-ALOUDS, ROUND 1

Appendix A
Research Experience Instrument (REI)

<u>Instructions</u>

The following questions are related to engineering graduate students' perceptions about how often in their graduate research experiences they utilized skills relevant to professional practice. Respondents are asked to take special note that this is NOT an assessment of their research skills; rather, it is an assessment of their perceptions about their research experience and how often they did things related to professional practice in their research experience.

In the survey below, there are 47 questions, and it is estimated it will take approximately 30 minutes to complete. For each of the questions that follow, please indicate the extent to which your research experience contributed to the item in question. You should do this by selecting the response that most closely matches from the options provided.

How often in your graduate research experience did you:

1. take on different roles or responsibilities within a research team?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

2. coordinate research tasks with other graduate students to accomplish research goals?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

3. share decision making responsibility with other graduate students to accomplish research goals?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

4. develop new skills based on the needs of the research team's goals?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

5. mutually depend on other graduate students to meet the desired research outcomes?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

6. present your research results to your sponsors or collaborators (i.e., practicing professional engineers) who are involved in your research work?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

7. interact with your sponsors or collaborators (i.e., practicing professional engineers) at your institution who are involved in your research work?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

Appendix A
Research Experience Instrument (REI)

How often in your graduate research experience did you:

8. correspond (e.g., email, phone, etc.) with your sponsors or collaborators (i.e., practicing professional engineers) who are involved in your research work?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

9. interact with your sponsors or collaborators at their place of work related to your research work?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

10. co-write journal or conference papers with your sponsors or collaborators?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

11. co-present at conferences with your sponsors or collaborators?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

12. develop professional relationships with working professionals (other than your sponsors or collaborators) through your research work?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

13. attend industry or government events (e.g., trade shows, exhibitions, etc.) as part of your research work?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

14. participate in industry or government conferences as part of your research work?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

15. participate in professional engineering societies (e.g., Institute of Electrical and Electronics Engineers, Society of Women Engineers, etc.) related to your graduate research studies?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

16. present results of your research to professional engineers other than your sponsors or collaborators?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

17. hold an internship or co-op during your graduate research studies?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

Appendix A

Research Experience Instrument (REI)

How often in your graduate research experience did you:

18. interact with support professionals (e.g., project managers, building maintenance, outside vendors, etc.) to accomplish research objectives?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

19. develop or utilize a mathematical model to help solve a research problem?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

20. specify constraints or assumptions in development of a mathematical model to help solve a research problem?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

21. utilize sophisticated engineering modeling or simulation tools to help solve a research problem?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

22. simulate the performance of a system to accomplish research goals?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

23. iterate on the development of a model or simulation to optimize research results?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

24. verify a model or simulation against real-world data or actual results?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

25. use physical equipment or instrumentation as an integral part of conducting your research?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

26. plan how to use or deploy experimental equipment or instrumentation to gather valid data relevant to your research?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

27. ensure the physical equipment or instrumentation is appropriately set-up (i.e., calibrated) before use?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

How often in your graduate research experience did you:

28. collect data from test equipment or physical apparatus using appropriate sensors or instrumentation?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

29. interpret data gathered from physical equipment or apparatus?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

30. troubleshoot or modify experimental equipment or instrumentation when it does not operate properly?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

Self-report Questions:

1. Including yourself, approximately how many members are in your research group?

    ____

2. How is your research group organized?

    1) Research group is structured where the advisor sets most of the interactions, communication, and mentoring of students

    2) Research group is structured where much of the communication and mentoring is student-to-student, with the faculty advisor leading in a functional role

    3) Other.

3. How is your research work organized?

    1) Most of the day-to-day work involves working by myself or with my advisor

    2) Most of the day-to-day work involves interaction with a broader team within the research group

    3) Other

4. What is your graduate engineering major?
    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

Appendix A
Research Experience Instrument (REI)

5. What type of research are you primarily working on?

   1) Basic (fundamental research without specific applications towards processes or products in mind)

   2) Applied (research that has specific applications towards processes or products)

   3) Other

6. What type of collaborators, either internal or external, do you work with primarily in your research?

   1) A strong emphasis on government collaborations

   2) A strong emphasis on industry collaborations

   3) A strong emphasis on research center collaborations

   4) Other

7. What type of interactions do you have with the collaborators identified in the previous question?

   1) Collaborations consist of infrequent contact, mostly written reports, resulting in a relationship with the collaborators that are not very deep.

   2) Collaborations consist of frequent contact, including email and face-to-face interaction for reporting results, resulting in a deep relationship with the collaborators

   3) Other

8. What type of equipment do you primarily use to conduct your research?

   1) The primary nature of the research work relies on modeling and simulation with sophisticated computers equipment and software tools.

   2) The primary of the research work relies on facilities, test equipment, and physical experiments

   3) Other

9. How is the work space for your research group organized?

   1) Housed in a lab space or office where I work mostly alone or near a few others.

   2) Housed in a lab space that is shared with multiple different types of research groups

   3) Other

Demographic Questions:

1. What is your gender?

   1) male, 2) female, 3) other.

Appendix A
Research Experience Instrument (REI)

2. What degree are you seeking?

   1) Master's, 2) PhD, 3) Both, 4) not applicable.

3. Have you completed your department/school qualification exam?

   1) yes, 2) no 3) not applicable.

4. What is your ethnicity of origin? Please check any that you identify with.

   1) White/Caucasian, 2) Black/African American, 3) Hispanic or Latino, 4) Native American, 5) Asian, 6) Pacific Islander, 7) Other, 8) Other –TEXT ENTER-, 9) I prefer not to respond

5. Have you ever worked full-time in industry (not including internships or co-ops)?

   1) yes, 2) no 3) not applicable.

6. If you had an internship or co-op during graduate school, was it related to your research work?

   1) yes, 2) no 3) not applicable.

7. Have you been a Teaching Assistant or Instructor during graduate school?

   1) yes, 2) no 3) not applicable.

8. What is the primary source of funding for your research?

   1) government (e.g., NSF, DOE, etc.), 2) industry, 3) not funded, 4) other.

RECRUITMENT FLYER USED FOR THINK-ALOUDS

PARTICIPANTS NEEDED

FOR A SURVEY THINK-ALOUD STUDY

We are looking for volunteers to take part in a study to read survey items about engineering graduate students' research experiences and indicate your thought process in selecting a response.

As a participant in this study, you will be asked to participate in an ***interview***. This protocol will take approximately ***30 minutes*** and will be scheduled at a time and location on campus that is convenient for you.

WHO IS ELIGIBLE

- Purdue Engineering PhD students
- 18 years of age or older

FOR MORE INFORMATION

about this study, please contact:

Eric Holloway
Graduate Student, School of Engineering Education
765-496-6051
eahollow@purdue.edu

or

Dr. Kerrie Douglas,
Assistant Professor, School of Engineering Education
765-494-6932
douglask@purdue.edu

To participate in this study, please contact Eric Holloway at eahollow@purdue.edu to indicate your interest and schedule an interview.

This study has been reviewed by, and received ethics clearance through, the Human Research Protection Program, Purdue University

To participate, contact Eric Holloway at: **eahollow@purdue.edu**	To participate, contact Eric Holloway at: **eahollow@purdue.edu**	To participate, contact Eric Holloway at: **eahollow@purdue.edu**	To participate, contact Eric Holloway at: **eahollow@purdue.edu**	To participate, contact Eric Holloway at: **eahollow@purdue.edu**	To participate, contact Eric Holloway at: **eahollow@purdue.edu**	To participate, contact Eric Holloway at: **eahollow@purdue.edu**	To participate, contact Eric Holloway at: **eahollow@purdue.edu**	To participate, contact Eric Holloway at: **eahollow@purdue.edu**	To participate, contact Eric Holloway at: **eahollow@purdue.edu**	To participate, contact Eric Holloway at: **eahollow@purdue.edu**	To participate, contact Eric Holloway at: **eahollow@purdue.edu**

IRB CONSENT FORM FOR THINK-ALOUDS

Purdue IRB Protocol #: 1810021221 - Expires: 09-JAN-2022

RESEARCH PARTICIPANT CONSENT FORM

REI assessment of construct validity
Principal Investigator: Kerrie Douglas
School of Engineering Education
Purdue University

Key Information

Please take time to review this information carefully. This is a research study. Your participation in this study is voluntary which means that you may choose not to participate at any time without penalty or loss of benefits to which you are otherwise entitled. You may ask questions to the researchers about the study whenever you would like. If you decide to take part in the study, you will be asked to sign this form, be sure you understand what you will do and any possible risks or benefits. The purpose of this study is to measure graduate students' perceptions about how often in their graduate research experiences students utilized skills relevant to professional practice. The duration of the study will be one session for approximately 30 minutes. Additional explanations may be more detailed in the sections below.

What is the purpose of this study?

You are being asked to participate in this study so that we can investigate how graduate students conceptualize potential survey items that assess their perceptions about their research experience. We would like to enroll 50 people in this study.

What will I do if I choose to be in this study?

You will be given a paper copy assessment survey and asked to 'think-aloud' while you complete the assessment. You will be asked to translate what you think the question is asking, what your thought process is in selecting the response, and justify your selection. The interview will be audio-recorded, and then evaluated later.

How long will I be in the study?

It is anticipated it will take approximately 30 minutes to complete.

What are the possible risks or discomforts?

Breach of confidentiality is always a risk with data, but we will take precautions to minimize this risk as described in the confidentiality section. There are no other risks associated with your participation in this study than what you would normally encounter in daily life. Should you not wish to continue with the interview you may stop at any time.

Are there any potential benefits?

There are no direct benefits to the participants. Indirect benefits include that the results of this study may be used to finalize a list of survey items that assess graduate students perceptions about their research experience.

Will information about me and my participation be kept confidential?

The project's research records may be reviewed by the departments at Purdue University responsible for regulatory and research oversight.

The only identifiable information will be the documentation of the consent form for participating in this study. The only information retained about the subjects will be some basic demographic information,

IRB No._______________ Page 1

to assist in analyzing the data, which will be encoded in the name of the data file. No identifiable information will be retained.

All data will be stored on a secure file server and only accessible to the research team consisting of Dr. Kerrie Douglas and Eric Holloway. Audio files will be transcribed and destroyed. Data, including transcriptions, will be stored indefinitely, and aggregate results could be utilized for publication.

What are my rights if I take part in this study?
Your participation in this study is voluntary. You may choose not to participate or, if you agree to participate, you can withdraw your participation at any time without penalty or loss of benefits to which you are otherwise entitled.

Who can I contact if I have questions about the study?

If you have questions, comments or concerns about this research project, you can talk to one of the researchers. Please contact:

Dr. Kerrie Douglas, Engineering Education, douglask@purdue.edu, 494-6932
Eric Holloway, Engineering Education, eahollow@purdue.edu, 496-6051

To report anonymously via Purdue's Hotline see www.purdue.edu/hotline

If you have questions about your rights while taking part in the study or have concerns about the treatment of research participants, please call the Human Research Protection Program at (765) 494-5942, email (irb@purdue.edu) or write to:

Human Research Protection Program - Purdue University
Ernest C. Young Hall, Room 1032
155 S. Grant St.
West Lafayette, IN 47907-2114

Documentation of Informed Consent
I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research study, and my questions have been answered. I am prepared to participate in the research study described above. I will be offered a copy of this consent form after I sign it.

_________________________________ ____________________
Participant's Signature Date

____
Participant's Name

_________________________________ ____________________
Researcher's Signature Date

ASSESSMENT QUESTIONS USED FOR THINK-ALOUDS, ROUND 2

Appendix A
Research Experience Instrument (REI)

Instructions

The following questions are related to engineering Ph.D. students' perceptions about how often in their Ph.D. research experiences they utilized skills relevant to professional practice. Respondents are asked to take special note that this is NOT an assessment of their research skills; rather, it is an assessment of their perceptions about their research experience and how often they did things related to professional practice in their research experience.

In the survey below, there are 47 questions, and it is estimated it will take approximately 15 minutes to complete. For each of the questions that follow, please how often in your Ph.D. research experience you did the items in question. You should do this by selecting the response that most closely matches from the options provided.

How often in your Ph.D. research experience did you:

1. take on different roles or responsibilities within a research team?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

2. coordinate research tasks with other graduate students?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

3. share decision making responsibility with other graduate students?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

4. develop new skills (e.g., presentation, project management, software, etc.) based on the needs of the research team's goals?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

5. mutually depend on other graduate students to meet the desired outcomes?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

6. present your research results to your sponsors or collaborators (i.e., practicing engineers) who are involved in your research?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

7. interact at your institution with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

Appendix A
Research Experience Instrument (REI)

How often in your Ph.D. research experience did you:

8. correspond (e.g., email, phone, etc.) with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

9. interact with your sponsors or collaborators at their place of work related to your research?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

10. co-author journal or conference papers with your sponsors or collaborators?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

11. co-create a presentation with your sponsors or collaborators?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

12. develop professional relationships with practicing engineers (other than your sponsors or collaborators) through your research?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

13. participate in industry or government conferences as part of your research?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

14. participate in professional engineering societies (e.g., Institute of Electrical and Electronics Engineers, Society of Women Engineers, etc.)?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

15. present results of your research to practicing engineers (other than your sponsors or collaborators)?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

16. interact with practicing engineers during internships or co-ops?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

17. interact with support professionals (e.g., project managers, building maintenance, outside vendors, etc.)?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

Appendix A
Research Experience Instrument (REI)

How often in your Ph.D. research experience did you:

18. develop or utilize a mathematical model to help solve a problem?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

19. specify constraints or assumptions in development of a mathematical model to help solve a problem?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

20. utilize sophisticated tools to help solve an engineering modeling or simulation problem?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

21. simulate the performance of a system to obtain results?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

22. iterate on the development of a model or simulation to optimize results?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

23. verify a model or simulation against real-world data or actual results?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

24. use test equipment or instrumentation as an integral part of conducting your research?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

25. develop plans to use test equipment or instrumentation?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

26. ensure the test equipment or instrumentation is appropriately set-up (i.e., calibrated) before use?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

27. collect data from test equipment or apparatus using appropriate sensors or instrumentation?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

Appendix A
Research Experience Instrument (REI)

How often in your Ph.D. research experience did you:

28. interpret data gathered from test equipment or apparatus?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

29. troubleshoot or modify test equipment or instrumentation when it does not operate properly?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

Self-report Questions:

1. Including yourself, approximately how many members are in your research group?

   ____

2. How is your Ph.D. research group organized?

   1) The research group is structured where the advisor sets most of the interactions, communication, and mentoring of students

   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

   3) Other (explain)

3. How is your Ph.D. research work organized?

   1) Most of the day-to-day work involves working by myself or with my advisor

   2) Most of the day-to-day work involves interaction with a broader team within the research group

   3) Other (explain)

4. What is your engineering Ph.D. major?

   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)

Appendix A
Research Experience Instrument (REI)

5. What type of Ph.D. research are you primarily working on?

    1) Basic (fundamental research without specific applications towards processes or products in mind)

    2) Applied (research that has specific applications towards processes or products)

    3) Other (explain)

6. What type of collaborators, either internal or external, do you work with primarily in your Ph.D. research?

    1) A strong emphasis on government collaborations

    2) A strong emphasis on industry collaborations

    3) A strong emphasis on research center collaborations

    4) Other (explain)

7. What type of interactions do you have with the collaborators identified in the previous question?

    1) Collaborations consist of infrequent contact, mostly written reports, resulting in a relationship with the collaborators that are not very deep.

    2) Collaborations consist of frequent contact, including email and face-to-face interaction for reporting results, resulting in a deep relationship with the collaborators

    3) Other (explain)

8. What type of equipment do you primarily use to conduct your Ph.D. research?

    1) The primary nature of the research work relies on modeling and simulation with sophisticated computer equipment and software tools.

    2) The primary nature of the research work relies on facilities, test equipment, and physical experiments.

    3) A combination of 1 & 2 above

    4) Other (explain)

9. How is the work space for your Ph.D. research group organized?

    1) Housed in a lab space or office where I work mostly alone or near a few others.

    2) Housed in lab space that is shared with my research team only

    3) Housed in a lab space that is shared with multiple different types of research groups

    4) Other (explain)

Appendix A
Research Experience Instrument (REI)

Demographic Questions:

1. What is your gender?

   1) male, 2) female, 3) other.

2. What degree are you seeking?

   1) Master's, 2) Ph.D., 3) Both, 4) not applicable.

3. Have you completed your department/school qualification exam (e.g., area exam)?

   1) yes, 2) no 3) not applicable.

4. What is your ethnicity of origin? Please check any that you identify with.

   1) White/Caucasian, 2) Black/African American, 3) Hispanic or Latino, 4) Native American, 5) Asian, 6) Pacific Islander, 7) Other, 8) Other –TEXT ENTER-, 9) I prefer not to respond

5. Have you ever worked full-time in industry (not including internships or co-ops)?

   1) yes, 2) no 3) not applicable.

6. If you had an internship or co-op during your Ph.D. research, was it related to your research?

   1) yes, 2) no 3) not applicable.

7. Have you been a Teaching Assistant or Instructor during your Ph.D. research?

   1) yes, 2) no 3) not applicable.

8. What is the primary source of funding for your Ph.D. research?

   1) government (e.g., NSF, DOE, etc.), 2) industry, 3) not funded, 4) other (explain).

9. Where do you see yourself working after graduation?

   1) government, 2) industry, 3) academia, 4) other (explain).

THINK-ALOUD RESULTS

Table B.2: *Assessment Question Expert Review Scores* (n = 10)

Assessment Question	Range	Scale Description	*n*	%
Q1: take on different roles or responsibilities within a research team?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	2	20
	Clearly Aligned	Clearly Aligned = 3	8	80
Q2: coordinate research tasks with other graduate students to accomplish research goals?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	0	0
	Clearly Aligned	Clearly Aligned = 3	10	100
Q3: share decision making responsibility with other graduate students to accomplish research goals?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	1	10
	Clearly Aligned	Clearly Aligned = 3	9	90
Q4: develop different skill sets to complement the needs of the research team's goals?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	4	40
	Clearly Aligned	Clearly Aligned = 3	6	60
Q5: depend on other graduate students to meet the desired research outcomes?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	2	20
	Clearly Aligned	Clearly Aligned = 3	8	80
Q6: present your research results to your sponsors or collaborators (i.e., practicing professional engineers) who are involved in your research work?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	0	0
	Clearly Aligned	Clearly Aligned = 3	10	100
Q7: meet at your institution with your sponsors or collaborators (i.e., practicing professional engineers) who are involved in your research work?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	2	20
	Clearly Aligned	Clearly Aligned = 3	8	80
Q8: correspond (e.g., email, phone, etc.) with your sponsors or collaborators (i.e., practicing professional engineers) who are involved in your research work?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	0	0
	Clearly Aligned	Clearly Aligned = 3	10	100

Assessment Question	Range	Scale Description	*n*	%
Q9: meet with your sponsors or collaborators at their place of work to discuss your research or results?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	2	20
	Clearly Aligned	Clearly Aligned = 3	8	80
Q10: co-write journal or conference papers with your sponsors or collaborators?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	0	0
	Clearly Aligned	Clearly Aligned = 3	10	100
Q11: co-present at conferences with your sponsors or collaborators?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	0	0
	Clearly Aligned	Clearly Aligned = 3	10	100
Q12: develop professional relationships with working engineers through your research work?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	2	20
	Clearly Aligned	Clearly Aligned = 3	8	80
Q13: attend industry or government trade shows as part of your research work?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	2	20
	Clearly Aligned	Clearly Aligned = 3	8	80
Q14: participate in industry or government conferences as part of your research work?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	0	0
	Clearly Aligned	Clearly Aligned = 3	9	100
Q15: participate in professional engineering societies (e.g., Institute of Electrical and Electronics Engineers, Society of Women Engineers, etc.) related to your graduate research studies?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	1	10
	Clearly Aligned	Clearly Aligned = 3	9	90
Q16: present results of your research to professional engineers (other than your sponsors or collaborators)?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	0	10
	Clearly Aligned	Clearly Aligned = 3	10	90
Q17: hold an internship or co-op during your graduate research studies?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	1	10
	Clearly Aligned	Clearly Aligned = 3	9	90

Assessment Question	Range	Scale Description	*n*	%
Q18: interact with support professionals (e.g., project managers, building maintenance, outside vendors, etc.) to accomplish research objectives?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	3	30
	Clearly Aligned	Clearly Aligned = 3	7	70
Q19: develop or utilize a mathematical model to help solve a research problem?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	1	10
	Clearly Aligned	Clearly Aligned = 3	9	90
Q20: utilize complex engineering modeling or simulation tools to help solve a research problem?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	1	10
	Clearly Aligned	Clearly Aligned = 3	9	90
Q21: simulate the performance of a system to accomplish research goals?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	1	10
	Clearly Aligned	Clearly Aligned = 3	9	90
Q22: iterate on the development of a model or simulation to optimize research results?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	1	10
	Clearly Aligned	Clearly Aligned = 3	9	90
Q23: verify a model or simulation against real-world data or actual results?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	0	0
	Clearly Aligned	Clearly Aligned = 3	10	100
Q24: use physical equipment or instrumentation as an integral part of conducting your research?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	1	10
	Clearly Aligned	Clearly Aligned = 3	9	90
Q25: plan how to use or deploy experimental equipment or instrumentation to gather valid data relevant to your research?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	0	0
	Clearly Aligned	Clearly Aligned = 3	10	100
Q26: ensure the physical equipment or instrumentation is appropriately set-up (i.e., calibrated) before use?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	0	0
	Clearly Aligned	Clearly Aligned = 3	10	100

Assessment Question	Range	Scale Description	*n*	%
Q27: collect data from test equipment or physical apparatus using appropriate sensors or instrumentation?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	2	20
	Clearly Aligned	Clearly Aligned = 3	8	80
Q28: interpret data gathered from physical equipment or apparatus?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	1	10
	Clearly Aligned	Clearly Aligned = 3	9	90
Q29: troubleshoot or modify experimental equipment or instrumentation when it does not operate properly?	Not Aligned	Not Aligned = 1	0	0
	Somewhat Aligned	Somewhat Aligned = 2	0	0
	Clearly Aligned	Clearly Aligned = 3	10	100

Table B.3: *Relevant Demographic Information for Think-Aloud Participants* (n = 12)

Characteristic	Explanation	Range	Scale Description	*n*	%
Gender	Ph.D. student's gender	Male	Male = 1	8	66.7
		Female	Female = 2	4	33.3
		Other	Other = 3	0	0.0
Degree sought	Ph.D. student's degree sought	Master's	Master's = 1	0	0.0
		Ph.D.	Ph.D. = 2	11	91.7
		Both	Both = 3	1	8.3
		N/A	N/A = 3	0	0.0
Qualifying/area exam	Ph.D. student completed department's qualifying/area exam?	Yes	Yes = 1	8	66.7
		No	No = 2	3	25.0
		N/A	N/A = 3	1	8.3
Ethnicity	Ph.D. student's race/ethnicity	White/Caucasian	White/Caucasian = 1	4	33.3
		Black/African American	Black/African American = 2	0	0.0
		Hispanic or Latino	Hispanic or Latino = 3	1	8.3
		Native American	Native American = 4	0	0.0
		Asian	Asian = 5	7	58.3
		Pacific Islander	Pacific Islander = 6	0	0.0
		Other	Other = 7	0	0.0
		Other (specified)	Other (specified) = 8	0	0.0
		Prefer not to respond	Prefer not to respond = 9	0	0.0
		Multiple selected		0	0.0

Table B.4: *Updated List of Assessment Changes from Think-Aloud 1*

Ontological Aspect	1. Work as a team member
What is the essence of this?	Students' experiences being a team member working on research – experiences where students do the types of working in a team that practicing engineers do.
Conceptualization:	This aspect is conceptualized as what it means for engineering Ph.D. students to be a member of a research team 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.
Definition:	Two or more engineering Ph.D. students who share a commitment to common research goals that are part of a larger research group in which members have differentiated skill sets, roles, and responsibilities in which they make decisions and coordinate tasks to accomplish research goals while exhibiting interdependencies with respect to workflow, goals, and outcomes (adapted from Fernandez et al. (2008)).
Ontological Aspect	2. Exposure to collaborator's form of practice
	Exhibit professional actions and behaviors through exposure to collaborator's form of practice (i.e., practicing engineers)
What is the essence of this?	Students' experiences being engaged with practicing engineers involved in the students' research – experiences where students exhibit professional behavior through interactions with practicing engineers.
Conceptualization:	This aspect is conceptualized as what it means for engineering Ph.D. students to exhibit professional actions and behaviors by working with practicing engineers who are the students' main collaborator in their research work. This opportunity to exhibit professional actions and behaviors typically occurs with regular interaction through email, face-to-face meetings, presenting of results, etc. where students exhibit professional actions and behaviors by emulating other practicing engineers.
Definition:	An engineering Ph.D. student exhibiting professional actions and behaviors with practicing engineers in the act of working in close collaboration together on research through regular interaction (adapted from Aldridge (1994)).
Ontological Aspect	3. Exposure to relevant professional practice
	Exhibit professional actions and behaviors through exposure to professional engineers
What is the essence of this?:	The students' wider experiences being engaged with practicing engineers (conferences, internships, professional societies, etc.) – experiences where students exhibit professional behavior through interactions with practicing engineers through their wider research experiences.
Conceptualization:	This aspect is conceptualized as what it means for engineering Ph.D. students to exhibit professional actions and behaviors by working with practicing engineers related to their wider research experiences, such as conferences, internships, professional societies, etc.

Definition:	A graduate engineering student exhibiting professional actions and behaviors with practicing professional engineers through to their wider research experiences, such as conferences, internships, and professional societies where professional networks are developed (adapted from Aldridge (1994)).
Ontological Aspect	4. Modeling and simulation tasks
What is the essence of this?:	Students' experiences being engaged with modeling and simulation tasks as a signification part of their research work – experiences where students do the types of modeling and simulation work that practicing engineers do.
Conceptualization:	This aspect is conceptualized as what it means for graduate engineering students to utilize to the computational thinking, methods, and techniques that practicing engineers use to solve research problems. It is expected that most students will have some exposure to this in their research experiences.
Definition:	The process of engineering Ph.D. students identifying engineering problems, specifying constraints and assumptions in order to design and develop a mathematical model, often utilizing sophisticated engineering tools. The process continues with the verification and optimization of the model by evaluating the simulated performance of the system in an iterative process that utilizes refinement of the constraints, assumptions, and the model itself, facilitated by knowledge and discovery (adapted from (Magana & Coutinho, 2017); Radcliffe (2014)).
Ontological Aspect	5. Practical Skills
What is the essence of this?:	Students' experiences being engaged with practical skills that translate to a real-world setting as a significant part of their research work – experiences where students do work that involves physical experiments, equipment set-up, and troubleshooting, and collect data from physical phenomena and have to interpret and translate results.
Conceptualization:	This aspect is conceptualized as what it means for engineering Ph.D. students to be exposed to research experiences that involve experiments that require students to engage with complex physical experiments that require machinery, instrumentation, etc. and require them to be a part of the installation, operation, and maintenance of the experiment and the machinery. This work often requires troubleshooting of broken equipment and interaction with the larger research enterprise, such as support staff, building maintenance, and outside vendors.
Definition:	Engineering research tasks in which engineering Ph.D. students plan, use, and/or deploy physical equipment or instrumentation, ensuring proper operation, collection, and interpretation of data, and troubleshooting and repair of the equipment or instrumentation to support the research endeavor (adapted from Lumpe and Oliver (1991); (Rivera-Reyes & Boyles, 2013)).

APPENDIX C. PILOT TEST 1

ASSESSMENT QUESTIONS USED FOR PILOT TEST 1

Research Experience Instrument (REI) – In Order

Instructions

The following questions are related to engineering Ph.D. students' perceptions about how often in their Ph.D. research experiences they utilized skills relevant to professional practice. Respondents are asked to take special note that this is NOT an assessment of their research skills; rather, it is an assessment of their perceptions about their research experience and how often they did things related to professional practice in their research experience.

In the survey below, there are 47 questions, and it is estimated it will take approximately 15 minutes to complete. For each of the questions that follow, please indicate how often in your Ph.D. research experience you did the items in question. You should do this by selecting the response that most closely matches from the options provided.

How often in your Ph.D. research experience did you:

1. take on different roles or responsibilities within a research group?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

2. coordinate research tasks with other graduate students?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

3. share decision making responsibility with other graduate students?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

4. develop new skills (e.g., presentation, project management, software, etc.) based on the needs of the research group's goals?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

5. mutually depend on other graduate students to meet the desired outcomes?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

6. present your research results to your sponsors or collaborators (i.e., practicing engineers) who are involved in your research?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

7. interact at your university with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

Research Experience Instrument (REI) – In Order

How often in your Ph.D. research experience did you:

8. correspond (e.g., email, phone, etc.) with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

9. interact with your sponsors or collaborators at their place of work related to your research?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

10. co-author journal or conference papers with your sponsors or collaborators?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

11. co-create a presentation with your sponsors or collaborators?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

12. develop professional relationships with practicing engineers (other than your sponsors or collaborators) through your research?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

13. participate in industry or government conferences as part of your research?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

14. participate in professional engineering societies (e.g., Institute of Electrical and Electronics Engineers, Society of Women Engineers, etc.)?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

15. present results of your research to practicing engineers (other than your sponsors or collaborators)?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

16. interact with practicing engineers during internships or co-ops?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

17. interact with support professionals (e.g., project managers, building maintenance, outside vendors, etc.)?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

Research Experience Instrument (REI) – In Order

How often in your Ph.D. research experience did you:

18. develop or utilize a mathematical model to help solve a problem?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

19. specify constraints or assumptions in development of a mathematical model to help solve a problem?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

20. utilize sophisticated tools to help solve a modeling or simulation problem?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

21. simulate a system to obtain results?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

22. iterate on the development of a model or simulation to optimize results?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

23. verify a model or simulation based on real-world data or actual results?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

24. use testing equipment or instrumentation as an integral part of conducting your research?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

25. develop plans to use testing equipment or instrumentation?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

26. ensure testing equipment or instrumentation is appropriately set-up (i.e., calibrated) before use?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

27. collect data from testing equipment or apparatus using appropriate sensors or instrumentation?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

Research Experience Instrument (REI) – In Order

How often in your Ph.D. research experience did you:

28. interpret data gathered from testing equipment or apparatus?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

29. troubleshoot or modify testing equipment or instrumentation when it does not operate properly?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

Self-report Questions:

1. Including yourself, approximately how many graduate student members are in your research group?

   ____

2. How is your Ph.D. research group organized?

   1) The research group is structured where the advisor sets most of the interactions, communication, and mentoring of students

   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

   3) Other (explain)

3. How is your Ph.D. research work organized?

   1) Most of the day-to-day work involves working by myself or with my advisor

   2) Most of the day-to-day work involves interaction with a broader team within the research group

   3) Other (explain)

4. What is your engineering Ph.D. major?

   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)

5. What type of Ph.D. research are you primarily working on?

   1) Basic (fundamental research without specific applications towards processes or products in mind)

   2) Applied (research that has specific applications towards processes or products)

   3) Other (explain)

6. What type of collaborators, either internal or external, do you work with primarily in your Ph.D. research?

   1) A strong emphasis on government collaborations

   2) A strong emphasis on industry collaborations

   3) A strong emphasis on university research center collaborations

   4) Other (explain)

7. What type of interactions do you have with the collaborators identified in the previous question?

   1) Collaborations consist of infrequent contact, mostly written reports, resulting in a relationship with the collaborators that are not very deep.

   2) Collaborations consist of frequent contact, including email and face-to-face interaction for reporting results, resulting in a deep relationship with the collaborators.

   3) Other (explain)

8. What type of equipment do you primarily use to conduct your Ph.D. research?

   1) The primary nature of the research work relies on modeling and simulation with sophisticated computer equipment and software tools.

   2) The primary nature of the research work relies on facilities, testing equipment, and physical experiments.

   3) A combination of 1 & 2 above

   4) Other (explain)

9. How is the work space for your Ph.D. research group organized?

   1) Housed in a lab space or office where I work mostly alone or near a few others.

   2) Housed in lab space or office that is shared with my research group only.

   3) Housed in a lab space that is shared with multiple different types of research groups.

   4) Other (explain)

Research Experience Instrument (REI) – In Order

Demographic Questions:

1. What is your gender?

   1) male, 2) female, 3) non-binary.

2. What degree are you seeking?

   1) Master's, 2) Ph.D., 3) Both, 4) not applicable.

3. Have you completed your department/school qualification exam (e.g., area exam)?

   1) yes, 2) no 3) not applicable.

4. What is your ethnicity of origin? Please check any that you identify with.

   1) White/Caucasian, 2) Black/African American, 3) Hispanic or Latino, 4) Native American, 5) Asian, 6) Pacific Islander, 7) Other, 8) Other –TEXT ENTER-, 9) I prefer not to respond

5. Have you ever worked full-time in industry (not including internships or co-ops)?

   1) yes, 2) no 3) not applicable.

6. If you had an internship or co-op during your Ph.D. research, was it related to your research?

   1) yes, 2) no 3) not applicable.

7. Have you been a Teaching Assistant or Instructor during your Ph.D. research?

   1) yes, 2) no 3) not applicable.

8. What is the primary source of funding for your Ph.D. research?

   1) government (e.g., NSF, DOE, etc.), 2) industry, 3) not funded, 4) other (explain).

9. Where do you see yourself working after graduation?

   1) government, 2) industry, 3) academia, 4) other (explain).

IRB APPROVAL FOR PILOT TESTING

PURDUE UNIVERSITY

HUMAN RESEARCH PROTECTION PROGRAM
INSTITUTIONAL REVIEW BOARDS

To:	DOUGLAS, KERRIE A
From:	Institutional Review Board
Date:	06 / 24 / 2019
Committee Action:	**IRB Approval of Amendment, Expedited Category (7)**
Approval Date:	06 / 21 / 2019
IRB Protocol #:	1902021788
Amendment Version	Amendment-001:
Study Title:	REI pilot data collection
Expiration Date:	05 / 07 / 2022
Subjects Approved:	5000

The above referenced protocol amendment has been approved by the Purdue IRB.

The expiration date for IRB approval has not been altered.

Approved study documents are in the Attachments section of this protocol in CoeusLite.

You are required to retain a copy of this letter for your records.

We appreciate your commitment towards ensuring the ethical conduct of human subject research and wish you well with your study.

Ernest C. Young Hall, 10th Floor - 155 S. Grant St. - West Lafayette, IN 47907-2114 - (765) 494-5942 - Fax: (765) 494-9911

REGISTRAR AGREEMENT

PURDUE
UNIVERSITY

OFFICE OF THE REGISTRAR

To: IRB Administrator/Chair

From: Keith Gehres, University Registrar

Date: 6/11/2019

Subject: Data Agreement Approval for Research Study

Project Title: REI Pilot Data Collection

IRB Number: 1902021788

This memo is in regards to the access of restricted student data requested by Kerrie Douglas, principal investigator for research purposes. The Office of the Registrar reviewed the IRB Proposal and the Data Agreement to ensure proper use of the student data including storage and destruction. The investigators will pull all student data and agree to withhold small subsets of student populations if they determine that students can be identified by race, gender, age or other demographic characteristics.

The following data elements will be pulled from COGNOS:

Target Population: Current PWL PhD studnets
Initial Email to request participation to target population (IRB approved verbiage)
2 follow up emails to target population (IRB approved verbiage)
Self reported data from survey participants as approved by IRB

610 PURDUE MALL • WEST LAFAYETTE, IN 47907-2040
(765) 494-8581 • FAX: (765) 494-0570

PURDUE
UNIVERSITY

OFFICE OF THE REGISTRAR

The co-investigators will extract student data through the University approved reporting tool (COGNOS) as outlined in the data agreement. All data must be destroyed, as defined in the data agreement, by December 31, 2025 . Individual student data will not be shared and only summary (non-identifiable) data will be published.

I approve of Kerrie Douglas and co-investigators accessing the student data as outlined in the data agreement.

C: Kerrie Douglas, Principal Investigator
Eric Holloway, Co-Investigator

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(765) 494-8581 • FAX: (765) 494-0570

Office of the Registrar - Purdue University

Revised 01/13

Data Agreement

IRB# 1902021788

Study Title: REI pilot data collection 1

1. Indicate how you will obtain the data:
   - ☐ Requesting the Office of the Registrar to provide data
   - ☐ Registrar data will be obtained through the University approved reporting tool COGNOS.
     Indicate who will be pulling the data: ______
   - ☒ Other (Please indicate) Distribute a survey via email to engineering PhD students at Purdue

2. List any publications or communications you intend to initiate as a result of the data analysis

   Aggregate results from the survey and analysis could be utilized for publication in journal and conference papers.

3. List the specific student data items you are requesting or obtaining through the University approved reporting tool Cognos and how you intend to use the data item to meet the purpose or goal of the project.

   We are requesting the Registrar's Office distribute a survey to engineering PhD students at Purdue West Lafayette via email per the approved IRB protocol 1902021788. Details are provided in the "Other Requirements" section.

4. Indicate specific values needed for targeted student population.

   Term(s): ______

   ☐ Undergraduate (01 to 08) Specific or All ______ ☐ Graduate (GR) ☐ Professional (PR)

   ☐ PUID ☐ Student Name

   ☐ West Lafayette Campus

   ☐ Regional Campus (Specify Campus) ______

   ☐ Statewide Tech (Specify Campus) ______

   Major: ______

   College/School: ______

   Minor: ______

   Course or Section Requirements:

Other Requirements:

Three emails to be sent to targeted engineering PhD students: (1) the 1st email (sent on 6/17/19) will include the IRB information sheet and a link to the Quartics survey asking for their participation in the study; (2) the 2nd email will be a reminder approximately half-way through the study (sent 7/1/19) to complete the survey if they have not done so; (3) the 3rd email will be a final reminder (sent 7/15/19) to complete the survey before the window for the survey closes. Email text included.

5. **Data Handling for identifiable student data**

The data will be stored on a password protected server located in a secure area. Only the individuals listed in this agreement will have access to the data. No external copies of the data will be made. No copies of the data will be stored on flash drives or removable hard drives. The data may not be transferred to any external electronic data storage device. The data **will not** be stored on either a university or a personal laptop.

The data will not be shared with any other individual or organization, except for the individuals stated in this agreement. No hardcopy printouts of student data will be made. At the completion of this project the data will be physically and electronically destroyed beyond all ability to recover any and all Purdue data which has either been extracted from the official University Student System or has been provided to you.

Identifiable data will not be shared at any conference, in any communication, publication or any other sharing method, except in aggregate non-identifiable form.

6. **Tangible Research Property and Research Data**

The University owns all rights, title, and interest in Tangible Research Property and Research Data developed with support from University Resources. Subject to the University's control of the Disposition of Intellectual Property under Section V of this policy, in most instances the University permits the creators of University-owned Tangible Research Property or Research Data to retain primary physical custody of it solely for use in scholarship and not for any commercial purpose.

This policy can be found at http://www.purdue.edu/policies/academic-research-affairs/ia1.html . The expectation is that a faculty member would have a discussion with the appropriate individual(s) such as their department head or the University Research Administration in the Office of Vice President for Research (OVPR), related to the disposition of the data prior to her/his departure. If human subjects research is part of an investigator's study and s/he leaves the University, s/he is instructed to deposit copies of the research records (e.g., consent forms, study information, etc.) with her/his department head. Additionally the investigator is expected to maintain the agreement between her/him and the research participants as was written and approved in both the study consent form(s) and study protocol.

7. **Family Educational Rights and Privacy Act of 1974 (FERPA)**

All individuals stated in the agreement will uphold all requirements and will ensure their FERPA certifications with Purdue University are current. Individuals having access to records that contain personally identifiable information, the disclosure of which is prohibited by FERPA, acknowledge and fully understand that intentional disclosure by the individual to any unauthorized person could be subject to criminal and civil penalties imposed by the law. Willful or unauthorized disclosure also violates Purdue University's policy and could constitute just cause for disciplinary action including termination of employment regardless of criminal or civil penalties.

In the event of any personnel changes listed in this agreement or changes in the research protocol, within the time frame of this agreement, the Office of the Registrar must be notified. The new individuals will ensure a current FERPA certification and uphold all requirements of this agreement.

By signing on the next page all individuals will use student data only for the purposes of the research project, ensure proper data handling procedures and uphold FERPA and University policy as stated in this agreement.

Investigator Name:	Dr. Kerrie Douglas	Registrar Use FERPA Certified ☒ Y ☐ N 6-11-19 RCS
Signature:	Kerrie Douglas	
Date:	5-15-19	
Co-Investigator Name:	Eric Holloway	Registrar Use FERPA Certified ☒ Y ☐ N 6-11-19 RCS
Signature:	Eric Holloway	
Date:	6-1-19	
Co-Investigator Name:		Registrar Use FERPA Certified ☐ Y ☐ N
Signature:		
Date:		
Co-Investigator Name:		Registrar Use FERPA Certified ☐ Y ☐ N
Signature:		
Date:		
Co-Investigator Name:		Registrar Use FERPA Certified ☐ Y ☐ N
Signature:		
Date:		

IRB Protocol #: 1902021788

Initial Email

Subject: Engineering PhD research experiences study

Dear ________________,

My name is Eric Holloway, and I am a PhD student at Purdue in Engineering Education studying the research experiences of engineering PhD students. I also work full-time in the Dean's office on industrial research projects for the College of Engineering. For my dissertation research, I am studying how the research experiences of engineering PhD students prepare them for professional practice. This purpose of this study is to advance basic knowledge about the variation and scope of the engineering PhD student research experiences so that the results could be shared with the wider community to influence change for education and evaluation purposes.

We are asking you to participate in an online survey about your PhD research experiences. The survey will take approximately 15 minutes to complete. Your answers will remain completely confidential. The survey will ask questions about your current PhD research experiences and your research group organization style. You were invited to participate in this survey because you are an engineering PhD student at Purdue.

This study has been approved by the Purdue IRB, and an information sheet for this study is attached so that you can see more about the purpose of this study.

Please click here to take the survey:
https://purdue.ca1.qualtrics.com/jfe/form/SV_24OcHDXC4kMUuTX. Your response is appreciated by Monday, July 22, as time is limited to participate in this study.

We realize that, as a PhD student, you have many demands on your time. We appreciate your contribution to advancing scientific understanding of the research experiences of engineering PhD students.

Sincerely,

Eric Holloway
Senior Director - Industry Research
College of Engineering - Purdue University
Email: eahollow@purdue.edu
Phone: (765)496-6051

My advisor's contact information is:
Dr. Kerrie Douglas
Assistant Professor – Engineering Education – Purdue University
Email: douglask@purdue.edu
Phone: (765) 494-6932

IRB Protocol #: 1902021788

Follow-Up Email #1

Subject: Engineering PhD research experiences study

Dear ________________,

Two weeks ago, we sent you an invitation to participate in a survey as part of a research study regarding the research experiences of engineering PhD students.

If you have already participated in this survey, we thank you!

If you have not yet participated, we ask you to complete the approximately 15-minute online survey. We need a high response rate for scientific validity, so please participate.

Please click here to take the survey:
https://purdue.ca1.qualtrics.com/jfe/form/SV_24OcHDXC4kMUuTX. Your response is appreciated by Monday, July 22, as time is limited to participate in this study.

Subject: Engineering PhD research experiences study

Dear ________________,

My name is Eric Holloway, and I am a PhD student at Purdue in Engineering Education studying the research experiences of engineering PhD students. I also work full-time in the Dean's office on industrial research projects for the College of Engineering. For my dissertation research, I am studying how the research experiences of engineering PhD students prepare them for professional practice. This purpose of this study is to advance basic knowledge about the variation and scope of the engineering PhD student research experiences so that the results could be shared with the wider community to influence change for education and evaluation purposes.

We are asking you to participate in an online survey about your PhD research experiences. The survey will take approximately 15 minutes to complete. Your answers will remain completely confidential. The survey will ask questions about your current PhD research experiences and your research group organization style. You were invited to participate in this survey because you are an engineering PhD student at Purdue.

This study has been approved by the Purdue IRB, and an information sheet for this study is attached so that you can see more about the purpose of this study.

IRB Protocol #: 1902021788

Please click here to take the survey:
https://purdue.ca1.qualtrics.com/jfe/form/SV_24OcHDXC4kMUuTX. Your response is appreciated by Monday, July 22, as time is limited to participate in this study.

We realize that, as a PhD student, you have many demands on your time. We appreciate your contribution to advancing scientific understanding of the research experiences of engineering PhD students.

Sincerely,

Eric Holloway
Senior Director - Industry Research
College of Engineering - Purdue University
Email: eahollow@purdue.edu
Phone: (765)496-6051

My advisor's contact information is:
Dr. Kerrie Douglas
Assistant Professor – Engineering Education – Purdue University
Email: douglask@purdue.edu
Phone: (765) 494-6932

IRB Protocol #: 1902021788

Follow-Up Email #2

Subject: FINAL REMINDER: Engineering PhD research experiences study

Dear ________________,

As a FINAL REMINDER, approximately a month ago, we sent you an invitation to participate in a survey as part of a research study regarding the research experiences of engineering PhD students.

If you have already participated in this survey, we thank you!

If you have not yet participated, we ask you to complete the approximately 15-minute online survey. We need a high response rate for scientific validity, so please participate.

Please click here to take the survey:
https://purdue.ca1.qualtrics.com/jfe/form/SV_24OcHDXC4kMUuTX. Your response is appreciated by Monday, July 22, as time is limited to participate in this study.

Subject: Engineering PhD research experiences study

Dear ________________,

My name is Eric Holloway, and I am a PhD student at Purdue in Engineering Education studying the research experiences of engineering PhD students. I also work full-time in the Dean's office on industrial research projects for the College of Engineering. For my dissertation research, I am studying how the research experiences of engineering PhD students prepare them for professional practice. This purpose of this study is to advance basic knowledge about the variation and scope of the engineering PhD student research experiences so that the results could be shared with the wider community to influence change for education and evaluation purposes.

We are asking you to participate in an online survey about your PhD research experiences. The survey will take approximately 15 minutes to complete. Your answers will remain completely confidential. The survey will ask questions about your current PhD research experiences and your research group organization style. You were invited to participate in this survey because you are an engineering PhD student at Purdue.

This study has been approved by the Purdue IRB, and an information sheet for this study is attached so that you can see more about the purpose of this study.

IRB Protocol #: 1902021788

Please click here to take the survey:
https://purdue.ca1.qualtrics.com/jfe/form/SV_24OcHDXC4kMUuTX. Your response is appreciated by Monday, July 22, as time is limited to participate in this study.

We realize that, as a PhD student, you have many demands on your time. We appreciate your contribution to advancing scientific understanding of the research experiences of engineering PhD students.

Sincerely,

Eric Holloway
Senior Director - Industry Research
College of Engineering - Purdue University
Email: eahollow@purdue.edu
Phone: (765)496-6051

My advisor's contact information is:
Dr. Kerrie Douglas
Assistant Professor – Engineering Education – Purdue University
Email: douglask@purdue.edu
Phone: (765) 494-6932

INFORMATION SHEET

Purdue IRB Protocol #: 1902021788 - Expires: 07-MAY-2022

Research Experience Instrument (REI) Survey

Information Sheet

Key Information

Please take time to review this information carefully. This is a research study. Your participation in this study is voluntary which means that you may choose not to participate at any time without penalty or loss of benefits to which you are otherwise entitled. You may ask questions to the researchers about the study whenever you would like. If you decide to take part in the study, you will be asked to sign this form, be sure you understand what you will do and any possible risks or benefits.

The purpose of this survey is to measure how graduate engineering students perceive their research experiences contribute to aspects of their professional practice preparation. The assessment is designed to specifically address areas of the research experiences where that contributed to opportunities for students to practice becoming a professional.

You will participate in an online survey consisting of selected-response questions related to how your research experience contributed to your professional preparation. The survey will take approximately 15 minutes to complete. Additional explanations may be more detailed in the sections below.

What are the possible risks or discomforts?

Breach of confidentiality is always a risk with data, but we will take precautions to minimize this risk as described in the confidentiality section. There are no other risks associated with your participation in this study than what you would normally encounter in daily life. Should you not wish to continue with the interview you may stop at any time.

Are there any potential benefits?

There are no direct benefits to the participants. Indirect benefits include that results of this study may be used to finalize a list of survey items that assess graduate students perceptions about their research experience.

Will information about me and my participation be kept confidential?

The project's research records may be reviewed by the departments at Purdue University responsible for regulatory and research oversight.

Your responses and participation will be kept confidential. The data will be stored on a secure file server and only accessible to the research team consisting of Dr. Kerrie Douglas and Eric Holloway. Data will be stored indefinitely, and aggregate results could be utilized for publication.

What are my rights if I take part in this study?
Your participation in this study is voluntary. You may choose not to participate or, if you agree to participate, you can withdraw your participation at any time without penalty or loss of benefits to which you are otherwise entitled.

Who can I contact if I have questions about the study?
If you have questions, comments or concerns about this research project, you can talk to one of the researchers. Please contact:

Dr. Kerrie Douglas, Engineering Education, douglask@purdue.edu, 494-6932
Eric Holloway, Engineering Education, eahollow@purdue.edu, 496-6051

If you have questions about your rights while taking part in the study or have concerns about the treatment of research participants, please call the Human Research Protection Program at (765) 494-5942, email (irb@purdue.edu), or write to:

Human Research Protection Program - Purdue University
Ernest C. Young Hall, Room 1032
155 S. Grant Street
West Lafayette, IN 47907-2114

To report anonymously via Purdue's Hotline see www.purdue.edu/hotline.

Documentation of Informed Consent
I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research study, and my questions have been answered. I am prepared to participate in the research study described above. By clicking "agree" below I consent to participate in this research study.

I agree to be part of this study AGREE____________ DISAGREE____________

Note: each participant should subject should print a copy of the information sheet for his/her records.

RESULTS

Table C.1: *Respondent Assessment Questions Descriptive Statistics* (n = 236)

Assessment Questions	Mean	Std. Error	Med.	Std. Dev.	Skew	Std. Error	Kurt	Std. Error	Kolmogorov-Smirnov[a] Shapiro-Wilk	*df*	*p*
Q1: take on different roles or responsibilities within a research group?	4.48	0.07	5	1.12	-0.97	0.16	1.31	0.31	0.221 0.867	236	< .001
Q2: coordinate research tasks with other graduate students?	4.43	0.08	5	1.22	-0.81	0.16	0.50	0.31	0.210 0.888	236	< .001
Q3: share decision making responsibility with other graduate students?	4.20	0.08	4	1.26	-0.80	0.16	0.30	0.31	0.211 0.889	236	< .001
Q4: develop new skills based on the needs of the research group's goals?	5.00	0.06	5	.91	-1.08	0.16	2.35	0.31	0.248 0.824	236	< .001
Q5: mutually depend on other graduate students to meet the desired outcomes?	3.90	0.09	4	1.34	-0.32	0.16	-0.47	0.31	0.187 0.928	236	< .001
Q6: present your research results to your sponsors or collaborators who are involved in your research?	3.93	0.11	4	1.65	-0.44	0.16	-0.95	0.31	0.182 0.893	236	< .001
Q7: interact at your university with your sponsors or collaborators who are involved in your research?	4.00	0.10	4	1.55	-0.57	0.16	-0.64	0.31	0.188 0.895	236	< .001
Q8: correspond (e.g., email, phone, etc.) with your sponsors or collaborators who are involved in your research?	3.88	0.09	4	1.50	-0.48	0.16	-0.75	0.31	0.202 0.905	236	< .001
Q9: interact with your sponsors or collaborators at their place of work related to your research?	2.92	0.10	3	1.57	0.11	0.16	-1.26	0.31	0.190 0.881	236	< .001
Q10: co-author journal or conf papers with your sponsors or collaborators?	3.50	0.11	4	1.71	-0.23	0.16	-1.22	0.31	0.187 0.888	236	< .001
Q11: co-create a presentation with your sponsors or collaborators?	3.15	0.11	3	1.61	0.04	0.16	-1.20	0.31	0.164 0.902	236	< .001
Q12: develop prof relationships with practicing engineers through research?	3.15	0.10	3	1.47	0.06	0.16	-0.93	0.31	0.175 0.920	236	< .001
Q13: participate in industry or gvmt conferences as part of research?	3.37	0.10	4	1.57	-0.17	0.16	-1.12	0.31	0.193 0.906	236	< .001
Q14: participate in professional engineering societies?	2.99	0.10	3	1.50	0.22	0.16	-0.93	0.31	0.136 0.915	236	< .001
Q15: present results of your research to practicing engineers?	3.31	0.09	4	1.44	-0.14	0.16	-0.99	0.31	0.209 0.916	236	< .001
Q16: interact with practicing engineers during internships or co-ops?	2.47	0.11	2	1.62	0.64	0.16	-.092	0.31	0.283 0.814	236	< .001

Assessment Questions	Mean	Std. Error	Med.	Std. Dev.	Skew	Std. Error	Kurt	Std. Error	Kolmogorov-Smirnov[a] Shapiro-Wilk	*df*	*p*
Q17: interact with support professionals (e.g., project managers, …, etc.)?	3.39	0.10	4	1.50	-0.13	0.16	-0.99	0.31	0.176 0.923	236	< .001
Q18: develop or utilize a mathematical model to help solve a problem?	4.32	0.10	5	1.46	-0.73	0.16	-0.32	0.31	0.218 0.883	236	< .001
Q19: specify constraints or assumptions in development of a mathematical model to help solve a problem?	4.14	0.11	5	1.68	-0.60	0.16	-0.86	0.31	0.209 0.871	236	< .001
Q20: utilize sophisticated tools to help solve a modeling or simulation problem?	4.05	0.10	4	1.57	-0.59	0.16	-0.68	0.31	0.197 0.890	236	< .001
Q21: simulate a system to obtain results?	4.61	0.10	5	1.54	-0.97	0.16	-0.05	0.31	0.219 0.823	236	< .001
Q22: iterate on the development of a model or simulation to optimize results?	4.50	0.10	5	1.59	-0.96	0.16	-0.10	0.31	0.231 0.828	236	< .001
Q23: verify a model or simulation based on real-world data or actual results?	3.96	0.11	4.5	1.67	-0.58	0.16	-0.93	0.31	0.233 0.870	236	< .001
Q24: use testing equipment or instrumentation as an integral part of conducting your research?	3.99	0.12	5	1.88	-0.42	0.16	-1.33	0.31	0.212 0.843	236	< .001
Q25: develop plans to use testing equipment or instrumentation?	3.85	0.11	4	1.74	-0.41	0.16	-1.14	0.31	0.186 0.879	236	< .001
Q26: ensure testing equipment or instrumentation is appropriately set-up (i.e., calibrated) before use?	3.95	0.12	5	1.90	-0.52	0.16	-1.25	0.31	0.235 0.830	236	< .001
Q27: collect data from testing equipment or apparatus using appropriate sensors or instrumentation?	3.94	0.12	5	1.89	-0.44	0.16	-1.34	0.31	0.238 0.839	236	< .001
Q28: interpret data gathered from testing equipment or apparatus?	4.47	0.11	5	1.71	-0.97	0.16	-0.38	0.31	0.273 0.796	236	< .001
Q29: troubleshoot or modify testing equipment or instrumentation when it does not operate properly?	3.89	0.12	5	1.87	-0.46	0.16	-1.30	0.31	0.227 0.842	236	< .001

[a.] Lilliefors Significance Correction

Table C.2: *Respondent Demographic Information* (n = 236)

Characteristic	Explanation	Range	Scale Description	*n*	%
Gender	Ph.D. student's gender	Male	Male = 1	165	69.9
		Female	Female = 2	70	29.7
		Non-binary	Non-binary = 3	1	0.4
Degree sought	Ph.D. student's degree sought	Master's	Master's = 1	0	0.0
		Ph.D.	Ph.D. = 2	224	94.9
		Both	Both = 3	12	5.1
		N/A	N/A = 3	0	0.0
Qualifying/area exam	Ph.D. student completed department's qualifying/area exam?	Yes	Yes = 1	157	66.5
		No	No = 2	55	23.3
		N/A	N/A = 3	24	10.2
Ethnicity	Ph.D. student's race/ethnicity	White/Caucasian	White/Caucasian = 1	95	40.3
		Black/African American	Black/African American = 2	5	2.1
		Hispanic or Latino	Hispanic or Latino = 3	14	5.9
		Native American	Native American = 4	0	0.0
		Asian	Asian = 5	95	40.3
		Pacific Islander	Pacific Islander = 6	0	0.0
		Other	Other = 7 or 8	4	1.7
		Prefer not to respond	Prefer not to respond = 9	7	3.0
		Multiple selected non-URM		6	2.5
		Multiple selected URM		10	4.2
		All URM	Combined URM	29	12.3
Worked full-time in industry	Ph.D. student worked full-time in industry (not including internship/co-op)	Yes	Yes = 1	69	29.2
		No	No = 2	166	70.3
		N/A	N/A = 3	1	0.4
Internship or co-op	Ph.D. student had internship or co-op related to their research	Yes	Yes = 1	37	15.7
		No	No = 2	73	30.9
		N/A	N/A = 3	126	53.4

Characteristic	Explanation	Range	Scale Description	*n*	%
TA/Instructor	Ph.D. student has been TA/Instructor during Ph.D. research	Yes	Yes = 1	116	49.2
		No	No = 2	111	47.0
		N/A	N/A = 3	9	3.8
Source of funding	Ph.D. student's source of funding during Ph.D. research	Government	Government = 1	149	63.1
		Industry	Industry = 2	35	14.8
		Not funded	Not funded = 3	12	5.1
		Other	Other = 4	40	17.0
After graduation	Ph.D. student's path after graduation	Government	Government = 1	26	11.0
		Industry	Industry = 2	101	42.8
		Academia	Academia = 3	99	42.0
		Other	Other = 4	10	4.2

Table C.3: *Respondent Self-Report Metrics for Number of Research Group Size* (n = 236)

Variable	Explanation	Min	Max	Range	Mean	Std. Dev
# of graduate students in research group	Ph.D. student's self-report of research group size	1	30	29	8.1	5.6

Table C.4: *Respondent Self-Report Metrics* (n = 236)

Characteristic	Explanation	Range	Scale Description	*n*	%
Research group organization	Ph.D. student's research group organization	Advisor dominant	Advisor dominant = 1	131	55.5
		Student-centric	Student-centric = 2	92	39.0
		Other	Other = 3	13	5.5
Research work organization	Ph.D. student's research work organization	Self or with advisor	Advisor dominant = 1	171	72.5
		Broader team	Student-centric = 2	57	24.1
		Other	Other = 3	8	3.4
Major	Ph.D. student's engineering major	Aero/Astro	Aero/Astro = 1	26	11.0
		Ag & Bio	Ag & Bio = 2	0	0.0
		Biomedical	Biomedical = 3	10	4.2
		Chemical	Chemical = 4	16	6.8
		Civil	Civil = 5	25	10.6
		Constr & Mgmt	Constr & Mgmt = 6	1	0.4
		Electrical & Comp	Electrical & Comp = 7	41	17.4
		Engineering Ed	Engineering Ed = 8	21	8.9
		Envir & Ecol	Envir & Ecol = 9	3	1.3
		Industrial	Industrial = 10	14	5.9
		Materials	Materials = 11	15	6.4
		Mechanical	Mechanical = 12	56	23.7
		Nuclear	Nuclear = 13	8	3.4
		Other	Other = 14	0	0.0

Characteristic	Explanation	Range	Scale Description	*n*	%
Research type	Ph.D. student's research type	Basic	Basic = 1	72	30.5
		Applied	Applied = 2	158	67.0
		Other	Other = 3	6	2.5
Collaborator type	Ph.D. student's collaborator type	Government	Government = 1	70	29.7
		Industry	Industry = 2	59	25.0
		Research center	Research center = 3	85	36.0
		Other	Other = 4	22	9.3
Collaborator interaction type	Ph.D. student's collaborator interaction type	Infrequent	Yes = 1	121	51.3
		Frequent	No = 2	101	42.8
		Other	Other = 3	14	5.9
Equipment type	Ph.D. student's type of equipment used for research	Model & sim w/ computer tools	Model & sim w/ computer tools = 1	91	38.6
		Testing, experiments	Testing, experiments = 2	65	27.5
		Combination of 1 & 2	Combination of 1 & 2 = 3	62	26.3
		Other	Other = 4	18	7.6
Work space organization	Ph.D. student's work space organization	Alone or with few	Alone or with few = 1	42	17.8
		Only with research group	Only with research group = 2	100	42.4
		Shared with multiple groups	Shared with multiple research groups = 3	89	37.7
		Other	Other = 4	5	2.1

Table C.5: *Inter-Item Correlation Matrix* (n = 236)

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21	Q22	Q23	Q24	Q25	Q26	Q27	Q28	Q29
Q1	1.000																												
Q2	.602**	1.000																											
Q3	.564**	.712**	1.000																										
Q4	.324**	.321**	.252**	1.000																									
Q5	.540**	.669**	.665**	.224**	1.000																								
Q6	.259**	.278**	.318**	.242**	.212**	1.000																							
Q7	.401**	.303**	.343**	.330**	.251**	.655**	1.000																						
Q8	.244**	.272**	.278**	.241**	.213**	.665**	.602	1.000																					
Q9	.224**	.175**	.152*	.207**	.133*	.519**	.509**	.626**	1.000																				
Q10	.225**	.219**	.170**	.243**	.097	.478**	.540**	.559**	.496**	1.000																			
Q11	.323**	.385**	.335**	.306**	.307**	.521**	.574**	.552**	.487**	.573**	1.000																		
Q12	.334**	.335**	.302**	.277**	.185**	.459**	.378**	.550**	.459**	.486**	.431**	1.000																	
Q13	.171**	.215**	.210**	.109	.197**	.409**	.316**	.376**	.228**	.331**	.311**	.496**	1.000																
Q14	.326**	.241**	.257**	.097	.247**	.198**	.325	.236	.191	.318	.281	.307	.231	1.000															
Q15	.168**	.243**	.124	.198**	.115	.440**	.324**	.478**	.498**	.447**	.360**	.610**	.441**	.263**	1.000														
Q16	.150**	.245**	.214**	.239**	.174**	.248**	.188**	.330**	.257**	.325**	.432**	.452**	.381**	.175**	.399**	1.000													
Q17	.398**	.433**	.366**	.234**	.268**	.375**	.341**	.398**	.327**	.264**	.300**	.511**	.333**	.210**	.351**	.259**	1.000												
Q18	-.072	.055	.018	.182**	.049	.152*	.014	.092	.048	.061	.052	.096	.154	-.014	.169	.214	.024	1.000											
Q19	-.091	-.045	-.033	.176**	.006	.159*	.017	.105	.161*	.082	.155*	.076	.157*	-.008	.211**	.232**	.011	.733**	1.000										
Q20	.042	.031	.040	.224**	.065	.254**	.143	.201**	.191**	.081	.185**	.122	.114	-.045	.222**	.206**	.136*	.604**	.644**	1.000									
Q21	-.026	.061	.060	.206**	.018	.166*	.019	.101	.139*	-.011	.072	.088	.097	-.107	.189**	.182**	.087	.510**	.580**	.561**	1.000								
Q22	-.093	-.035	-.048	.185**	.018	.169**	.009	.097	.115	.053	.113	.060	.185**	-.063	.206**	.229**	.081	.630**	.808**	.672**	.677**	1.000							
Q23	.042	.142**	.044	.234**	.059	.219**	.076	.112	.127	.138*	.189**	.167*	.101	-.009	.237**	.148*	.108	.540**	.542**	.592**	.492**	.592**	1.000						
Q24	.342**	.251**	.266**	.190**	.219**	.096	.175**	.102	.098	-.012	.189**	.176**	.119	.009	-.027	.074	.381**	-.101	-.138*	-.004	-.007	-.143*	.072	1.000					
Q25	.404**	.334**	.331**	.240**	.281**	.214**	.300**	.232**	.239**	.111	.234**	.263**	.187**	.094	.134*	.089	.533**	-.074	-.125	.052	.002	-.106	.096	.777**	1.000				
Q26	.344**	.273**	.303**	.233**	.222**	.149*	.199**	.157*	.172**	.090	.196**	.235**	.136*	.099	.082	.139*	.512**	-.081	-.118	.058	.017	-.079	.106	.757**	.824**	1.000			
Q27	.360**	.276**	.292**	.213**	.274**	.177**	.236**	.119	.163*	.059	.195**	.208**	.158*	.051	.079	.068	.490**	-.111	-.086	.051	-.014	-.075	.122	.797**	.857**	.844**	1.000		
Q28	.310**	.313**	.312**	.218**	.271**	.248**	.265**	.251**	.190**	.125	.226**	.277**	.264**	.070	.095	.135*	.417**	.077	.022	.057	.065	-.006	.212	.699**	.734**	.720**	.755**	1.000	
Q29	.370**	.280**	.276**	.176**	.243**	.191**	.199**	.201**	.175**	.115**	.228**	.285**	.190**	.135*	.080	.129*	.502**	-.045	-.071	-.005	-.051	-.101	.055	.769**	.746**	.772**	.797**	.702**	1.000

** Indicates correlation is significant at the .01 level (2-tailed)

* Indicates correlation is significant at the .05 level (2-tailed)

Table C.6: *Initial Structure Coefficients for EFA (All Questions)*

Latent Construct	Assessment Question	Standardized Structure Coefficients				
		F1	F2	F3	F4	F5
F1: Working as a team member	Q1: take on different roles or responsibilities within a research group	**.70**	.39	.30	-.05	.42
	Q2: coordinate research tasks with other graduate students	**.86**	.36	.38	.03	.34
	Q3: share decision making responsibility with other graduate students	**.83**	.36	.29	.01	.35
	Q4: develop new skills (e.g., presentation, project management, software, etc.) based on the needs of the research group's goals	.35	.35	.28	.24	.25
	Q5: mutually depend on other graduate students to meet the desired outcomes	**.78**	.27	.21	.06	.30
F2: Exposure to collaborator's form of practice	Q6: present your research results to your sponsors or collaborators (i.e., practicing engineers) who are involved in your research	.34	**.78**	.50	.23	.22
	Q7: interact at your university with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research	.41	**.83**	.36	.05	.28
	Q8: correspond (e.g., email, phone, etc.) with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research	.32	**.80**	.60	.14	.21
	Q9: interact with your sponsors or collaborators at their place of work related to your research	.20	**.69**	.52	.16	.21
	Q10: co-author journal or conference papers with your sponsors or collaborators	.23	**.69**	.55	.08	.11
	Q11: co-create a presentation with your sponsors or collaborators	.43	**.70**	.49	.17	.25
F3: Exposure to relevant professional practice	Q12: develop professional relationships with practicing engineers (other than your sponsors or collaborators) through your research	.35	.59	**.84**	.11	.29
	Q13: participate in industry or government conferences as part of your research	.25	.44	**.57**	.19	.20
	Q14: participate in professional engineering societies (e.g., Institute of Electrical and Electronics Engineers, Society of Women Engineers, etc.)	.31	.35	.33	-.05	.10
	Q15: present results of your research to practicing engineers (other than your sponsors or collaborators)	.20	.54	**.73**	.25	.11

	Q16: interact with practicing engineers during internships or co-ops	.25	.36	**.56**	.26	.12
	Q17: interact with support professionals (e.g., project managers, building maintenance, outside vendors, etc.)	.45	.45	**.54**	.09	.56
F4: Modeling and simulation tasks	Q18: develop or utilize a mathematical model to help solve a problem	.03	.09	.20	**.76**	-.08
	Q19: specify constraints or assumptions in development of a mathematical model to help solve a problem	-.05	.13	.20	**.88**	-.10
	Q20: utilize sophisticated tools to help solve a modeling or simulation problem	.06	.24	.20	**.77**	.05
	Q21: simulate a system to obtain results	.04	.11	.17	**.71**	.01
	Q22: iterate on the development of a model or simulation to optimize results	-.04	.11	.20	**.89**	-.09
	Q23: verify a model or simulation based on real-world data or actual results	.10	.18	.23	**.68**	.13
F5: Practical skills	Q24: use testing equipment or instrumentation as an integral part of conducting your research	.33	.16	.12	-.08	**.85**
	Q25: develop plans to use testing equipment or instrumentation	.42	.31	.24	-.04	**.91**
	Q26: ensure testing equipment or instrumentation is appropriately set-up (i.e., calibrated) before use	.36	.22	.22	-.03	**.90**
	Q27: collect data from testing equipment or apparatus using appropriate sensors or instrumentation	.37	.23	.17	-.02	**.94**
	Q28: interpret data gathered from testing equipment or apparatus	.38	.30	.26	.08	**.81**
	Q29: troubleshoot or modify testing equipment or instrumentation when it does not operate properly	.36	.24	.27	-.04	**.85**

Table C.7: *Structure Coefficients for EFA after Assessment Question Removal*

Latent Construct	Assessment Question	Standardized Structure Coefficients				
		F1	F2	F3	F4	F5
F1: Working as a team member	Q1: take on different roles or responsibilities within a research group	**.69**	.38	.26	-.06	.41
	Q2: coordinate research tasks with other graduate students	**.86**	.35	.35	.02	.33
	Q3: share decision making responsibility with other graduate students	**.83**	.36	.26	.01	.34
	Q5: mutually depend on other graduate students to meet the desired outcomes	**.79**	.27	.19	.05	.29
F2: Exposure to collaborator's form of practice	Q6: present your research results to your sponsors or collaborators (i.e., practicing engineers) who are involved in your research	.33	**.79**	.48	.22	.20
	Q7: interact at your university with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research	.39	**.82**	.33	.05	.27
	Q8: correspond (e.g., email, phone, etc.) with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research	.30	**.80**	.58	.14	.19
	Q9: interact with your sponsors or collaborators at their place of work related to your research	.19	**.69**	.50	.16	.20
	Q10: co-author journal or conference papers with your sponsors or collaborators	.21	**.68**	.54	.08	.09
	Q11: co-create a presentation with your sponsors or collaborators	.42	**.70**	.48	.16	.24
F3: Exposure to relevant professional practice	Q12: develop professional relationships with practicing engineers (other than your sponsors or collaborators) through your research	.33	.59	**.82**	.11	.27
	Q13: participate in industry or government conferences as part of your research	.24	.44	**.56**	.19	.19
	Q15: present results of your research to practicing engineers (other than your sponsors or collaborators)	.18	.54	**.73**	.25	.09
	Q16: interact with practicing engineers during internships or co-ops	.24	.35	**.58**	.26	.11

F4: Modeling and simulation tasks	Q18: develop or utilize a mathematical model to help solve a problem	.03	.09	.22	**.76**	-.08
	Q19: specify constraints or assumptions in development of a mathematical model to help solve a problem	-.05	.13	.23	**.88**	-.11
	Q20: utilize sophisticated tools to help solve a modeling or simulation problem	.05	.23	.21	**.77**	.04
	Q21: simulate a system to obtain results	.04	.10	.19	**.71**	.00
	Q22: iterate on the development of a model or simulation to optimize results	-.05	.11	.22	**.90**	-.10
	Q23: verify a model or simulation based on real-world data or actual results	.10	.18	.25	**.67**	.12
F5: Practical skills	Q24: use testing equipment or instrumentation as an integral part of conducting your research	.33	.16	.09	-.09	**.86**
	Q25: develop plans to use testing equipment or instrumentation	.41	.31	.19	-.05	**.91**
	Q26: ensure testing equipment or instrumentation is appropriately set-up (i.e., calibrated) before use	.35	.22	.18	-.04	**.90**
	Q27: collect data from testing equipment or apparatus using appropriate sensors or instrumentation	.36	.23	.13	-.03	**.94**
	Q28: interpret data gathered from testing equipment or apparatus	.38	.30	.24	.07	**.81**
	Q29: troubleshoot or modify testing equipment or instrumentation when it does not operate properly	.35	.24	.23	-.05	**.85**

APPENDIX D. PILOT TEST 2

ASSESSMENT QUESTIONS USED FOR PILOT TEST 2

Research Experience Instrument (REI) – In Order

Instructions

The following questions are related to engineering Ph.D. students' perceptions about how often in their Ph.D. research experiences they utilized skills relevant to professional practice. Respondents are asked to take special note that this is NOT an assessment of their research skills; rather, it is an assessment of their perceptions about their research experience and how often they did things related to professional practice in their research experience.

In the survey below, there are 47 questions, and it is estimated it will take approximately 15 minutes to complete. For each of the questions that follow, please indicate how often in your Ph.D. research experience you did the items in question. You should do this by selecting the response that most closely matches from the options provided.

How often in your Ph.D. research experience did you:

1. take on different roles or responsibilities within a research group?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

2. coordinate research tasks with other graduate students?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

3. share decision making responsibility with other graduate students?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

4. mutually depend on other graduate students to meet the desired outcomes?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

5. present your research results to your sponsors or collaborators (i.e., practicing engineers) who are involved in your research?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

6. interact at your university with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

7. correspond (e.g., email, phone, etc.) with your sponsors or collaborators (i.e., practicing engineers) who are involved in your research?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

Research Experience Instrument (REI) – In Order

How often in your Ph.D. research experience did you:

8. interact with your sponsors or collaborators at their place of work related to your research?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

9. co-author journal or conference papers with your sponsors or collaborators?

   1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

10. co-create a presentation with your sponsors or collaborators?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

11. develop professional relationships with practicing engineers (other than your sponsors or collaborators) through your research?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

12. participate in industry or government conferences as part of your research?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

13. participate in professional engineering societies (e.g., Institute of Electrical and Electronics Engineers, Society of Women Engineers, etc.)?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

14. present results of your research to practicing engineers (other than your sponsors or collaborators)?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

15. interact with practicing engineers during internships or co-ops?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

16. develop or utilize a mathematical model to help solve a problem?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

17. specify constraints or assumptions in development of a mathematical model to help solve a problem?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

Research Experience Instrument (REI) – In Order

How often in your Ph.D. research experience did you:

18. utilize sophisticated tools to help solve a modeling or simulation problem?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

19. simulate a system to obtain results?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

20. iterate on the development of a model or simulation to optimize results?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

21. verify a model or simulation based on real-world data or actual results?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

22. use testing equipment or instrumentation as an integral part of conducting your research?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

23. develop plans to use testing equipment or instrumentation?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

24. ensure testing equipment or instrumentation is appropriately set-up (i.e., calibrated) before use?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

25. collect data from testing equipment or apparatus using appropriate sensors or instrumentation?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

26. interpret data gathered from testing equipment or apparatus?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

27. troubleshoot or modify testing equipment or instrumentation when it does not operate properly?

    1) Never, 2) Very Rarely, 3) Rarely, 4) Occasionally, 5) Frequently, 6) Very Frequently.

Research Experience Instrument (REI) – In Order

Self-report Questions:

1. Including yourself, approximately how many graduate student members are in your research group?

   ____

2. How is your Ph.D. research group organized?

   1) The research group is structured where the advisor sets most of the interactions, communication, and mentoring of students

   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

   3) Other (explain)

3. How is your Ph.D. research work organized?

   1) Most of the day-to-day work involves working by myself or with my advisor

   2) Most of the day-to-day work involves interaction with a broader team within the research group

   3) Other (explain)

4. What is your engineering Ph.D. major?

   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)

5. What type of Ph.D. research are you primarily working on?

   1) Basic (fundamental research without specific applications towards processes or products in mind)

   2) Applied (research that has specific applications towards processes or products)

   3) Other (explain)

6. What type of collaborators, either internal or external, do you work with primarily in your Ph.D. research?

   1) A strong emphasis on government collaborations

   2) A strong emphasis on industry collaborations

   3) A strong emphasis on university research center collaborations

   4) Other (explain)

7. **What type of interactions do you have with the collaborators identified in the previous question?**

   1) Collaborations consist of infrequent contact, mostly written reports, resulting in a relationship with the collaborators that are not very deep.

   2) Collaborations consist of frequent contact, including email and face-to-face interaction for reporting results, resulting in a deep relationship with the collaborators.

   3) Other (explain)

8. **What type of equipment do you primarily use to conduct your Ph.D. research?**

   1) The primary nature of the research work relies on modeling and simulation with sophisticated computer equipment and software tools.

   2) The primary nature of the research work relies on facilities, testing equipment, and physical experiments.

   3) A combination of 1 & 2 above

   4) Other (explain)

9. **How is the work space for your Ph.D. research group organized?**

   1) Housed in a lab space or office where I work mostly alone or near a few others.

   2) Housed in lab space or office that is shared with my research group only.

   3) Housed in a lab space that is shared with multiple different types of research groups.

   4) Other (explain)

Demographic Questions:

1. What is your gender?

   1) male, 2) female, 3) non-binary.

2. **What degree are you seeking?**

   1) Master's, 2) Ph.D., 3) Both, 4) not applicable.

3. **Have you completed your department/school qualification exam (e.g., area exam)?**

   1) yes, 2) no 3) not applicable.

4. **What is your ethnicity of origin? Please check any that you identify with.**

   1) White/Caucasian, 2) Black/African American, 3) Hispanic or Latino, 4) Native American, 5) Asian,

   6) Pacific Islander, 7) Other, 8) Other –TEXT ENTER-, 9) I prefer not to respond

Research Experience Instrument (REI) – In Order

5. **Please indicate the name of your university (e.g. Example University)**

   ____

6. **Please indicate the location of your university (city, state, country)**

   ____

7. **Have you ever worked full-time in industry (not including internships or co-ops)?**

   1) yes, 2) no 3) not applicable.

8. **If you had an internship or co-op during your Ph.D. research, was it related to your research?**

   1) yes, 2) no 3) not applicable.

9. Have you been a Teaching Assistant or Instructor during your Ph.D. research?

   1) yes, 2) no 3) not applicable.

10. **What is the primary source of funding for your Ph.D. research?**

    1) government (e.g., NSF, DOE, etc.), 2) industry, 3) not funded, 4) other (explain).

11. **Where do you see yourself working after graduation?**

    1) government, 2) industry, 3) academia, 4) other (explain).

IRB APPROVAL FOR ASEE LISTSERV

PURDUE UNIVERSITY

HUMAN RESEARCH PROTECTION PROGRAM
INSTITUTIONAL REVIEW BOARDS

To:	DOUGLAS, KERRIE A
From:	Institutional Review Board
Date:	10 / 10 / 2019
Committee Action:	**IRB Approval of Amendment, Expedited Category (7)**
Approval Date:	10 / 10 / 2019
IRB Protocol #:	1902021788
Amendment Version	Amendment-002:
Study Title:	REI pilot data collection
Expiration Date:	05 / 07 / 2022
Subjects Approved:	5000

The above referenced protocol amendment has been approved by the Purdue IRB.

The expiration date for IRB approval has not been altered.

Approved study documents are in the Attachments section of this protocol in CoeusLite.

You are required to retain a copy of this letter for your records.

We appreciate your commitment towards ensuring the ethical conduct of human subject research and wish you well with your study.

Ernest C. Young Hall, 10th Floor - 155 S. Grant St. - West Lafayette, IN 47907-2114 - (765) 494-5942 - Fax: (765) 494-9911

IRB APPROVAL FOR GENERIC PRIVATE LISTSERVS AT R1 UNIVERSITIES

PURDUE UNIVERSITY

HUMAN RESEARCH PROTECTION PROGRAM
INSTITUTIONAL REVIEW BOARDS

To:	DOUGLAS, KERRIE A
From:	Institutional Review Board
Date:	10 / 29 / 2019
Committee Action:	**IRB Approval of Amendment, Expedited Category (7)**
Approval Date:	10 / 29 / 2019
IRB Protocol #:	1902021788
Amendment Version	Amendment-003:
Study Title:	REI pilot data collection
Expiration Date:	05 / 07 / 2022
Subjects Approved:	5000

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IRB APPROVED RECRUITMENT EMAIL FOR LISTSERVS OWNERS

CALL FOR PARTICIPATION: Engineering PhD Research Experiences Study

We are researchers at Purdue University studying how the research experiences of engineering PhD students prepare them for professional practice. We are hoping that this message and the survey link below is shared by students, faculty, and professionals across engineering. The purpose of this study is to advance basic knowledge about the variation and scope of the engineering PhD student research experiences so that the results could be shared with the wider community to influence change for education and evaluation purposes.

We are asking engineering PhD students to participate in an online survey about their PhD research experiences. The survey will take approximately 15 minutes to complete. Answers will remain completely confidential. The survey will ask questions about a student's current PhD research experiences and research group organization style. A student must be 18 years or older and an engineering PhD student to participate in the study. Please click the link below for more information and to begin the survey: link to be added

For questions, please contact PI Kerrie Douglas (douglask@purdue.edu) or graduate student Eric Holloway (eahollow@purdue.edu).

RESULTS

Table D.1: *Respondent Assessment Questions Descriptive Statistics* (n = 215)

Assessment Questions	Mean	Std. Error	Med.	Std. Dev.	Skew	Std. Error	Kurt	Std. Error	Kolmogorov-Smirnov[a] Shapiro-Wilk	*df*	*p*
Q1: take on different roles or responsibilities within a research group?	4.63	0.09	5	1.33	-1.01	0.17	0.47	0.33	0.224 0.849	215	< .001
Q2: coordinate research tasks with other graduate students?	4.27	0.10	4	1.44	-0.71	0.17	-0.22	0.33	0.185 0.889	215	< .001
Q3: share decision making responsibility with other graduate students?	4.11	0.09	4	1.36	-0.65	0.17	-0.20	0.33	0.199 0.903	215	< .001
Q5: mutually depend on other graduate students to meet the desired outcomes?	3.68	0.10	4	1.54	-0.20	0.17	-0.96	0.33	0.154 0.925	215	< .001
Q6: present your research results to your sponsors or collaborators who are involved in your research?	4.11	0.10	4	1.52	-0.76	0.17	-0.40	0.33	0.220 0.870	215	< .001
Q7: interact at your university with your sponsors or collaborators who are involved in your research?	3.98	0.11	4	1.67	-0.43	0.17	-1.11	0.33	0.213 0.885	215	< .001
Q8: correspond (e.g., email, phone, etc.) with your sponsors or collaborators who are involved in your research?	3.99	0.11	4	1.63	-0.57	0.17	-0.81	0.33	0.205 0.879	215	< .001
Q9: interact with your sponsors or collaborators at their place of work related to your research?	3.17	0.12	3	1.74	0.18	0.17	-1.29	0.33	0.160 0.892	215	< .001
Q10: co-author journal or conf papers with your sponsors or collaborators?	3.59	0.12	4	1.72	-0.41	0.17	-1.21	0.33	0.228 0.857	215	< .001
Q11: co-create a presentation with your sponsors or collaborators?	3.36	0.12	4	1.69	-0.06	0.17	-1.25	0.33	0.169 0.900	215	< .001
Q12: develop prof relationships with practicing engineers through research?	3.27	0.10	3	1.47	0.00	0.17	-0.87	0.33	0.179 0.923	215	< .001
Q13: participate in industry or gvmt conferences as part of research?	3.66	0.11	4	1.61	-0.44	0.17	-1.02	0.33	0.207 0.884	215	< .001
Q15: present results of your research to practicing engineers?	3.56	0.10	4	1.50	-0.33	0.17	-0.86	0.33	0.211 0.910	215	< .001
Q16: interact with practicing engineers during internships or co-ops?	2.50	0.11	2	1.65	0.61	0.17	-1.00	0.33	0.279 0.814	215	< .001
Q18: develop or utilize a mathematical model to help solve a problem?	4.33	0.10	5	1.53	-0.71	0.17	-0.42	0.33	0.185 0.874	215	< .001

Assessment Questions	Mean	Std. Error	Med.	Std. Dev.	Skew	Std. Error	Kurt	Std. Error	Kolmogorov-Smirnov[a] Shapiro-Wilk	*df*	*p*
Q19: specify constraints or assumptions in development of a mathematical model to help solve a problem?	3.99	0.11	4	1.67	-0.57	0.17	-0.88	0.33	0.201 0.873	215	< .001
Q20: utilize sophisticated tools to help solve a modeling or simulation problem?	3.91	0.12	4	1.72	-0.51	0.17	-1.00	0.33	0.186 0.873	215	< .001
Q21: simulate a system to obtain results?	4.48	0.11	5	1.56	-0.89	0.17	-0.29	0.33	0.220 0.839	215	< .001
Q22: iterate on the development of a model or simulation to optimize results?	4.38	0.11	5	1.63	-0.89	0.17	-0.34	0.33	0.229 0.835	215	< .001
Q23: verify a model or simulation based on real-world data or actual results?	4.08	0.11	4	1.57	-0.70	0.17	-0.56	0.33	0.204 0.874	215	< .001
Q24: use testing equipment or instrumentation as an integral part of conducting your research?	4.31	0.13	5	1.87	-0.76	0.17	-0.97	0.33	0.254 0.793	215	< .001
Q25: develop plans to use testing equipment or instrumentation?	4.11	0.13	5	1.84	-0.65	0.17	-1.02	0.33	0.117 0.826	215	< .001
Q26: ensure testing equipment or instrumentation is appropriately set-up (i.e., calibrated) before use?	4.28	0.12	5	1.83	-0.83	0.17	-0.76	0.33	0.248 0.798	215	< .001
Q27: collect data from testing equipment or apparatus using appropriate sensors or instrumentation?	4.20	0.13	5	1.90	-0.70	0.17	-1.03	0.33	0.232 0.800	215	< .001
Q28: interpret data gathered from testing equipment or apparatus?	4.76	0.12	5	1.69	-1.31	0.17	0.31	0.33	0.295 0.717	215	< .001
Q29: troubleshoot or modify testing equipment or instrumentation when it does not operate properly?	4.10	0.12	5	1.82	-0.59	0.17	-1.05	0.33	0.201 0.840	215	< .001

[a.] Lilliefors Significance Correction

Table D.2: *Respondent Demographic Information* (n = 215)

Characteristic	Explanation	Range	Scale Description	*n*	%
Gender	Ph.D. student's gender	Men	Men = 1	129	60.0
		Women	Women = 2	85	39.5
		Non-binary	Non-binary = 3	1	0.5
Degree sought	Ph.D. student's degree sought	Master's	Master's = 1	0	0.0
		Ph.D.	Ph.D. = 2	203	94.4
		Both	Both = 3	12	5.6
		N/A	N/A = 3	0	0.0
Qualifying/area exam	Ph.D. student completed department's qualifying/area exam?	Yes	Yes = 1	141	65.6
		No	No = 2	65	30.2
		N/A	N/A = 3	9	4.2
Ethnicity	Ph.D. student's race/ethnicity	White/Caucasian	White/Caucasian = 1	107	49.8
		Black/African American	Black/African American = 2	4	1.9
		Hispanic or Latino	Hispanic or Latino = 3	12	5.6
		Native American	Native American = 4	0	0.0
		Asian	Asian = 5	64	29.8
		Pacific Islander	Pacific Islander = 6	0	0.0
		Other	Other = 7 or 8	8	3.7
		Prefer not to respond	Prefer not to respond = 9	2	0.9
		Multiple selected non-URM		12	5.6
		Multiple selected URM		6	2.8
		All URM	Combined URM	22	10.2
Worked full-time in industry	Ph.D. student worked full-time in industry (not including internship/co-op)	Yes	Yes = 1	69	32.1
		No	No = 2	146	67.9
		N/A	N/A = 3	0	0.0

Characteristic	Explanation	Range	Scale Description	*n*	%
Internship or co-op	Ph.D. student had internship or co-op related to their research	Yes	Yes = 1	36	16.7
		No	No = 2	63	29.3
		N/A	N/A = 3	116	54.0
TA/Instructor	Ph.D. student has been TA/Instructor during Ph.D. research	Yes	Yes = 1	139	64.7
		No	No = 2	72	34.4
		N/A	N/A = 3	2	0.9
Source of funding	Ph.D. student's source of funding during Ph.D. research	Government	Government = 1	155	72.1
		Industry	Industry = 2	19	8.8
		Not funded	Not funded = 3	13	6.0
		Other	Other = 4	28	13.0
After graduation	Ph.D. student's path after graduation	Government	Government = 1	26	12.1
		Industry	Industry = 2	96	44.7
		Academia	Academia = 3	77	35.8
		Other	Other = 4	16	7.4

Table D.3: *Respondent Self-Report Metrics for Number of Research Group Size* (n = 215)

Variable	Explanation	Min	Max	Range	Mean	Std. Dev
# of graduate students in research group	Ph.D. student's self-report of research group size	1	23	22	6.4	4.7

Table D.4: *Respondent Self-Report Information* (n = 215)

Characteristic	Explanation	Range	Scale Description	*n*	%
Research group organization	Ph.D. student's research group organization	Advisor dominant	Advisor dominant = 1	141	53.0
		Student-centric	Student-centric = 2	73	34.0
		Other	Other = 3	28	13.0
Research work organization	Ph.D. student's research work organization	Self or with advisor	Advisor dominant = 1	161	74.9
		Broader team	Student-centric = 2	42	19.5
		Other	Other = 3	12	5.6
Major	Ph.D. student's engineering major	Aero/Astro	Aero/Astro = 1	9	4.2
		Ag & Bio	Ag & Bio = 2	1	0.5
		Biomedical	Biomedical = 3	29	13.5
		Chemical	Chemical = 4	34	15.8
		Civil	Civil = 5	10	4.7
		Constr & Mgmt	Constr & Mgmt = 6	2	0.9
		Electrical & Comp	Electrical & Comp = 7	41	19.1
		Engineering Ed	Engineering Ed = 8	7	3.3
		Envir & Ecol	Envir & Ecol = 9	9	4.2
		Industrial	Industrial = 10	6	2.8
		Materials	Materials = 11	17	7.9
		Mechanical	Mechanical = 12	31	14.4
		Nuclear	Nuclear = 13	0	0.0
		Other	Other = 14	19	8.8

Characteristic	Explanation	Range	Scale Description	*n*	%
Research type	Ph.D. student's research type	Basic	Basic = 1	51	23.7
		Applied	Applied = 2	156	72.6
		Other	Other = 3	8	3.7
Collaborator type	Ph.D. student's collaborator type	Government	Government = 1	55	25.6
		Industry	Industry = 2	39	18.1
		Research center	Research center = 3	97	45.1
		Other	Other = 4	24	11.2
Collaborator interaction type	Ph.D. student's collaborator interaction type	Infrequent	Yes = 1	101	47.0
		Frequent	No = 2	95	44.2
		Other	Other = 3	19	8.8
Equipment type	Ph.D. student's type of equipment used for research	Model & sim w/ computer tools	Model & sim w/ computer tools = 1	69	32.1
		Testing, experiments	Testing, experiments = 2	84	39.1
		Combination of 1 & 2	Combination of 1 & 2 = 3	51	23.7
		Other	Other = 4	11	5.1
Work space organization	Ph.D. student's work space organization	Alone or with few	Alone or with few = 1	48	22.3
		Only with research group	Only with research group = 2	98	45.6
		Shared with multiple groups	Shared with multiple research groups = 3	63	29.3
		Other	Other = 4	6	2.8

Table D.5: *Respondent Demographic Information for University* (n = 215)

Characteristic	Explanation	Values	*n*	%
University	Ph.D. student's University	Arizona State University	33	15.3
		Auburn University	4	1.9
		Clemson University	26	12.1
		Cornell University	10	4.7
		Florida Institute of Technology	1	0.5
		Georgia Institute of Technology	1	0.5
		Iowa State University	4	1.9
		Michigan State University	12	5.6
		Michigan Technological University	2	0.9
		None listed	4	1.9
		Northwestern University	8	3.7
		Pennsylvania State University	1	0.5
		Purdue University	5	2.3
		Southern Illinois University	1	0.5
		The Ohio State University	19	8.8
		The University of Oklahoma	3	1.4
		The University of Texas at Austin	8	3.7
		University of Cincinnati	9	4.2
		University of Dayton	1	0.5
		University of Illinois at Chicago	1	0.5
		University of Illinois at Urbana Champaign	5	2.3
		University of Michigan	14	6.5
		University of North Texas	2	0.9
		University of Notre Dame	6	2.8
		University of Pittsburgh	14	6.5
		University of Utah	7	3.3
		University of Virginia	3	1.4
		Vanderbilt University	1	0.5
		Virginia Polytechnic Institute and State University	3	1.4
		Western Michigan University	7	3.3

APPENDIX E. INSTRUMENT SCORING AND GROUP ANALYSIS: RESULTS

Table E.1: *Respondent Assessment Questions Descriptive Statistics* (n = 451)

Assessment Questions	Mean	Std. Error	Med.	Std. Dev.	Skew	Std. Error	Kurt	Std. Error	Kolmogorov-Smirnov[a] Shapiro-Wilk	*df*	*p*
Q1: take on different roles or responsibilities within a research group?	4.55	0.06	5	1.23	-0.97	0.12	0.83	0.23	0.220 0.865	451	< .001
Q2: coordinate research tasks with other graduate students?	4.35	0.06	5	1.33	-0.79	0.12	0.18	0.23	0.197 0.888	451	< .001
Q3: share decision making responsibility with other graduate students?	4.16	0.06	4	1.31	-0.73	0.12	0.06	0.23	0.199 0.896	451	< .001
Q5: mutually depend on other graduate students to meet the desired outcomes?	3.80	0.07	4	1.44	-0.28	0.12	-0.71	0.23	0.173 0.928	451	< .001
Q6: present your research results to your sponsors or collaborators who are involved in your research?	4.02	0.08	4	1.59	-0.59	0.12	-0.72	0.23	0.201 0.885	451	< .001
Q7: interact at your university with your sponsors or collaborators who are involved in your research?	3.99	0.08	4	1.61	-0.50	0.12	-0.88	0.23	0.194 0.893	451	< .001
Q8: correspond (e.g., email, phone, etc.) with your sponsors or collaborators who are involved in your research?	3.93	0.07	4	1.57	-0.52	0.12	-0.77	0.23	0.203 0.895	451	< .001
Q9: interact with your sponsors or collaborators at their place of work related to your research?	3.04	0.08	3	1.65	0.18	0.12	-1.22	0.23	0.168 0.892	451	< .001
Q10: co-author journal or conf papers with your sponsors or collaborators?	3.54	0.08	4	1.71	-0.32	0.12	-1.21	0.23	0.207 0.875	451	< .001
Q11: co-create a presentation with your sponsors or collaborators?	3.25	0.08	3	1.65	0.00	0.12	-1.22	0.23	0.166 0.902	451	< .001
Q12: develop prof relationships with practicing engineers through research?	3.21	0.07	3	1.47	0.03	0.12	-0.89	0.23	0.177 0.922	451	< .001
Q13: participate in industry or gvmt conferences as part of research?	3.51	0.08	4	1.59	-0.30	0.12	-1.10	0.23	0.199 0.898	451	< .001
Q15: present results of your research to practicing engineers?	3.43	0.07	4	1.47	-0.23	0.12	-0.93	0.23	0.210 0.915	451	< .001
Q16: interact with practicing engineers during internships or co-ops?	2.48	0.08	2	1.63	0.63	0.12	-0.95	0.23	0.282 0.814	451	< .001

Assessment Questions	Mean	Std. Error	Med.	Std. Dev.	Skew	Std. Error	Kurt	Std. Error	Kolmogorov-Smirnov[a] Shapiro-Wilk	*df*	*p*
Q18: develop or utilize a mathematical model to help solve a problem?	4.33	0.07	5	1.49	-0.72	0.12	-0.35	0.23	0.202 0.880	451	< .001
Q19: specify constraints or assumptions in development of a mathematical model to help solve a problem?	4.06	0.08	4	1.67	-0.59	0.12	-0.86	0.23	0.200 0.874	451	< .001
Q20: utilize sophisticated tools to help solve a modeling or simulation problem?	3.98	0.08	4	1.64	-0.56	0.12	-0.83	0.23	0.191 0.882	451	< .001
Q21: simulate a system to obtain results?	4.55	0.07	5	1.55	-0.93	0.12	-0.16	0.23	0.215 0.832	451	< .001
Q22: iterate on the development of a model or simulation to optimize results?	4.44	0.08	5	1.60	-0.93	0.12	-0.21	0.23	0.230 0.832	451	< .001
Q23: verify a model or simulation based on real-world data or actual results?	4.02	0.08	4	1.62	-0.64	0.12	-0.75	0.23	0.217 0.873	451	< .001
Q24: use testing equipment or instrumentation as an integral part of conducting your research?	4.14	0.09	5	1.88	-0.58	0.12	-1.19	0.23	0.232 0.822	451	< .001
Q25: develop plans to use testing equipment or instrumentation?	3.97	0.08	4	1.79	-0.52	0.12	-1.09	0.23	0.200 0.857	451	< .001
Q26: ensure testing equipment or instrumentation is appropriately set-up (i.e., calibrated) before use?	4.11	0.09	5	1.87	-0.66	0.12	-1.05	0.23	0.242 0.816	451	< .001
Q27: collect data from testing equipment or apparatus using appropriate sensors or instrumentation?	4.06	0.09	5	1.90	-0.57	0.12	-1.20	0.23	0.235 0.823	451	< .001
Q28: interpret data gathered from testing equipment or apparatus?	4.61	0.08	5	1.71	-1.12	0.12	-0.09	0.23	0.284 0.761	451	< .001
Q29: troubleshoot or modify testing equipment or instrumentation when it does not operate properly?	4.55	0.09	5	1.85	-0.52	0.12	-1.18	0.23	0.215 0.843	451	< .001

[a.] Lilliefors Significance Correction

Table E.2: *Combined Respondent Demographic Information* (n = 451)

Characteristic	Explanation	Range	Scale Description	*n*	%
Gender	Ph.D. student's gender	Men	Men = 1	294	65.2
		Women	Women = 2	155	34.4
		Non-binary	Non-binary = 3	2	0.4
Degree sought	Ph.D. student's degree sought	Master's	Master's = 1	0	0.0
		Ph.D.	Ph.D. = 2	427	94.7
		Both	Both = 3	24	5.3
		N/A	N/A = 3	0	0.0
Qualifying/area exam	Ph.D. student completed department's qualifying/area exam?	Yes	Yes = 1	298	66.1
		No	No = 2	120	26.6
		N/A	N/A = 3	33	7.3
Ethnicity	Ph.D. student's race/ethnicity	White	White = 1	202	44.8
		Black/African American	Black/African American = 2	9	2.0
		Hispanic or Latino	Hispanic or Latino = 3	26	5.8
		Native American	Native American = 4	0	0.0
		Asian	Asian = 5	159	35.3
		Pacific Islander	Pacific Islander = 6	0	0.0
		Other	Other = 7 or 8	12	2.7
		Prefer not to respond	Prefer not to respond = 9	9	2.0
		Multiple selected non-URM		18	4.0
		Multiple selected URM		16	3.5
		All URM	Combined URM	51	11.3
Worked full-time in industry	Ph.D. student worked full-time in industry (not including internship/co-op)	Yes	Yes = 1	138	30.6
		No	No = 2	312	69.2
		N/A	N/A = 3	1	0.2
Internship or co-op	Ph.D. student had internship or co-op related to their research	Yes	Yes = 1	73	16.2
		No	No = 2	136	30.1
		N/A	N/A = 3	242	53.7

Characteristic	Explanation	Range	Scale Description	*n*	%
TA/Instructor	Ph.D. student has been TA/Instructor during Ph.D. research	Yes	Yes = 1	255	56.6
		No	No = 2	185	41.0
		N/A	N/A = 3	11	2.4
Source of funding	Ph.D. student's source of funding during Ph.D. research	Government	Government = 1	304	67.4
		Industry	Industry = 2	54	12.0
		Not funded	Not funded = 3	25	5.5
		Other	Other = 4	68	15.1
After graduation	Ph.D. student's path after graduation	Government	Government = 1	52	11.5
		Industry	Industry = 2	197	43.7
		Academia	Academia = 3	176	39.0
		Other	Other = 4	26	5.8

Table E.3: *Combined Respondent Self-Report Metrics for # of Research Group Size* (n = 451)

Variable	Explanation	Min	Max	Range	Mean	Std. Dev
# of graduate students in research group	Ph.D. student's self-report of research group size	1	30	29	7.3	5.2

Table E.4: *Combined Respondent Self-Report Information* (n = 451)

Characteristic	Explanation	Range	Scale Description	*n*	%
Research group organization	Ph.D. student's research group organization	Advisor dominant	Advisor dominant = 1	245	54.3
		Student-centric	Student-centric = 2	165	36.6
		Other	Other = 3	41	9.1
Research work organization	Ph.D. student's research work organization	Self or with advisor	Advisor dominant = 1	332	73.6
		Broader team	Student-centric = 2	99	22.0
		Other	Other = 3	20	4.4
Major	Ph.D. student's engineering major	Aero/Astro	Aero/Astro = 1	35	7.8
		Ag & Bio	Ag & Bio = 2	1	0.2
		Biomedical	Biomedical = 3	39	8.6
		Chemical	Chemical = 4	50	11.1
		Civil	Civil = 5	35	7.8
		Constr & Mgmt	Constr & Mgmt = 6	3	0.7
		Electrical & Comp	Electrical & Comp = 7	82	18.2
		Engineering Ed	Engineering Ed = 8	28	6.2
		Envir & Ecol	Envir & Ecol = 9	12	2.7
		Industrial	Industrial = 10	20	4.4
		Materials	Materials = 11	32	7.1
		Mechanical	Mechanical = 12	87	19.3
		Nuclear	Nuclear = 13	8	1.8
		Other	Other = 14	19	4.2
Research type	Ph.D. student's research type	Basic	Basic = 1	123	27.3
		Applied	Applied = 2	314	69.6
		Other	Other = 3	14	3.1

Characteristic	Explanation	Range	Scale Description	*n*	%
Collaborator type	Ph.D. student's collaborator type	Government	Government = 1	125	27.7
		Industry	Industry = 2	98	21.7
		Research center	Research center = 3	182	40.4
		Other	Other = 4	46	10.2
Collaborator interaction type	Ph.D. student's collaborator interaction type	Infrequent	Yes = 1	222	49.2
		Frequent	No = 2	196	43.5
		Other	Other = 3	33	7.3
Equipment type	Ph.D. student's type of equipment used for research	Model & sim w/ computer tools	Model & sim w/ computer tools = 1	160	35.5
		Testing, experiments	Testing, experiments = 2	149	33.0
		Combination of 1 & 2	Combination of 1 & 2 = 3	113	25.1
		Other	Other = 4	29	6.4
Work space organization	Ph.D. student's work space organization	Alone or with few	Alone or with few = 1	90	20.0
		Only with research group	Only with research group = 2	198	43.9
		Shared with multiple groups	Shared with multiple research groups = 3	152	33.7
		Other	Other = 4	11	2.4

Table E.5: *Combined Respondent Demographic Information for University* (n = 451)

Characteristic	Explanation	Values	*n*	%
University	Ph.D. student's University	Arizona State University	33	7.3
		Auburn University	4	0.9
		Clemson University	26	5.8
		Cornell University	10	2.2
		Florida Institute of Technology	1	0.2
		Georgia Institute of Technology	1	0.2
		Iowa State University	4	0.9
		Michigan State University	12	2.7
		Michigan Technological University	2	0.4
		None listed	4	0.9
		Northwestern University	8	1.8
		Pennsylvania State University	1	0.2
		Purdue University	241	53.4
		Southern Illinois University	1	0.2
		The Ohio State University	19	4.2
		The University of Oklahoma	3	0.7
		The University of Texas at Austin	8	1.8
		University of Cincinnati	9	2.0
		University of Dayton	1	0.2
		University of Illinois at Chicago	1	0.2
		University of Illinois at Urbana Champaign	5	1.1
		University of Michigan	14	3.1
		University of North Texas	2	0.4
		University of Notre Dame	6	1.3
		University of Pittsburgh	14	3.1
		University of Utah	7	1.6
		University of Virginia	3	0.7
		Vanderbilt University	1	0.2
		Virginia Polytechnic Institute and State University	3	0.7
		Western Michigan University	7	1.6

REI Scoring Instruction Guide

The following is a scoring guide to assist higher-education administrators, faculty, and researchers who wish to use the Research Experiences Instrument (REI). There are five aspects, or factors, that the REI is intended to measure relative to engineering Ph.D. students' opportunities to practice being a professional in their research experiences, and an overall REI score.

5 Factors: (F1) Working as a team member, (F2) Exposure to collaborator's form of practice, (F3) Exposure to relevant professional practice, (F4) Modeling and simulation tasks, and (F5) Practical skills.

Each factor is comprised of four to six questions. Within the factor, these questions are to be scored and then averaged with the other questions within that factor. The individual factor scores will remain on the original scale: 1) never, 2) very rarely, 3) rarely, 4) occasionally, 5) frequently, 6) very frequently, and should be interpreted as such. The minimum/maximum individual factor scores also remain on the original scale: minimum - 1) never; maximum - 6) very frequently.

The overall REI score is the sum of the five factor scores, and indicates the overall opportunities to practice being a professional (higher scores indicate more opportunities). The overall scale will be on a 30-point scale: 5-7) never, 8-12) very rarely, 13-17) rarely, 18-22) occasionally, 23-27) frequently, 28-30) very frequently. The minimum/maximum overall factor scores will be: minimum 5) never; maximum 30) very frequently.

The REI is not designed as an individual assessment, but rather scores should be compared with relative peer groups across mean scores. When comparing peer groups, the overall REI score should first be compared for which groups have higher and lower scores, then the individual factor scores should be examined for an indication of why the overall REI scores for the peer groups are higher/lower comparatively.

Overall stem: How often in your Ph.D. research experiences did you:

Factor F1: Working as a team member
Q1: take on different roles or responsibilities within a research group?
Q2: coordinate research tasks with other graduate students?
Q3: share decision making responsibility with other graduate students?
Q5: mutually depend on other graduate students to meet the desired outcomes?
F1 score = (Q1 + Q2 + Q3 + Q5) / 4

Factor F2: Exposure to collaborator's form of practice

Q6: present your research results to your sponsors or collaborators who are involved in your research?

Q7: interact at your university with your sponsors or collaborators who are involved in your research?

Q8: correspond (e.g., email, phone, etc.) with your sponsors or collaborators who are involved in your research?

Q9: interact with your sponsors or collaborators at their place of work related to your research?

Q10: co-author journal or conference papers with your sponsors or collaborators?

Q11: co-create a presentation with your sponsors or collaborators?

F2 score = (Q6 + Q7 + Q8 + Q9 + Q10 + Q11) / 6

Factor F3: Exposure to relevant professional practice

Q12: develop professional relationships with practicing engineers through research?

Q13: participate in industry or government conferences as part of research?

Q15: present results of your research to practicing engineers?

Q16: interact with practicing engineers during internships or co-ops?

F3 score = (Q11 + Q13 + Q15 + Q16) / 4

Factor F4: Modeling and simulation tasks

Q18: develop or utilize a mathematical model to help solve a problem?

Q19: specify constraints or assumptions in development of a mathematical model to help solve a problem?

Q20: utilize sophisticated tools to help solve a modeling or simulation problem?

Q21: simulate a system to obtain results?

Q22: iterate on the development of a model or simulation to optimize results?

Q23: verify a model or simulation based on real-world data or actual results?

F4 score = (Q18 + Q19 + Q20 + Q21 + Q22 + Q23) / 6

Factor F5: Modeling and simulation tasks

Q24: use testing equipment or instrumentation as an integral part of conducting your research?

Q25: develop plans to use testing equipment or instrumentation?

Q26: ensure testing equipment or instrumentation is appropriately set-up (i.e., calibrated) before use?

Q27: collect data from testing equipment or apparatus using appropriate sensors or instrumentation?

Q28: interpret data gathered from testing equipment or apparatus?

Q29: troubleshoot or modify testing equipment or instrumentation when it does not operate properly?

F5 score = (Q24 + Q25 + Q26 + Q27 + Q28 + Q29) / 6

Overall REI score = F1 + F2 + F3 + F4 + F5

Table E.6: *Respondent Factor Scores Descriptive Statistics* (n = 451)

Factor	Min	Max	Mean	Std. Error	Med.	Std. Dev.	Skew	Std. Error	Kurt	Std. Error	Kolmogorov-Smirnov[a] Shapiro-Wilk	*df*	*p*
F1: Working as a team member	1.00	6.00	4.21	0.05	5	1.12	-0.72	0.12	0.13	0.23	0.107 0.953	451	< .001
F2: Exposure to collaborator's form of practice	1.00	6.00	3.63	0.06	5	1.29	-0.38	0.12	-0.72	0.23	0.095 0.964	451	< .001
F3: Exposure to relevant professional practice	1.00	6.00	3.16	0.06	4	1.17	0.02	0.12	-0.68	0.23	0.083 0.980	451	< .001
F4: Modeling and simulation tasks	1.00	6.00	4.23	0.08	4	1.31	-0.75	0.12	-0.38	0.23	0.137 0.925	451	< .001
F5: Practical skills	1.00	6.00	4.15	0.08	4	1.66	-0.71	0.12	-0.87	0.23	0.167 0.872	451	< .001
Overall REI score:	7.75	28.75	19.38	0.19	19.58	4.05	-0.24	0.12	-0.20	0.23	0.036 0.993	451	.20

[a.] Lilliefors Significance Correction

Table E.7: *Social Group Clustering* (n = 451)

Group	Cluster Values	*n*	%
Social Group (Group Size / Group Org / Work Org)	1 – Large / Advis dom / Indiv	1	0.2
	2 – Large / Group foc/ Indiv	5	1.1
	3 – Large / Group foc / Team	4	0.9
	4 – Med / Advis dom / Indiv	121	26.8
	5 – Med / Advis dom/ Team	22	4.9
	6 – Med / Group foc/ Indiv	70	15.5
	7 – Med / Group foc/ Team	42	9.3
	8 – Small / Advis dom/ Indiv	82	18.2
	9 – Small / Advis dom/ Team	12	2.7
	10 – Small / Group foc/ Indiv	26	5.8
	11 – Small / Group /foc Team	13	2.9
	12 – Other (various)	53	11.8

Table E.8: *Cultural Group Clustering* (n = 451)

Group	Cluster Values	*n*	%
Cultural Group (Work Type / Collaborator / Interaction)	1 – Applied / Center / Freq	59	13.1
	2 - Applied / Center / Infreq	48	10.6
	3 - Applied / Govt / Freq	31	6.9
	4 - Applied / Govt / Infreq	54	12.0
	5 - Applied / Indus / Freq	47	10.4
	6 - Applied / Indus / Infreq	38	8.4
	7 - Basic / Center / Freq	29	6.4
	8 - Basic / Center / Infreq	31	6.9
	9 - Basic / Govt / Freq	5	1.1
	10 - Basic / Govt / Infreq	27	6.0
	11 - Basic / Indus / Freq	6	1.3
	12 – Basic / Indus / Infreq	6	1.3
	13 – Other (various)	70	15.5

Table E.9: *Material Group Clustering* (n = 451)

Group	Cluster Values	*n*	%
Material Group (Equipment Type / Work Space)	1 – Model / Isolated	43	9.5
	2 - Model / Shared	113	25.1
	3 - Physical / Isolated	40	8.9
	4 - Physical / Shared	218	48.3
	5 – Other (various)	37	8.2

Table E.10: *Group Mean REI Scores Summary – Selected Demographic Information* (n = 451)

Group	Values	*n*	%	Mean Scores: F1: Working as a team member	F2: Exposure to collaborator's form of practice	F3: Exposure to relevant prof. practice	F4: Modeling and simulation tasks	F5: Practical skills	Overall score *M* (SD)
All Sample		451	100	4.21	3.63	3.16	4.23	4.15	19.38 (4.05)
Gender	Men	294	65.2	4.22	3.55	3.12	4.34	4.16	19.39 (3.99)
	Women	155	34.4	4.20	3.79	3.23	4.01	4.13	19.38 (4.17)
	Non-binary	2	0.4	3.50	2.50	2.50	4.50	3.92	16.91 (5.54)
Qualifying/area exam	Yes	298	66.1	4.20	3.62	3.18	4.21	4.23	19.45 (4.02)
	No	120	26.6	4.35	3.73	3.13	4.28	4.09	19.57 (4.06)
	N/A	33	7.3	3.79	3.31	3.05	4.25	3.62	18.01 (4.13)
Worked full-time in industry	Yes	138	30.6	4.13	3.60	3.20	4.18	3.87	18.97 (4.12)
	No	312	69.2	4.25	3.64	3.14	4.25	4.28	19.57 (4.00)
	N/A	1	0.2	4.00	2.00	1.00	5.50	1.17	13.67
Internship or co-op	Yes	73	16.2	4.36	4.06	3.98	4.54	4.42	21.37 (3.53)
	No	136	30.1	4.24	3.64	3.28	4.24	4.01	19.41 (4.39)
	N/A	242	53.7	4.15	3.49	2.84	4.13	4.14	18.76 (3.81)
TA/Instructor	Yes	255	56.6	4.28	3.70	3.30	4.21	4.23	19.71 (3.93)
	No	185	41.0	4.11	3.53	2.98	4.29	4.00	18.92 (4.19)
	N/A	11	2.4	4.41	3.53	2.89	3.86	4.58	19.26 (3.91)
Source of funding	Government	304	67.4	4.28	3.58	3.16	4.21	4.25	19.47 (3.85)
	Industry	54	12.0	4.36	4.25	3.63	4.64	4.55	21.41 (3.53)
	Not funded	25	5.5	3.77	3.20	2.97	4.13	3.57	17.64 (5.32)
	Other	68	15.1	3.97	3.51	2.86	4.05	3.58	17.98 (4.08)

Group	Values	*n*	%	Mean Scores					
				F1: Working as a team member	F2: Exposure to collaborator's form of practice	F3: Exposure to relevant prof. practice	F4: Modeling and simulation tasks	F5: Practical skills	Overall score *M* (SD)
All Sample		451	100	4.21	3.63	3.16	4.23	4.15	19.38 (4.05)
After graduation	Government	52	11.5	4.22	3.49	3.35	4.16	4.33	19.56 (4.00)
	Industry	197	43.7	4.22	3.62	3.21	4.32	4.37	19.74 (3.96)
	Academia	176	39.0	4.22	3.71	3.07	4.19	3.83	19.00 (4.11)
	Other	26	5.8	4.10	3.44	3.00	3.98	4.23	18.7 (4.35)
Participation in professional engineering societies	Never	91	20.2	3.73	2.87	2.44	4.02	3.76	16.83 (3.79)
	Very Rarely	71	15.7	3.88	3.29	2.75	4.32	4.24	18.48 (3.92)
	Rarely	90	20.0	4.44	3.96	3.50	4.51	4.30	20.70 (2.94)
	Occasionally	106	23.5	4.20	3.80	3.29	4.26	4.18	19.72 (3.92)
	Frequently	58	12.9	4.55	4.24	3.79	4.15	4.26	21.00 (3.97)
	Very Frequently	35	7.8	5.05	3.91	3.51	3.94	4.28	20.69 (4.53)

Table E.11: *Group Mean REI Scores Summary – Ethnicity Information* (n = 451)

Group	Values	*n*	%	Mean Scores					
				F1: Working as a team member	F2: Exposure to collaborator's form of practice	F3: Exposure to relevant prof. practice	F4: Modeling and simulation tasks	F5: Practical skills	Overall score *M* (SD)
All Samples		451	100	4.21	3.63	3.16	4.23	4.15	19.38 (4.05)
Ethnicity	White	202	44.8	4.24	3.53	3.08	4.08	4.27	19.21 (3.99)
	Black/African American	9	2.0	3.94	2.80	2.91	3.19	2.96	15.81 (5.11)
	Hispanic or Latino	26	5.8	4.20	3.84	3.39	3.97	3.40	18.81 (4.25)
	Native American	0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
	Asian	159	35.3	4.25	3.83	3.31	4.53	4.25	20.17 (3.94)
	Pacific Islander	0	0.0	0.0	0.00	0.00	0.00	0.00	0.00
	Other	12	2.7	4.25	3.83	3.31	4.53	4.25	20.17 (3.94)
	Prefer not to respond	9	2.0	4.08	3.30	2.75	4.20	4.31	18.65 (3.53)
	Multiple selected non-URM	18	4.0	4.07	3.67	3.32	4.26	4.24	19.56 (3.53)
	Multiple selected URM	16	3.5	4.58	3.31	2.61	4.03	3.57	18.10 (4.41)
	Non-URM	400	88.7	4.21	3.65	3.17	4.28	4.24	19.55 (3.96)
	All URM	51	11.3	4.27	3.49	3.06	3.85	3.38	18.06 (4.50)

Table E.12: *Group Mean REI Scores Summary – Discipline Information* (n = 451)

Group	Values	*n*	%	Mean Scores F1: Working as a team member	F2: Exposure to collaborator's form of practice	F3: Exposure to relevant prof. practice	F4: Modeling and simulation tasks	F5: Practical skills	Overall score *M* (SD)
All Samples		451	100	4.21	3.63	3.16	4.23	4.15	19.38 (4.05)
Major (i.e. Discipline)	Aero/Astro	35	7.8	4.22	3.51	3.34	4.66	3.66	19.39 (4.15)
	Ag & Bio	1	0.2	3.25	3.17	1.50	4.33	4.33	16.58
	Biomedical	39	8.6	4.62	3.73	3.01	3.91	4.86	20.14 (3.04)
	Chemical	50	11.1	4.82	3.43	3.07	4.07	4.72	20.10 (3.35)
	Civil	35	7.8	4.14	3.74	3.36	4.56	4.15	20.00 (3.67)
	Constr & Mgmt	3	0.7	3.08	4.11	3.17	4.11	3.28	17.75 (6.87)
	Electrical & Comp	82	18.2	4.07	3.67	3.36	4.82	4.01	19.93 (3.94)
	Engineering Ed	28	6.2	4.64	3.85	2.68	2.34	2.26	15.76 (3.73)
	Envir & Ecol	12	2.7	3.69	3.60	3.52	3.89	3.85	18.54 (4.27)
	Industrial	20	4.4	3.26	3.31	3.11	4.14	3.30	17.13 (4.81)
	Materials	32	7.1	4.35	4.18	3.45	3.63	5.16	20.76 (3.07)
	Mechanical	87	19.3	4.02	3.27	2.86	4.47	4.36	18.98 (4.41)
	Nuclear	8	1.8	4.22	4.00	3.34	4.54	4.15	20.25 (3.11)
	Other	19	4.2	4.09	4.27	3.54	4.24	3.99	20.13 (4.50)

Table E.13: *Group Mean REI Scores Summary – Self-Report Information* (n = 451)

Group	Values	*n*	%	Mean Scores F1: Working as a team member	F2: Exposure to collaborator's form of practice	F3: Exposure to relevant prof. practice	F4: Modeling and simulation tasks	F5: Practical skills	Overall score *M* (SD)
All Sample		451	100	4.21	3.63	3.16	4.23	4.15	19.38 (4.05)
Size of research group	Large (> 20)	10	2.2	4.50	3.55	3.33	3.58	5.12	20.08 (2.47)
	Med (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)
Research 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)
Research 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)
Research 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)
Collaborator Type	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)
	Univ. 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)
Collaborator 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)

Group	Values	*n*	%	Mean Scores					
				F1: Working as a team member	F2: Exposure to collaborator's form of practice	F3: Exposure to relevant prof. practice	F4: Modeling and simulation tasks	F5: Practical skills	Overall score *M* (SD)
All Sample		451	100	4.21	3.63	3.16	4.23	4.15	19.38 (4.05)
	Mod/Sim Only	160	35.5	3.86	3.54	3.15	4.91	2.76	18.23 (4.25)
Equipment Type	Some facil/test	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)
	Isolated	90	20.0	3.58	3.20	3.01	4.33	3.67	17.80 (4.48)
Work Space	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)

Table E.14: *Group Mean REI Scores Summary – Social Group Information* (n = 451)

Group	Values	*n*	%	Mean Scores: F1: Working as a team member	F2: Exposure to collaborator's form of practice	F3: Exposure to relevant prof. practice	F4: Modeling and simulation tasks	F5: Practical skills	Overall score *M* (SD)
All Sample		451	100	4.21	3.63	3.16	4.23	4.15	19.38 (4.05)
Social Group (Group Size / Group Org / Work Org)	4 – Med / Advis dom / Indiv	121	26.8	3.82	3.49	3.00	4.60	4.01	18.93 (3.74)
	6 – Med / Group foc / Indiv	70	15.5	4.53	3.69	3.22	4.21	4.14	19.80 (4.31)
	7 – Med / Group foc / Team	42	9.3	5.01	3.72	3.31	3.62	4.94	20.60 (3.79)
	8 – Small / Advis dom / Indiv	82	18.2	3.68	3.40	3.02	4.29	3.65	18.04 (4.13)

Table E.15: *Group Mean REI Scores Summary – Cultural Group Information* (n = 451)

Group	Values	*n*	%	Mean Scores: F1: Working as a team member	F2: Exposure to collaborator's form of practice	F3: Exposure to relevant prof. practice	F4: Modeling and simulation tasks	F5: Practical skills	Overall score *M* (SD)
All Sample		451	100	4.21	3.63	3.16	4.23	4.15	19.38 (4.05)
Cultural Group (Work Type / Collaborator / Interaction)	1 – Applied / Center / Freq	59	13.1	4.46	4.05	3.29	4.27	4.51	20.58 (3.72)
	2 – Applied / Center / Infreq	48	10.6	4.30	3.35	2.90	4.08	3.99	18.63 (3.58)
	4 – Applied / Govt / Infreq	54	12.0	4.23	3.23	3.30	4.34	4.53	19.65 (3.96)
	5 – Applied / Indus / Freq	47	10.4	4.53	4.65	3.83	4.59	4.47	22.07 (3.06)

Table E.16: *Group Mean REI Scores Summary – Material Group Information* (n = 451)

Group	Values	*n*	%	Mean Scores F1: Working as a team member	F2: Exposure to collaborator's form of practice	F3: Exposure to relevant prof. practice	F4: Modeling and simulation tasks	F5: Practical skills	Overall score *M* (SD)
All Sample		451	100	4.21	3.63	3.16	4.23	4.15	19.38 (4.05)
Material Group (Equipment Type / Work Space	1 – Model / Isolated	43	9.5	3.26	3.07	2.93	5.04	2.32	16.62 (4.48)
	2 – Model / 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)

Table E.17: *Group Mean Comparison Selections*

Comparison Groups	Values	*n*	%	Selected Group Size	Overall score *M* (SD)
<u>Demographic Groups</u>					
Group 1: Internship or co-op	Yes	73	16.2	73	21.37 (3.53)
	No	136	30.1		19.41 (4.39)
	N/A	242	53.7		18.76 (3.81)
Group 2: Source of funding	Government	304	67.4	54	19.47 (3.85)
	Industry	54	12.0		21.41 (3.53)
Group 3: Participation in professional engineering societies	Never	91	20.2	58	16.83 (3.79)
	Very Rarely	71	15.7		18.48 (3.92)
	Rarely	90	20.0		20.70 (2.94)
	Occasionally	106	23.5		19.72 (3.92)
	Frequently	58	12.9		21.00 (3.97)
<u>Ethnicity Groups</u>					
Group 4: Ethnic groups	White	202	44.8	159	19.21 (3.99)
	Asian	159	35.3		20.21 (3.94)
Group 5: URM	Non-URM	400	88.7	51	19.55 (3.96)
	All URM	51	11.3		18.06 (4.50)
<u>Discipline Group</u>					
Group 6: Major (i.e., Discipline)	Chemical	50	11.1	50	20.10 (3.35)
	Electrical & Comp	82	18.2		19.93 (3.94)
	Mechanical	87	19.3		18.98 (4.41)
<u>Self-Report Groups</u>					
Group 7: Size of research group	Med (5 -20)	290	64.3	151	19.74 (3.94)
	Small (< 5)	151	33.5		18.63 (4.25)
Group 8: Research group organization	Advisor dominant	245	54.3	165	19.05 (3.97)
	Group focused	165	36.6		19.72 (4.16)

Comparison Groups	Values	*n*	%	Selected Group Size	Overall score *M* (SD)
Group 9: Research work organization	Individual	332	73.6	99	18.93 (4.03)
	Team	99	22.0		20.76 (3.79)
Group 10: Research work type	Basic	123	27.3	123	18.15 (4.18)
	Applied	314	69.6		19.86 (3.96)
Group 11: Collaborator Type	Government	125	27.7	98	19.87 (3.65)
	Industry	98	21.7		20.72 (3.64)
	Univ. Center	182	40.4		18.93 (3.95)
Group 12: Collaborator Interactions	Infrequent	222	49.2	196	18.74 (3.81)
	Frequent	196	43.5		20.70 (3.73)
Group 13: Equipment Type	Mod/Sim Only	160	35.5	160	18.23 (4.25)
	Some facil/test	262	58.1		20.53 (3.45)
Group 14: Work Space	Isolated	90	20.0	90	17.80 (4.48)
	Shared	350	77.6		19.85 (3.81)
<u>Social/Cultural/Material Groups</u>					
Group 15: Social Group (Group Size / Group Org / Work Org)	4 – Med / Advis dom / Indiv	121	26.8	42	18.93 (3.74)
	6 – Med / Group foc / Indiv	70	15.5		19.80 (4.31)
	7 – Med / Group foc / Team	42	9.3		20.60 (3.79)
	8 – Sm / Advis dom / Indiv	82	18.2		18.04 (4.13)
Group 16: Cultural Group (Work Type / Collaborator / Interaction)	1 – Applied / Center / Freq	59	13.1	47	20.58 (3.72)
	2 – Applied / Center / Infreq	48	10.6		18.63 (3.58)
	4 – Applied / Govt / Infreq	54	12.0		19.65 (3.96)
	5 – Applied / Indus / Freq	47	10.4		22.07 (3.06)
Group 17: Material Group (Equipment Type / Work Space	1 – Model / Isolated	43	9.5	40	16.62 (4.48)
	2 – Model / Shared	113	25.1		18.94 (3.98)
	3 – Physical / Isolated	40	8.9		19.54 (4.04)
	4 – Physical / Shared	218	48.3		20.74 (3.33)

Table E.18: *Group Mean Comparison – Demographic Groups – Kruskal-Wallis H Tests*

Comparison Groups	Values	Group Size	Overall score *M* (SD)	χ^2	*df*	*p*	Mean Rank (*)	*p (**)*
Group 1: Internship or co-op	Yes	73	21.37 (3.53)	16.570	2	< .001	134.2	N/A: Yes, *p* < .001
	No		19.41 (4.39)				101.2	
	N/A		18.76 (3.81)				94.0	No: Yes, *p* = .006
Group 3: Participation in professional engineering societies	Never	58	16.83 (3.79)	45.260	4	< .001	90.3	Never: Occasion, *p* < .001
	Very Rarely		18.48 (3.92)				126.7	Never: Rarely *p* < .001
	Rarely		20.70 (2.94)				174.8	
	Occasion		19.72 (3.92)				157.2	Never: Frequently, *p* < .001
	Freq		21.00 (3.97)				178.5	Very Rarely: Rarely, *p* = .020 Very Rarely: Freq, *p* = .009

(*) Pairwise Dunn's with Bonferroni correction (**) Pairwise significance; If not listed, pairwise not significant.

Table E.19: *Group Mean Comparison – Demographic Groups – Mann-Whitney U Test*

Comparison Groups	Values	Group Size	Overall score *M* (SD)	*U*	*z*	*p*	Mean Rank
Group 2: Source of funding	Govt	54	19.47 (3.85)	1,960.0	3.085	.002	45.2
	Industry		21.41 (3.53)				63.8

Table E.20: *Group Mean Comparison – Ethnicity Groups – Mann-Whitney U Tests*

Comparison Groups	Values	Group Size	Overall score *M* (SD)	*U*	*z*	*p*	Mean Rank
Group 4: Ethnic groups	White	159	19.21 (3.99)	14,282.0	2.002	.045	149.2
	Asian		20.21 (3.94)				169.8
Group 5: URM	Non-URM	51	19.55 (3.96)	1003.5	-1.988	.047	57.3
	All URM		18.06 (4.50)				45.7

Table E.21: *Group Mean Comparison – Discipline Groups – Kruskal-Wallis H Test*

Comparison Groups	Values	Group Size	Overall score *M* (SD)	χ^2	*df*	*p*
Group 6: Major (i.e. Discipline)	Chemical	50	20.10 (3.35)	2.856	2	.240
	Electrical & Comp		19.93 (3.94)			
	ME		18.98 (4.41)			

Table E.22: *Group Mean Comparison – Self-Report Groups – Mann-Whitney U Tests*

Comparison Groups	Values	Group Size	Overall score *M* (SD)	*U*	*z*	*p*	Mean Rank
Group 7: Size of research group	Med	151	19.74 (3.94)	13,452.5	-2.705	.007	165.1
	Small		18.63 (4.25)				137. 9
Group 8: Research group organization	Advisor dominant	165	19.05 (3.97)	14,847.0	1.425	.154	158.0
	Group focused		19.72 (4.16)				173. 0
Group 9: Research work organization	Individual	99	18.93 (4.03)	6,259.0	3.370	.001	85.8
	Team		20.76 (3.79)				113. 2
Group 10: Research work type	Basic	123	18.15 (4.18)	9,237.5	2.998	.003	109.9
	Applied		19.86 (3.96)				137. 1
Group 12: Collaborator Interactions	Infrequent	196	18.74 (3.81)	24,590.5	4.799	< .001	169.0
	Frequent		20.70 (3.73)				224. 0
Group 13: Equipment Type	Mod/Sim Only	160	18.23 (4.25)	16,976.0	5.047	< .001	134.4
	Some facil/test		20.53 (3.45)				186. 6
Group 14: Work Space	Isolated	90	17.80 (4.48)	5,274.5	3.503	< .001	76.9
	Shared		19.85 (3.81)				104.1

Table E.23: *Group Mean Comparison – Self-Report Groups – Kruskal-Wallis H Test*

Comparison Groups	Values	Group Size	Overall score *M* (SD)	χ^2	*df*	*p*	Mean Rank (*)	*p (**)*
Group 11: Collaborator Type	Govt	98	19.87 (3.65)	10.068	2	.007	150.4	Center: Industry, $p = .005$
	Industry		20.72 (3.64)				165.2	
	Univ. Center		18.93 (3.95)				126.9	

(*) Pairwise Dunn's with Bonferroni correction (**) Pairwise significance; If not listed, pairwise not significant.

Table E.24: *Group Mean Comparison – Social, Cultural, Material Groups – Kruskal-Wallis H Tests*

Comparison Groups	Values	Group Size	Overall score *M* (SD)	χ^2	*df*	*p*	Mean Rank (*)	*p (**)*
Group 15: Social Group (Group Size / Group Org / Work Org)	4 – Med / Adv dom / Indiv	42	18.93 (3.74)	8.351	3	.039	81.1	Group 7: Group 8, $p = .029$
	6 – Med / Gr foc / Indiv		19.80 (4.31)				87.8	
	7 – Med / Gr foc / Team		20.60 (3.79)				99.5	
	8 – Sm / Adv dom / Indiv		18.04 (4.13)				69.6	
Group 16: Cultural Group (Work Type / Collaborator / Interaction)	1 – App / Center / Freq	47	20.58 (3.72)	22.818	3	< .001	98.5	Group 2: Group 1, $p = .013$ Group 2: Group 5, $p < .001$ Group 4: Group 5, $p = .008$
	2 – App / Center / Infreq		18.63 (3.58)				70.7	
	4 – App / Govt / Infreq		19.65 (3.96)				86.4	
	5 – App / Indus / Freq		22.07 (3.06)				122.5	
Group 17: Material Group (Equipment Type / Work Space	1 – Model / Isolated	40	16.62 (4.48)	18.372	3	< .001	56.7	Group 1: Group 3, $p = .013$ Group 1: Group 4, $p < .001$
	2 – Model / Shared		18.94 (3.98)				77.7	
	3 – Physical / Isolated		19.54 (4.04)				88.5	
	4 – Physical / Shared		20.74 (3.33)				98.2	

(*) Pairwise Dunn's with Bonferroni correction (**) Pairwise significance; If not listed, pairwise not significant.

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