Final-text- JEE-0116-text

Running heads

recto: Supporting Engineers' Interdisciplinary Competence

verso: Lattuca, Knight, Ro, & Novoselich

files:

text

tables

figures

caption

&&&&&&&&&&&&&&&&&&&&&&&&&

Supporting the Development of Engineers' Interdisciplinary Competence

Lisa R. Lattuca[a], David B. Knight[b], Hyun Kyoung Ro[c],
and Brian J. Novoselich[d]

[a]University of Michigan, [b]Virginia Tech, [c]Bowling Green State University,
[d]United States Military Academy

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version record. Please cite this article as doi:10.1002/jee.20155.

(1)Abstract

Background Although interdisciplinarity has been a subject of interest and debate for decades, few investigations of interdisciplinary education exist. Existing studies examine the effects of interdisciplinary experiences on students' development of generic cognitive skills but not the development of interdisciplinary competencies.

Purpose/Hypothesis This study sought to explore how engineering students' characteristics, college experiences, and engineering faculty beliefs relate to students' reports of interdisciplinary competence.

Design/Method The study used a nationally representative survey sample of 5,018 undergraduate students and 1,119 faculty members in 120 U.S. engineering programs at 31 institutions. Using hierarchical linear modeling, we investigated the relationships among students' curricular and co-curricular experiences and faculty beliefs regarding interdisciplinarity in engineering education on students' reports of interdisciplinary competence.

Results This study found that a curricular emphasis on interdisciplinary topics and skills, as well as co-curricular activities, specifically, participating in in nonengineering clubs and organizations, study abroad, and humanitarian engineering projects, significantly and positively relate to engineering students' reports of interdisciplinary skills. Faculty members' beliefs regarding interdisciplinarity in engineering education moderated the relationships between particular co-curricular experiences and students' interdisciplinary skills, as well as between curricular emphasis and students' interdisciplinary skills.

Conclusions This study identified a small set of experiences that are related to students' reported development of interdisciplinary competence. The study points to the critical role of the curriculum in promoting interdisciplinary thinking and habits of mind, as well as the potential of co-curricular opportunities that bring engineering students together nonmajors to build interdisciplinary competence.

Keywords: Interdisciplinary, curriculum, extracurricular, faculty attitudes

(1) Introduction

It has become commonplace to note that the increasing complexity of the concerns and problems of modern-day society require innovative solutions that draw from multiple perspectives, have broad appeal, and enhance opportunities for success (Association of American Colleges and Universities [AAC&U], 2011; Klein, 2010). The scientific community, in particular, increasingly views interdisciplinary problem solving as necessary for solving society's most pressing problems (National Academy of Engineering [NAE], 2004; National Academy of Sciences [NAS], 2004; National Institutes of Health, 2006; National Research Council, [NRC] 2012). Interdisciplinary problem solving is viewed as a means of fostering innovation (e.g., NAE, 2004; U.S. Department of Education, 2006) and of supporting graduates' successful integration into a workforce marked by multidimensional and messy problems (NRC, 2012). Consequently, colleges and universities have been called to help students develop the capacity to engage in interdisciplinary thinking, collaboration, and problem solving.

In engineering, the emphasis on multidisciplinary teamwork in accreditation criteria has contributed to the interest in multi- and interdisciplinary learning and competencies. In a study of engineering department chairs' awareness of engineering education reforms and innovations, Borrego, Froyd, and Hall (2010) observed that the high level of awareness of interdisciplinary capstone design projects was "an obvious response to ABET EC2000 criteria" (p. 197). Richter and Paretti (2009) demonstrated the burgeoning interest in interdisciplinary learning experiences through a review of engineering journals and conference proceedings that identified more than 1,500 articles on interdisciplinary courses and projects published in an eight-year period. During this same period, two reports on engineering education – *The Engineer of 2020*, sponsored by the National Academy of Engineering (2004), and *Creating a Culture for Scholarly and Systematic Innovation in Engineering Education* (Jamieson & Lohmann, 2009), sponsored by the American Society for Engineering Education – placed the responsibility for promoting the development of future engineers' interdisciplinary habits of mind squarely on engineering faculty.

The *Engineer of 2020*, in particular, acknowledged the increasingly interdisciplinary nature of engineering practice and called for greater attention in preparing engineers to work in cross-disciplinary teams and settings. To be successful in the global, diverse, and technologically fluid workplace of the near-future, the authors of the report argued, engineers would need the strong analytical skills fundamental to engineering practice, but also a number of other attributes, such as creativity; skills in communication, management, and leadership; high ethical standards and professionalism; agility, resilience, and flexibility; and an understanding of the complex societal, global, and professional contexts in which engineering is practiced. A new kind of engineering education would be required to develop this diverse set of interdisciplinary knowledge and skills.

In this study, we investigated how undergraduate engineering students' interdisciplinary skills relate to an array of curricular and co-curricular experiences, and to the characteristics and beliefs of faculty in their programs since all could affect the development of interdisciplinary competence. Using multilevel modeling and a multi-institution sample of engineering faculty and students from seven engineering disciplines, our study contributes to our understanding of teaching and learning experiences that promote students' interdisciplinary competence.

(1)Interdisciplinary Learning

Many terms, definitions, and interpretations confound the understanding and study of interdisciplinary education, learning, and learning outcomes. Scholars appear to be converging on definitions of interdisciplinarity as both a process and outcome. This agreement has led to the conception of interdisciplinarity as a process that requires synthesis of various disciplinary knowledges and methods to provide a more holistic understanding of a given problem (e.g., Baillie, Ko, Newstetter, & Radcliffe, 2011; Collin, 2009; Klein, 1996; Kockelmans, 1979; Miller, 1982; O'Donnell & Derry, 2005; Richards, 1996). In this usage of the term, interdisciplinarity is understood, as Klein and Newell (1997) describe, to be "a process of answering a question, solving a problem, or addressing a topic that is too broad or complex to be dealt with adequately by a single discipline or profession" (pp. 393–394). In science and engineering, Borrego and Newswander (2010) showed that faculty members tend to view interdisciplinary research as a team-based process and tend to structure students' learning experiences accordingly.

The term *interdisciplinarity* is also commonly used to describe the outcome of a research or educational process that synthesizes knowledge or methods from several disciplines (e.g., Jacobs, 2014; Klein, 1996; Lattuca, 2001). Surprisingly, while the definition and pursuit of interdisciplinarity have been subjects of interest and debate for decades, Brint, Turk-Bicakci, Proctor, and Murphy (2009) and Jacobs (2014) note that few investigations of interdisciplinary education exist. Several early, single-institution studies reported differences in cognitive outcomes between students enrolled in interdisciplinary and noninterdisciplinary programs (e.g., Newell, 1992) or those enrolled in different kinds of interdisciplinary programs (e.g., Schilling, 1991; Wright, 1992). These early studies examined the effect of interdisciplinary experiences on students' development of generic cognitive skills, such as critical thinking, problem solving, and creativity, rather than the development of more specific learning outcomes.

One challenge associated with assessing interdisciplinary learning outcomes in educational contexts is whether to consider it an ability, skill, or competence that one develops, or a characteristic of a particular insight, problem solution, or design. Some researchers have sought to assess the interdisciplinary thinking associated with a particular student work product (e.g., Coso, Bailey, & Minzenmayer, 2010); others have focused on identifying the conditions that affect students' interdisciplinary learning overall, stressing, the development of lasting thinking skills or abilities. In one of the few large-scale studies of interdisciplinary competence, we took the latter approach (see Lattuca, Knight, & Bergom, 2013). We developed a self-report measure of students' interdisciplinary competence to measure students' thinking skills with regard to interdisciplinary work (such as the ability to integrate and synthesize disciplinary insights) as well as the value they placed on interdisciplinary work and their beliefs about the nature of engineering problems. We used the term *competence* to capture the multidimensionality of this concept, and assume that beliefs about the usefulness of interdisciplinary approaches are necessary if not sufficient for the task of interdisciplinary problem solving.

Another question raised by this review of the literature is the relationship between self-reported abilities or skills and actual behaviors. For our purposes, research on social cognitive career theory is helpful in that it suggests that self-beliefs (for example, my belief that I can do a particular thing) serve as precursors to outcome expectations, interests, and goals (Lent et al., 2008) and actual behaviors (Lent, Brown, & Hackett, 1994).

In recent years, engineering education researchers have expanded the study of interdisciplinary educational conditions and outcomes by studying the design of interdisciplinary courses (e.g., Borrego, Newswander, McNair, McGinnis, & Paretti, 2009) and programs at the undergraduate and graduate levels (e.g., Drezek, Olson, & Borrego, 2008; Newswander & Borrego, 2009). Researchers have also focused on interdisciplinary problem solving or thinking as a learning outcome (e.g., Coso et al., 2010). These investigations advanced the literature on interdisciplinary education in several ways. First, they remedied a limitation of early studies of interdisciplinary learning outcomes that treated the educational experience as a black box with unknown characteristics by describing, to varying degrees, the educational processes intended to promote interdisciplinary thinking (e.g., Pierrakos, Borrego, & Lo, 2007; Coso et al., 2010). Second, studies of interdisciplinarity in engineering education settings identified theoretical or empirical linkages between those educational experiences and interdisciplinary thinking as an educational outcome (e.g., Newswander & Borrego, 2009; Coso et al., 2010). Finally, several studies expanded the focus on the educational process by suggesting that the beliefs and attitudes of engineering faculty are critical to the quality of interdisciplinary learning processes and outcomes (Boden, Borrego, & Newswander, 2011; Newswander & Borrego, 2009).

These studies, though, have some limitations. Notably, they examine learning experiences of limited duration and with small groups of students. For example, several studies examined students' experiences in interdisciplinary teams (e.g., Pierrakos et al., 2007; Schaffer, Chen, Zhu, & Oakes, 2012), in single courses (McNair, Newswander, Boden, & Borrego, 2011; Richter & Paretti, 2009), or in the context of an assigned performance task (Coso et al., 2010). Scholars have yet to examine how the overall engineering education experience may affect the development of interdisciplinary competencies in a broad cross section of engineering students. There is also limited evidence of how faculty beliefs about interdisciplinarity might affect interdisciplinary competence in students in a given engineering program.

This study sought to complement the research on interdisciplinary educational experiences and outcomes in undergraduate engineering programs through an analysis of data from a large-scale, multisite study. This analysis provides information on the relative importance of curricular and co-curricular experiences and faculty beliefs about the role of interdisciplinarity in engineering education to the development of students' interdisciplinary skills, which we define as the willingness and ability to think about and use different disciplinary perspectives in solving engineering problems or to make connections across academic fields.

(1)Conceptual Framework

In reviews of several decades of research on students, Pascarella and Terenzini (1991, 2005) demonstrated that students' development of content knowledge and higher-order thinking skills (as well as other outcomes, such as persistence) are affected by their undergraduate experiences. Terenzini and Reason (2005, 2010) synthesized the insights from this literature in a "college impacts" framework that seeks to explain student outcomes such as persistence and learning. This conceptual framework, which we adapted for the Prototype-to-Production project (described below) , which provided the data for this analysis (Figure 1), hypothesized that students' precollege characteristics shape their engagement with various aspects of their college or university. That engagement is comprised of curricular, classroom, and co-curricular experiences. These experiences occur within an institutional context with particular characteristics – leadership; organizational and curricular structures, practices, and policies; and faculty cultures – as well as peer environments. Because Terenzini and Reason's college impacts framework synthesizes research from hundreds of studies of the college experience, it is not based on a single theory, but its basic assumptions are consistent with those of a situative perspective on learning in which all learning is understood to be situated in formal and informal social contexts that shape the construction of students' knowledge, skills, beliefs, and attitudes (Greeno, Collins, & Resnick, 1996; Johri, Olds, & O'Connor, 2014). The social practices, as well as the material and technological conditions, that characterize these educational contexts are further assumed to have certain affordances that can facilitate particular kinds of learning (such as interdisciplinary thinking), as well as constraints that can hinder that same learning.

Insert Figure 1 About Here

In this study, we focused on those components of our conceptual framework that prior research and theory suggest are important to the development of interdisciplinary competence. These components include the student experience component (which includes the curriculum, classroom, and co-curriculum) and the faculty culture dimension of the organizational context component (Figure 1). Specifically, our study assumes that curricular and co-curricular experiences that require students to think across and beyond engineering disciplines, to apply knowledge from disciplines other than their own, and to engage with other engineering students and nonmajors may influence their desire and ability to think and act in interdisciplinary ways. Our study further assumed that faculty members' beliefs shape the student experience inside and outside the classroom. In their conceptual model, Terenzini and Reason included faculty culture as a dimension of the organizational context and defined it as the dominant philosophies of education to which most faculty members subscribe and their perceptions of their roles. This view of culture is consistent with that of Berger and Milem (2000), who defined culture as "enduring patterns of behavior, perceptions, assumptions, beliefs, attitudes, ideologies, and values . . . that are held and maintained by members" of an organization (p. 274). In this study, we assumed that faculty members' beliefs about interdisciplinarity influence the extent to which they emphasize interdisciplinary topics and problems in their courses. The collective views of faculty in an academic program can thus create a culture that supports – or does not support – interdisciplinary approaches to engineering problems. This faculty culture may indirectly influence student learning by shaping the student experience in an academic program.

Finally, we accounted for the potential influence of students' precollege characteristics in order to isolate the effects of the undergraduate experience on interdisciplinary competence as a learning outcome. We had two research questions:

> How do engineering students' precollege characteristics and college experiences relate to their interdisciplinary competence?
>
> How do engineering faculty members' views on interdisciplinarity relate to the link between students' college experiences and interdisciplinary competence?

By including a broad array of potential influences on engineering students in our analysis, we hope to contribute to a comprehensive understanding of how engineering programs and student experiences in those programs may affect the development of interdisciplinary competence.

(1)Data and Methods

(2)Data Collection

Data were collected for the Prototype-to-Production: Process and Conditions for Preparing the Engineer of 2020 (P2P) project funded by the National Science Foundation (NSF EEC-0550608). The study was designed to benchmark the current state of undergraduate engineering, specifically, its readiness and ability to produce three critical engineering learning outcomes: design and problem solving, interdisciplinary competence, and contextual competence. Table 1 lists the 31 four-year colleges and universities that participated in the study. ASEE's Engineering Data Management system served as the study's sampling framework. Using institution- and program-level information for the 2007–08 academic year for enrolled students and faculty, we identified 288 eligible institutions (those that offered two or more ABET-accredited programs in the six engineering disciplines targeted for the study). The survey research center at Penn State conducted the sampling, which was disproportionate, random, and 6 × 3 × 2 stratified with the following strata for 23 institutions: six engineering disciplines (bioengineering and biomedical, chemical, civil, electrical, industrial, and mechanical), three levels of highest degree offered (bachelor's, master's, doctorate), and two levels of institutional control (public and private). Institutions that declined to participate were replaced through further random selection. We purposefully included in the sample five case study institutions from a companion qualitative study, Prototyping the Engineer of 2020: A 360-degree Study of Effective Education (NSF DUE-0618712). Because one of these institutions offers only a general engineering degree, three institutions that offer general engineering degrees were included in the sample to serve as comparisons. Together, these seven disciplines (i.e., six from the sampling frame plus general engineering) accounted for 70% of all baccalaureate engineering degrees awarded in 2008.

Insert Table 1 about here

The student population for the study was defined as all sophomore, junior, and senior students in one of the targeted engineering disciplines. Students' home institutions provided the contact lists for these class years, and students self-identified into a class year on the survey. We did not include first-year students in the sample because some engineering schools do not allow students to declare a major in a specific engineering discipline until their sophomore year. Participating institutions provided contact lists of all undergraduate students (sophomore and above) in the targeted fields. The contact lists included information on each student's gender, race/ethnicity, class year, and engineering major. Students first received a heads-up email from the dean of their engineering school explaining the importance of the study and encouraging their participation. The survey research center next sent a personal email invitation with a unique link to the web-based survey to each student. Nonrespondents to this email received up to two email follow-ups. Institutions also provided faculty contact lists with information on gender, race/ethnicity, rank, and department affiliation. Faculty similarly received a heads-up email from their dean that encouraged their participation and noted the endorsement of the study by the engineering professional societies representing the disciplines targeted for the study (American Institute of Chemical Engineers, American Society of Civil Engineers, IEEE, Institute of Industrial Engineers, and American Society of Mechanical Engineers) as well as the Dean's Council of the American Society for Engineering Education. In return for their participation, institutions received an institutional dataset of student, alumni, faculty, and administrator responses (de-identified) for local analyses, and a report providing comparative information (by institutional type) for their institution. (Only student and faculty responses are included in this analysis.)

Chi-square goodness-of-fit tests indicated that respondents were marginally unrepresentative of the overall population of engineering students (population-sample differences ranged from one to 11 percentage points). Consequently, individual weights were created to adjust for any campus-specific response biases based on student respondents' gender, race/ethnicity, class year, and engineering discipline. We also weighted responses to account for differing response rates across institutions. An overall weight was calculated by multiplying the gender by race/ethnicity by class year, by discipline, and by institutional response weight and applied to all student respondents. We adjusted the data so that the samples were representative of the populations of engineering students and faculty members at the 31 institutions that participated in the study. The student sample is representative by gender, race/ethnicity, discipline, institutional response rate, and class year and the faculty sample is representative by gender, race/ethnicity, discipline, academic rank, and institutional response rate.

Missing data were imputed using the expectation-maximization (EM) algorithm of the Statistical Package for the Social Sciences (SPSS) software (v.18). This procedure is recommended by Dempster, Laird, and Rubin (1977) and by Graham (2009). Although EM algorithms are perhaps the most commonly used in the educational literature (Cox, McIntosh, Reason, & Terenzini, 2014), EM yields standard errors that are artificially small, threatening the validity of subsequent hypothesis testing (Graham, 2009; von Hippel, 2004). Thus, we acknowledge the increased likelihood of Type I errors.

The survey research center collected data through a web-based questionnaire. Out of a population of 32,737, we received 5,249 (16%) student responses, which is a response rate on par with other national-scale, web-based surveys. Out of the 2,942 surveys sent to faculty members, we received usable responses from 1,119 for a response rate of 38%. Survey response rates have been in decline for several decades (Baruch, 1999; Dey, 1997; Smith, 1995), and web-based surveys often have relatively low response rates (Porter & Umbach, 2006; Van Horn, Green, & Martinussen, 2009). Still, the low student survey response rate, despite corrective weighting, may pose threats to the external validity of the study's findings. Descriptive statistics of the weighted student and faculty samples are given in Table 2. (The characteristics of the student and faculty populations, survey respondents, and their institutions are included in Appendixes B and C.)

Insert Table 2 about here

(2)Measures

Instrument development Our team of researchers from education and engineering collaborated on instrument development, beginning with an extensive literature review on topics (such as interdisciplinarity) related to key learning outcomes identified by the National Academy of Engineering's (2004) *Engineer of 2020* report. In addition to providing conceptual guidance for survey development, findings from this literature review generated a bank of potential survey items related to engineering students' college experiences and learning outcomes. In cases where available scales had acceptable psychometric properties, items were adopted or minimally revised. We also conducted interviews and focus groups with engineering administrators, faculty members, students, and alumni at Penn State's University Park and Altoona campuses and City University of New York to develop new survey items and to ensure appropriate coverage of key topics. We also asked engineering faculty and administrators to review and evaluate drafts of these potential survey items to refine the surveys. The student survey instrument was pilot tested with 482 students at the Penn State University Park and Altoona campuses for newly developed items. We used factor analysis techniques to explore these pilot results and further revised survey items on the basis of these findings. We again met with focus groups of engineering faculty members and administrators from Penn State to review the revised student survey and assess its construct validity (i.e., whether the items represent their intended purpose; Shadish, Cook, & Campbell, 2002) before administering the final version (i.e., Educating the Engineer of 2020 Student Survey). To provide a more compact, aggregated summary of the individual items, we used factor analysis and selected the principal axis factoring method (oblimin with Kaiser normalization rotation). This statistical procedure determined the degree of correlation between items, and highly correlated items were combined to form scales. Items were assigned to scales based on the magnitude of loading from the principal axis analysis method, the effect of keeping or discarding the item on the scale's internal consistency reliability, and professional judgment. We computed scales by summing respondents' scores on component items and dividing the sum by the number of items in the scale, as recommended by Armor (1974).

Figure 2 diagrams the operationalization of the conceptual framework used for this analysis. The following sections describe each variable in greater detail as well as the analytical procedures to investigate relationships between the variables representing the engineering program context and student experiences and the dependent variable of students' interdisciplinary skills.

Insert Figure 2 about here

Dependent variable The dependent variable for this study was measured by the Interdisciplinary Skills scale that emerged following the factor analysis procedures (see Analytical Method section). We reported on the development of these items and documented the scale's validity and reliability in Lattuca, Knight, and Bergom (2013). The Interdisciplinary Skills scale has eight items (Table 3), which operationalize the conception of engineering interdisciplinary competence as combining students' perceived understanding of existing disciplines with their assessments of their ability to work across disciplines both within and outside the field of engineering. The reliability coefficient (Cronbach's alpha) of .80 is well above the conventional .70 threshhold (George & Mallery, 2003).

Insert Table 3 about here

Student-level (independent) variables Table 4 lists the variables from the student survey that were used in our analyses (see Appendix A). Students' personal characteristics (e.g., class year gender, race/ethnicity) and precollege academic abilities (e.g., composite Scholastic Assessment Test [SAT] scores), all self-reported, are control variables in this study. Other independent variables were students' reports of the kinds of knowledge and skills emphasized in their engineering program (as measured by the four curricular emphasis scales), the instructional strategies they reported experiencing in their engineering program (two scales assessing frequency of instructional strategies), and their reported participation in co-curricular activities both related to engineering and outside the field (10 single items assessing students' level of participation). The instructional strategies scales were adapted from the Classroom Activities and Outcomes Survey (Cabrera, Colbeck, & Terenzini, 2001; Terenzini, Cabrera, Colbeck, Parente, & Bjorklund, 2001).

Four curricular experiences scales measure students' perceptions of the emphasis placed on particular engineering knowledge and skills in their courses. Scales reflect engineering students' reports on the extent to which their engineering courses emphasized core engineering thinking (five-item scale; Cronbach's alpha =. 85), professional values (four-item scale; alpha = .82) professional skills (five-item scale; alpha = .88), and broad and systems perspectives (five-item scale; alpha=.84). Instructional approaches contain students' reports of the extent to which they experienced different instructional techniques throughout their engineering programs. Two scales include student reports of student-centered teaching (five-item scale; alpha = .81) and group learning (four-item scale, alpha = .77). Co-curricular student experiences consist of 10 single-item measures: how many months students participated in undergraduate research, engineering internship, and co-operative education experiences; how many weeks students participated in study abroad, humanitarian engineering projects, nonengineering community service, and student design projects; and the extent to which they actively participated in engineering clubs or student chapters of a professional society (e.g., IEEE, ASME, ASCE), engineering-related clubs or programs for women or minority students (e.g., National Society of Black Engineers, Society of Hispanic Professional Engineers, Society of Women Engineers), and nonengineering clubs or activities (e.g., hobbies, civic or church organizations, campus publications, student government, Greek life, sports) during their undergraduate experience.

Program-level (independent) variables To assess the relationship between program characteristics and students' interdisciplinary skills, we entered the averages for each of the student-level variables at the program level (e.g., electrical engineering at University X). We also included variables at the program level that might explain variation in students' interdisciplinary skills, such as their engineering discipline. We created a variable with the following categories of students' disciplinary majors: electrical engineering (reference group), bioengineering and biomedical engineering, chemical engineering, civil engineering, general engineering, industrial engineering, and mechanical engineering. Exploring more specific differences by disciplines is beyond the scope of our analysis.

Insert Table 4 about here

The next step in our analyses drew on data from the faculty survey to determine how faculty beliefs relate to the relationship between student experiences and their interdisciplinary competence. Our analyses included five questions assessing faculty members' beliefs about interdisciplinarity. Two of these questions focus on faculty members' beliefs about the place of interdisciplinarity and sustainability in undergraduate education; an additional three questions tap faculty members' beliefs about their responsibilities as teachers to help students integrate their learning and understand multiple and diverse perspectives. We also included a single-item measure of prior experiences in industry on the assumption that workplace experiences in teams or real-world problem solving might shape attitudes toward interdisciplinarity. These six variables (Table 5) seek to operationalize the faculty culture component of the conceptual framework and were aggregated at the program level as well. Although the faculty survey collected many additional variables about faculty backgrounds, experiences, and attitudes, our previous research identified the six specific variables discussed above as significantly relating to faculty members' reports of the emphasis on interdisciplinarity in their courses (Lattuca, Knight, & Brown, 2014).

Insert Table 5 about here

(2)Analytical Method

We used hierarchical linear modeling (HLM; Raudenbush & Bryk, 2002) to relate the suite of independent variables that operationalize components of the conceptual framework to the interdisciplinary skills outcome. HLM allowed us to partition variance in the outcome variable between an individual student level (n = 3,808) and a program level (n = 106; e.g., electrical engineering at University X). Setting group level to be the program allowed for a finer-grained analysis that allowed for entering engineering discipline at the group level; the small sample size of programs within each institution precluded a three-level model. Our focus on program-level differences is also supported by prior research; Ro, Terenzini, and Yin (2013) found that an institution's organizational features (e.g., programs, internal policies, and faculty culture) have more influence on students' learning-related experiences than do the structural characteristics of the institution (e.g., institutional type, size, wealth, or selectivity).

We used HLM because students are nested within programs, and students in one program would have had access to a different set of faculty members and opportunities from students in another program. HLM allows parameters to vary by case grouping (i.e., the program) and thus accounts for the nested nature of the data.

The first step of the HLM process was to run an unconditional model, which partitioned the variance of the interdisciplinary skills variables into student-level and program-level components. Next, we produced preliminary block regression models to examine the unique contribution of each block of independent variables (i.e., the variable groupings shown in Table 4) in explaining the variance in the Interdisciplinary Skills scale at both individual and program level. The variance-explained statistic was calculated following Snijders and Bosker (1994) as recommended by Luo and Azen (2012). The change in variance as new variables were added at the student level indicates the amount of additional variance in students' interdisciplinary skills that was explained by the addition of those variables; the change in variance at the program level indicated the additional variance in the program means of the Interdisciplinary Skills scale. We present the results of the final individual and program-level models that incorporated all independent variable blocks into a composite model in this article.

Finally, we explored the extent to which faculty beliefs about interdisciplinarity (aggregated at the program level) influenced the relationship between the statistically significant student-level variables and the Interdisciplinary Skills scale. This multilevel analytical approach examines if and how these faculty beliefs indirectly moderate students' interdisciplinary skills by enhancing or inhibiting the relationship of different student experiences with this learning outcome.

(2)Limitations

The first limitation of this study is that all measures used are respondents' self-reports. Higher education researchers and administrators have frequently used self-reported gains as indicators of student learning or ability, but the literature disagrees on their accuracy. Bowman (2010) reported that some researchers found a strong correlation between subjective and objective assessments, while others reported a strong divergence (see examples cited in Bowman, 2010). Although direct measures of learning, such as standardized objective tests, might be preferable, there is no standardized test of students' interdisciplinary skills. Until such assessments are available, self-reports of this ability, such as the Interdisciplinary Skills scale, provide a reasonable proxy, albeit one that should be interpreted with care. Interpretation should also consider how study conditions support the validity of self-reports. These supporting conditions include the information requested is known to the respondents; the questions are phrased clearly and unambiguously; the questions refer to recent activities; the respondents think the questions merit a serious and thoughtful response; and answering the questions does not threaten, embarrass, or violate the privacy of the respondent or encourage the respondent to answer in socially desirable rather than in truthful ways (Hayek, Carini, O'Day, & Kuh, 2001; Kuh, 2005).

Second, many features of the learning environments investigated in this study remain unknown. We assumed that students' interdisciplinary skills result, at least in part, from their engagement in the college or university environment. In this study, we focused on high-level measures of the curriculum, instructional strategies, and students' co-curricular participation. More fine-grained details of each of these, as well as other environmental factors (such as program size, available resources, and students' interactions with peers and faculty) also shape students' experiences and their learning. We were limited in the extent of the educational environment that could be captured by our survey and our analytical method. Our operationalization of faculty culture was also limited by the survey questions we asked; there may be elements of faculty culture that we did not examine that promote faculty support of interdisciplinary curriculum and teaching. Further, our survey questions about faculty beliefs also did not distinguish between technical and nontechnical interdisciplinary experiences and learning; these experiences may be viewed differently by faculty.

Third, the findings are generalizable only to students in the engineering disciplines studied. Although these combined fields award more than 70% of all undergraduate engineering degrees annually, students in other engineering disciplines may or may not have experiences similar to those reported by respondents in this study.

(1)Results

The unconditional model partitioned the variance of the interdisciplinary skills dependent variable into student-level components. Nine percent of the variance in interdisciplinary skills was accounted for by the program level, and the remaining 91% of the variance was accounted for by the student level. With an intraclass correlation greater than 5%, we proceeded in our analyses using a multilevel modeling approach (Porter, 2005). As described in the Analytical Methods section, modeling procedures resulted in student- and program-level models that incorporated all independent variable blocks into an overarching composite model (results presented in Table 6).

Insert Table 6 about here

Addressing our first research question, regarding what precollege characteristics and college experiences relate to self-reported interdisciplinary skills, we found that although none of the demographic variables related significantly to interdisciplinary skills, the SAT composite score maintained a strong, positive relationship with this learning outcome even with the inclusion of all independent variables. Three co-curricular experiences also positively and significantly related to interdisciplinary skills: participation in nonengineering clubs and activities, study abroad opportunities, and humanitarian engineering projects. With other variables taken into consideration, the instructional strategies scales did not significantly relate to the interdisciplinary skills measure. In contrast, the scale assessing curricular emphasis on broad and systems perspectives strongly and positively related to interdisciplinary skills, net of the influence of all other variables. With a standardized coefficient of 0.22, this variable exhibited the strongest relationship with interdisciplinary skills out of all variables included in the model. No program-level variable was significant in this model.

To address our second research question, regarding how engineering faculty members' beliefs about interdisciplinarity relate to the link between students' college experiences and interdisciplinary competence, we next investigated how faculty beliefs and prior industry experience moderated the relationship between students' experiences and outcomes. The goal of this analysis was to explore how a program's faculty culture enhances or declines the degree of the relationship between students' experiences and interdisciplinary skills. In this analysis, we investigated only the significant variables of the model results shown in Table 7.

Faculty members' beliefs and years of industry experience (aggregated at the program level) did not moderate the positive relationship between SAT scores and interdisciplinary skills (Table 7). Because SAT scores are generated before students arrive to campus and interact with faculty members, this finding was expected. Two of the five faculty belief variables, however, acted as moderators in our analyses. First, the relationship between students' participation in humanitarian engineering projects and their reports of interdisciplinary skills was stronger when their program faculty believed they had a responsibility as teachers to help students understand of the value of diversity (Figure 3). Second, the relationship between students' perceptions of the extent to which their programs emphasized broad and systems perspectives and their reports of interdisciplinary skills was stronger when faculty in the program thought it was important to emphasize interdisciplinary learning in the curriculum (Figure 4). Other program-level faculty beliefs and average years of industry experience of a program's faculty did not alter the relationship between the significant student experiences (identified in Table 6) and student reports of interdisciplinary skills.

Insert Table 7 about here

Insert Figure 3 about here

Insert Figure 4 about here

(1)Discussion

Previous research on the development of student interdisciplinary competence is primarily based on studies of single courses or programs, and has only recently focused on overtly interdisciplinary skills (rather than more general cognitive outcomes such as critical thinking). We sought to contribute to the scholarship on interdisciplinary competence in undergraduate engineering by defining a set of interdisciplinary engineering skills and identifying potential influences on students' development of those skills across multiple programs and institutions. This approach provided a more comprehensive understanding of what might shape interdisciplinary skills in undergraduate engineering by examining the potential influences of curricular and co-curricular experiences, as well as elements of faculty culture, that contribute to undergraduate engineers' interdisciplinary skill development.

Precollege characteristics, college experiences, and interdisciplinary skills A multilevel analysis of our student data revealed that only one of the student precollege characteristics included in our study significantly related to students' self-reported interdisciplinary skills. Students with higher SAT composite scores reported higher levels of interdisciplinary skills. In addition, only three of the 10 co-curricular experiences positively and significantly related to interdisciplinary skills: participation in nonengineering clubs and activities, study abroad, and humanitarian engineering projects. Each of these experiences engages engineering majors in activities with students from other academic fields and across their college or university or in work conducted in unique or diverse contexts. Humanitarian engineering projects may also require substantive interactions with communities outside the university that are being served through the engineering projects. The identification of co-curricular experiences is an important contribution because previous studies in engineering have focused on course-based or -related academic interventions. This finding may further suggest that experiences and ideas that are very unfamiliar or different may be most likely to stimulate students' reflection on, and appreciation of, the need for interdisciplinary approaches to engineering problems and help them build interdisciplinary skills.

Because our analysis is not causal, we cannot say that engagement in study abroad, humanitarian engineering projects, or nonengineering clubs influences students' perceptions of their interdisciplinary skills; it is possible that students who believe they have interdisciplinary skills gravitate toward these kinds of co-curricular activities. This connection, however, provides direction for future research on the development of interdisciplinary skills. That future research should employing longitudinal methods to capture baseline data on students' perceptions of and interest in interdisciplinarity to study how students' interdisciplinary skills develop over time.

Our present findings will assist researchers in prioritizing co-curricular activities that might serve as appropriate sites for such studies, and could demonstrate the specific effects of substantive engagement with nonengineers on engineering students' interdisciplinary competence.

Despite the emphasis on team projects in engineering courses, such as first-year and capstone design courses, none of the instructional strategies we studied significantly related to interdisciplinary skills once other variables were taken into account. Only a curricular emphasis on broad and systems perspectives remained strongly related to interdisciplinary skills in the final model; students reported higher levels of interdisciplinary competence when they also reported that hat their engineering programs emphasized that the solutions of engineering problems required understanding and applying knowledge from fields outside of engineering as well as understanding how different contexts (e.g., cultural, environmental, economic) shape engineering solutions. reported. These findings suggest that interdisciplinary skills are not likely to develop without focused practice and guidance. Engineering programs seeking to promote interdisciplinary competence should intentionally and explicitly engage students in discussion and problem solving that emphasizes the role of contextual factors in engineering solutions and the contributions that disciplines outside engineering can make to those solutions. Repeated opportunities to think about complex engineering problems that are situated in multifaceted real-world contexts will engage students in the kinds of discussions, investigations, and problem solving that are likely to build their interdisciplinary skills over time. The fields of human-computer interaction /and human factors provides ready examples of the importance of organizational and human interfaces with technical systems. Instructors in a variety of engineering fields can point to discipline-relevant large-scale complex engineered systems to demonstrate the interdisciplinary nature of systems development – for example in aerospace (e.g., space systems), maritime (e.g., submarines), and nuclear (e.g., power plants) engineering. Large-scale civil infrastructure systems, such as the Alps Transit tunneling project in Switzerland, and notable failures, such as the Deepwater Horizon oil spill, can be used to promote thinking about how knowledge and practices from different engineering fields – and fields beyond engineering – can inform engineers' thinking and action. These two examples demonstrate how engineering problem solving and decision making can involve a variety of engineering subfields (e.g., civil, mining, electrical, safety, and transportation engineering, among others) while also requiring attention to environmental laws and community buy-in to proposals and solutions.

Our results revealed that none of the program-level variables were significantly related to interdisciplinary skills in the final model. In a previous analysis of the relationships between engineering faculty members' experiences and beliefs and their emphasis on interdisciplinarity in their courses (Lattuca et al., 2014), we found that disciplinary affiliation was one of several influences on faculty members' emphasis on interdisciplinary knowledge in courses they regularly taught (although not the strongest one). The hierarchical modeling used in this study, however, suggests that engineering subfield is unrelated to students' perceptions of their interdisciplinary skills.

Faculty views, college experiences, and interdisciplinary skills In answering our second research question, we found that faculty members' beliefs that they should help students understand the value of diversity moderated the relationship between students' participation in humanitarian engineering projects and their reports of their interdisciplinary skills, although this was a weak relationship. We found a stronger moderating relationship between students' perceptions of the extent to which their programs emphasized broad and systems perspectives in courses, and their reports of their interdisciplinary skills was stronger when faculty in the program thought it was important to emphasize interdisciplinary learning in the curriculum. This finding is noteworthy because in a previous analysis (Lattuca et al., 2014), we found that a faculty member's belief that interdisciplinary learning should be a part of the engineering curriculum was related to his or her emphasis on interdisciplinarity in their course. In that previous analysis, we also found a relationship between an emphasis on interdisciplinarity in courses and the belief that sustainability should be a major focus of the undergraduate engineering curriculum, but this variable was not significant in this study. Together, our prior and current work provide evidence that the belief that interdisciplinary learning should be part of engineering education is not simply reflected in faculty members' courses, as demonstrated in the previous study, but that this belief plays a role in student learning outcomes as well.

Still, the absence of a stronger connection between faculty members' beliefs and the relationship between students' experiences and self-reported interdisciplinary skills deserves attention. We offer two possible explanations. First, these findings may suggest that while faculty members agree that undergraduate programs should seek to educate well-rounded, interdisciplinary engineers, engineering programs have not yet determined effective means of helping students develop these skills. Richter and Paretti (2009) demonstrated that while evidence points to increasing use of interdisciplinary approaches, there is little research – and thus limited guidance – on instructional and assessment practices that support student learning in interdisciplinary settings. Their review of conference papers on interdisciplinary curricula and projects found that few authors articulated measurable learning outcomes or described how curricula and projects were used to teach students particular interdisciplinary skills. Future research on interdisciplinary curricula should thus examine how interdisciplinary courses and programs seek to achieve specific learning outcomes associated with interdisciplinary problem solving or collaboration as well as how these learning outcomes are assessed to understand whether learning goals, activities, and assessment are aligned. Future researchers might also study whether engineering programs that emphasize design throughout the curriculum (rather than only in the first or last years of study) provide students with more opportunities to experience interdisciplinary approaches and thus to develop their interdisciplinary skills.

A second possible explanation of our findings, and one that may complement rather than compete with the first, is that faculty members may perceive that they are unable to give greater emphasis to interdisciplinary approaches in courses because of the highly prescribed and sequenced nature of the engineering curriculum. Faculty members may feel the need to cover particular topics in specific ways so that students are prepared for the courses that follow; this perception may work to constrain engineering faculty members' willingness to discuss and apply knowledge and skills from outside engineering in problem solving. Further investigation of faculty members' beliefs and behaviors related to interdisciplinary learning could not only reveal the extent of such concerns but also identify successful approaches, such as interdisciplinary minor programs, that integrate disciplinary and interdisciplinary learning experiences.

In an era when engineers are increasingly asked to solve problems that cross the boundaries of social, economic, political, and environmental realms, our findings are a step toward understanding how to effectively develop students' interdisciplinary competence. Future research should focus on what influences engineering faculty as they plan their courses and programs. Engineers hold attitudes and beliefs that appear conducive to interdisciplinary educational approaches, but they report only a moderate emphasis on such approaches in their courses (Lattuca et al., 2014). A critical question is why these beliefs do not translate into higher levels of curricular attention.

(1)Conclusion

While few educators seem to question the value of interdisciplinary education, there is little research to guide educational practice. As engineering schools add majors and minors in areas such as sustainability, biomedical engineering, entrepreneurship, and science and technology studies, further research can identify educational experiences that support the development of interdisciplinary competence and demonstrate the positive effects of these experiences. This study identified a small set of experiences that are related to students' reported development of interdisciplinary skills. Specifically, our study points to the critical role of the curriculum in promoting interdisciplinary habits of mind and action, as well as the potential of co-curricular opportunities that bring engineering students together with those from other disciplines to build interdisciplinary competence. Our findings provide researchers with direction for future studies that further investigate the relationships between curricular emphasis on systems perspectives and co-curricular experiences with nonengineers on the development of students' interdisciplinary skills.

(1)Appendix A

Items in the Independent Variable Scales

Curriculum emphasis[a]

Overall, how much have the courses you've taken in your engineering program emphasized each of the following:

Core engineering thinking (alpha = .85)
- Generating and evaluating ideas about how to solve an engineering problem
- How theories are used in engineering practice
- Emerging engineering technologies
- Defining a design problem
- Creativity and innovation

Professional values (alpha = .82)
- Examining my beliefs and values and how they affect my ethical decisions
- The value of gender, racial/ethnic, or cultural diversity in engineering
- Ethical issues in engineering practice
- The importance of life-long learning

Professional skills (alpha = .88)
- Leadership skills
- Working effectively in teams
- Professional skills (knowing codes and standards, being on time, meeting deadlines, etc.)
- Written and oral communication skills
- Project management skills (budgeting, monitoring progress, managing people, etc.)

Broad and systems perspectives (alpha = .84)
- Understanding how nonengineering fields can help solve engineering problems
- Applying knowledge from other fields to solve an engineering problem
- Understanding how engineering solutions can be shaped by environmental, cultural, economic, and other considerations

Instructional practice[b]

In your engineering courses, how often have your instructors

Student-centered teaching (alpha = .81):
- Set clear expectations for performance
- Conveyed the same material in multiple ways (in writing, diagrams, orally, etc.)
- Explained new concepts by linking them to what students already know
- Used examples, cases, or metaphors to explain concepts
- Answered questions or gone over material until students "got it"

Group learning (alpha = .77)
- Provided guidance or training in how to work effectively in groups
- Provided hands-on activities and/or assignments
- Used in-class, small group learning
- Assigned group projects

[a] Response option for each item were: 1 = little/no emphasis; 2 = slight; 3 = moderate; 4 = strong; 5 = very strong.
[b] Response option for each item were: 1 = never; 2 = rarely; 3 = sometimes; 4 = often; 5 = very often.

(1)Appendix B

Student Sample and Respondents

Characteristics of the population of engineering students, survey respondents, and their institutions

Characteristic	288-institution population [a] (*N* = 136,761)	31-institution sample [a] (*n* = 32,565)	Respondents [b] (*n*= 5,249)
Engineering discipline			
Bioengineering and biomedial	6.5%	6.5%	6.3%
Chemical	10.4	10.4	10.5
Civil	19.5	16	18.1
Electrical	21.8	21.4	18.9
Industrial	6.1	6	4.9
Mechanical	32.1	27.8	34.7
General	3.6	11.9	6.6
Gender			
Male	81.5%	80.7%	80.6%
Female	18.5	19.3	19.4
Race/Ethnicity			
African American	5.2%	5.9%	4.3%
Asian or Pacific Islander	12.1	12.3	13.2
Hispanic	6.5	6.1	11.2
American Indian/Alaskan Native	0.6	0.6	0.3
Other[c]	6.1	7.2	12.9*
Foreign	5.9	7.1	7.3
Caucasian	63.5	60.7	50.9
Class year			
Sophomore	6.1%	27.9%	22.3%
Junior	39.0	29.0	35.0
Senior	54.9	43.1	42.7

Source: American Society of Engineering Education.
Note. Responses in each category total 100%.
[a]Weighted by discipline, gender, race/ethnicity, class year, and adjusted for institutional response rate. [b]Weighted *n* may be smaller than unadjusted number of respondents due to missing data on a weighting variable. [c]Other category includes naturalized citizen, Middle Eastern, multirace, and other.

(1)Appendix C

Faculty Sample and Respondents

Characteristics of the population of engineering faculty, survey respondents, and their institutions

Characteristic	288-institution population[a] (*N* = 15,671)	31-institution sample[a] (*n* = 2,586)	Respondents[b] (*n* = 1,258)
Engineering discipline			
Bioengineering and biomedical	6.2%	6.5%	6.9%
Chemical	11.1	10.4	12.4
Civil	17.2	16.1	18.9
Electrical	33.1	36.5	46.9
Industrial	6.9	5.9	6.8
Mechanical	25.5	24.6	8.1
Gender			
Male	88.6%	87.9%	84.7%
Female	11.4	12.1	15.3
Race/Ethnicity			
African American	2.8%	4.3%	2.7%
Asian or Pacific Islander	23.5	24.7	10.8
Hispanic	3.4	3.0	2.6
American Indian/Alaskan Native	0.1	0.2	0.1
Other[b]	5.6	1.3	4,0
Foreign	0.1	0.1	14.2
Caucasian	64.6	66.5	65.6
Class year			
Assistant	23.1%	21.8%	25.2%
Associate	26.1	25.4	25.4
Full	50.8	52.8	49.4

Source. American Society of Engineering Education.
Note. Responses in each category total 100%.
[a]Weighted by discipline and gender, and adjusted for institutional response rate. [b]Other category includes naturalized citizen, Middle Eastern, multirace, and other.

(1)Acknowledgments

A grant from the National Science Foundation (EEC-0550608) supported this study. Opinions expressed herein are those of the authors, and no endorsement by the National Science Foundation should be inferred. This article substantially extends Lattuca, Knight, Ro, & Novoselich (2014).

(1)References

Association of American Colleges and Universities (2011). *What works in facilitating interdisciplinary learning in science and mathematics*. Washington, DC: Author.

Armor, D. J. (1974). Theta reliability and factor scaling. In H. L. Costner (Ed.), *Sociological methodology*. San Francisco, CA: Jossey-Bass.

Baillie, C., Ko, E., Newstetter, W., & Radcliffe, D. F. (2011). Advancing diverse and inclusive engineering education practices through interdisciplinary research and scholarship. *Journal of Engineering Education*, *100*(1), 6–13. http://dx.doi.org/10.1002/j.2168-9830.2011.tb00002.x

Baruch, Y. (1999). Response rate in academic studies – A comparative analysis. *Human* Relations, *52*, 421–438. http://dx.doi.org/10.1177/001872679905200401

Berger, J., & Milem, J. (2000). Organizational behavior in higher education and student outcomes. In J. C. Smart (Ed.), *Higher education: Handbook of theory and research* (Vol. 15, pp. 268–338). New York, NY: Agathon.

Boden, D., Borrego, M., & Newswander, L. K. (2011). Student socialization in interdisciplinary doctoral education. *Higher Education*, *62*, 741–755. http://dx.doi.org/10.1007/s10734-011-9415-1

Borrego, M., Froyd, J. E., & Hall, T. S. (2010). Diffusion of engineering education innovations: A survey of awareness and adoption rates in US engineering departments. *Journal of Engineering Education*, *99*(3), 185–207. http://dx.doi.org/10.1002/j.2168-9830.2010.tb01056.x

Borrego, M., & Newswander, L. K. (2010). Definitions of interdisciplinary research: Toward graduate-level interdisciplinary learning outcomes. *Review of Higher Education*, *34*(1), 61–84. http://dx.doi.org/10.1353/rhe.2010.0006

Borrego, M., Newswander, C. B., McNair, L. D., McGinnis, S., & Paretti, M. C. (2009). Using concept maps to assess interdisciplinary integration of green engineering knowledge. *Advances in Engineering Education*, *2*(1), 1–26.

Bowman, N. A. (2010). Can 1st-year college students accurately report their learning and development? *American Educational Research Journal*, *47*(2), 466–496. http://dx.doi.org/10.3102/0002831209353595

Brint, S.G., Turk-Bicakci, L., Proctor, K., & Murphy, S.P. (2009). Expanding the social frame of knowledge: Interdisciplinary, degree-granting fields in American colleges and universities, 1975-2000. *Review of Higher Education*, *32*(2), 155–183. http://dx.doi.org/10.1353/rhe.0.0042

Cabrera, A. F., Colbeck, C. L., & Terenzini, P. T. (2001). Developing performance indicators for assessing classroom teaching practices and student learning: The case of engineering.

Research in Higher Education, 42(3), 327–352. http://dx.doi.org/10.1023/A:1018874023323

Collin, A. (2009). Multidisciplinary, interdisciplinary, and transdisciplinary collaboration: Implications for vocational psychology. *International Journal for Educational and Vocational Guidance*, *9*(2), 101–110. http://dx.doi.org/10.1007/s10775-009-9155-2

Coso, A. E., Bailey, R. R., & Minzenmayer, E. (2010). *How to approach an interdisciplinary engineering problem: Characterizing undergraduate engineering students' perceptions*. IEEE Frontiers in Education Conference, Washington, DC. http://dx.doi.org/10.1109/FIE.2010.5673313

Cox, B. E., McIntosh, K. L., Reason, R. D., & Terenzini, P. T. (2014). Working with missing data in higher education research: A primer and real-world example. *Review of Higher Education, 37*(3), 377–402. http://dx.doi.org/10.1353/rhe.2014.0026

Dempster, A. P., Laird, N. M., & Rubin, D. B. (1977). Maximum likelihood from incomplete data via EM algorithm. *Journal of the Royal Statistical Society. Series B, 39*(1), 1–38. http://www.jstor.org/stable/2984875

Dey, E. L. (1997). Working with low survey response rates: The efficacy of weighting adjustments. *Research in Higher Education, 38*(2), 215–227. http://dx.doi.org/10.1023/A:1024985704202

Drezek, K. M., Olson, D., & Borrego, M. (2008). *Crossing disciplinary borders: A new approach to preparing students for interdisciplinary research*. IEEE Frontiers in Education Conference, Saratoga Springs, NY. http://dx.doi.org/10.1109/FIE.2008.4720585

Educating the Engineer of 2020 Student Survey [Survey Instruments for the Engineer of 2020 Study website]. https://deepblue.lib.umich.edu/handle/2027.42/107459

George, D., & Mallery, P. (2003). SPSS for Windows step by step: A simple guide and reference. 11.0 update (4th Ed.). Boston, MA: Allyn & Bacon.

Graham, J. W. (2009). Missing data analysis: Making it work in the real world. *Annual Review of Psychology, 60,* 549–576. http://dx.doi.org/10.1146/annurev.psych.58.110405.085530

Greeno, J. G., Collins, A. M. & Resnick, L. B. (1996). Cognition and learning. In D.C. Berliner & R. C. Calfee (Eds.) *Handbook of educational psychology* (pp. 15–46). New York, NY: Macmillan.

Hayek, J. C., Carini, R. M., O'Day, P. T., & Kuh, G. D. (2001). Triumph or tragedy: Comparing student engagement levels of members of Greek-letter organizations and other students. *Journal of College Student Development, 43*(5), 643–663.

Jacobs, J. A. (2014). *In defense of disciplines: Interdisciplinarity and specialization in the research university.* Chicago, IL: University of Chicago Press.

Jamieson, L. H., & Lohmann, J. R. (2009). *Creating a culture for scholarly and systematic innovation in engineering education: Ensuring US engineering has the right people with the right talent for a global society*. Washington, DC: American Society of Engineering Education.

Johri, A., Olds, B. M., & O'Connor, K. (2014). Situative frameworks for engineering learning research. In A. Johri & B. M. Olds (Eds.) *Cambridge handbook of engineering education research* (pp. 47–66). New York, NY: Cambridge University Press.

Klein, J. T. (1996). *Crossing boundaries: Knowledge, disciplinarities, and interdisciplinarities*. Charlottesville, VA: University Press of Virginia.

Klein, J. T. (2010). *Creating interdisciplinary campus cultures: A model for strength and sustainability*. San Francisco, CA: Jossey-Bass.

Klein, J. T, & Newell, W. H. (1997). Advancing interdisciplinary studies. In J. G. Gaff, J. L. Ratcliff and Associates (Eds.), *Handbook of the undergraduate curriculum: A comprehensive guide to purposes, structures, practices, and change* (pp. 393–415). San Francisco, CA: Jossey-Bass.

Kockelmans, J. (1979). *Interdisciplinarity and higher education*. University Park, PA: The Pennsylvania State University Press.

Kuh, G. D. (2005). Imagine asking the client: Using student and alumni surveys for accountability in higher education. . In J. C. B. Associates (Eds.), *In Achieving accountability in higher education: Balancing public, academic, and market demands* (pp. 148–172). San Francisco, CA: Jossey-Bass.

Lattuca, L. R. (2001). *Creating interdisciplinarity: Interdisciplinary research and teaching among college and university faculty*. Nashville, TN: Vanderbilt University Press.

Lattuca, L. R., Knight, D. B., & Bergom, I. (2013). Developing a measure of interdisciplinary competence. *International Journal of Engineering Education, 29* (3), 726–739.

Lattuca, L. R., Knight, D. B., &Brown, M. B. (2014). *Influences on engineering instructors' emphasis on interdisciplinarity in undergraduate courses*. ASEE Annual Conference, Indianapolis, IN. https://peer.asee.org/20637

Lattuca, L.R., Knight, D.B., Ro, H.K., Bronzina, S. C., & Novoselich, B.C. (2014). *Promoting broad thinkers: College experiences, organizational conditions, and faculty cultures that support the development of students' interdisciplinary skills*. Paper presented at the Annual Meeting of the Association for the Study of Higher Education, Washington, D.C.

Lent, R. W., Brown, S. D., & Hackett, G. (1994). Toward a unifying social cognitive theory of career and academic interest, choice, and performance. *Journal of Vocational Behavior, 45*, 79–122. http://dx.doi.org/10.1006/jvbe.1994.1027

Lent, R. W., Sheu, H-B., Singley, D., Schmidt, J. A., Schmidt, L. C., & Gloster, C. S. (2008). Longitudinal relations of self-efficacy to outcomes expectations, interests, and major choice goals in engineering students. *Journal of Vocational Behavior, 73*, 328–335. http://dx.doi.org/10.1016/j.jvb.2008.07.005

Luo, W., & Azen, R. (2012). Determining predictor importance in hierarchical linear models using dominance analysis. *Journal of Educational and Behavioral Statistics, 38*(1), 3–31. http://dx.doi.org/10.3102/1076998612458319

McNair, L. D., Newswander, C., Boden, D., & Borrego, M. (2011). Student and faculty interdisciplinary identities in self-managed teams. *Journal of Engineering Education, 100*(2), 374–396. http://dx.doi.org/10.1002/j.2168-9830.2011.tb00018.x

Miller, R. C. (1982). Varieties of interdisciplinary approaches in the social sciences: A 1981 overview. *Issues in Integrative Studies*, *1,* 1–37.

National Academy of Engineering. (2004). *The engineer of 2020: Visions of engineering in the new century*. Washington, D.C.: National Academies Press.

National Academy of Sciences. (2004). *Facilitating interdisciplinary research*. Washington, D.C.: National Academies Press.

National Institutes of Health. (2006). *Summary of the President's FY 2006 budget*. Washington, D.C.: National Institutes of Health.

National Research Council. (2012). *Education for life and work: Developing transferable knowledge and skills in the 21st century*. J. W. Pellegrino & M. L. Hilton (Eds.).. Washington, DC: National Academies Press.

Newell, W. H. (1992). Academic disciplines and undergraduate interdisciplinary education: Lessons from the School of Interdisciplinary Studies at Miami University, Ohio. *European Journal of Education*, 211–221. http://dx.doi.org/10.2307/1503450

Newswander, L. K., & Borrego, M. (2009). Engagement in two interdisciplinary graduate programs. *Higher Education 58*(4), 551–662. http://dx.doi.org/10.1007/s10734-009-9215-z

O'Donnell, A. M., & Derry, S. J. (2005). Cognitive processes in interdisciplinary groups: Problems and possibilities. In S. J. Derry, M.A. Gernsbacher, & Christian D. Schunn, *Interdisciplinary collaboration: An emerging cognitive science* (pp. 51–82). Mahwah, NJ: Lawrence Erlbaum.

Pascarella, E.T. & Terenzini. P.T. (1991). *How college affects students: Findings and insights from twenty years of research*. San Francisco, CA: Jossey-Bass.

Pascarella, E.T., & Terenzini, P.T. (2005). *How college affects students*. San Francisco, CA: Jossey-Bass.

Pierrakos, O., Borrego, M., & Lo, J. (2007). *Assessment of student's learning outcomes during design experiences: Empirical evidence to support interdisciplinary teams*. Paper presented at the Fourth WSEAS/IASME International Conference on Engineering Education, Agios, Crete, Greece.

Porter, S. R. (2005). Survey research policies: An emerging issue for higher education. *New Directions for Institutional Research*, issue 127, 5–15. San Francisco, CA: Jossey-Bass. http://dx.doi.org/10.1002/ir.152

Porter, S. R., & Umbach, P. D. (2006). Student survey response rates across institutions: Why do they vary? *Research in Higher Education*, *47*, 229–247. http://dx.doi.org/10.1007/s11162-005-8887-1

Raudenbush, S. E., & Bryk, A. S. (2002). *Hierarchical linear models: Applications and data analysis methods* (2nd ed.). Thousand Oaks, CA: Sage.

Richards, D. G. (1996). The meaning and relevance of "synthesis" in interdisciplinary studies. *Journal of General Education*, *45(*2)114–128. http://www.jstor.org/stable/27797295

Richter, D. M. & Paretti, M. C. (2009). Identifying barriers to and outcomes of interdisciplinarity in the engineering classroom. *European Journal of Engineering Education*, *34*(1), 29–45. http://dx.doi.org/10.1080/03043790802710185

Ro, H. K., Terenzini, P. T., & Yin, A. C. (2013). Between-college effects on students reconsidered. *Research in Higher Education*, *54*(3), 253–282. http://dx.doi.org/10.1007/s11162-012-9269-0

Schaffer, S. P., Chen, X., Zhu, X., & Oakes, W. C. (2012). Self-efficacy for cross-disciplinary learning in project-based teams. *Journal of Engineering Education*, *101*(1), 82–94.

Schilling, K. (1991). *Assessing models of liberal education: An empirical comparison*. (ERIC Document Reproduction Service No. ED 359 864). Washington, DC: Fund for the Improvement of Postsecondary Education..

Shadish, W. R., Cook, T. D., & Campbell, D. T. (2001). *Experimental and quasi-experimental designs for generalized causal inference.* Boston, MA: Houghton, Mifflin.

Smith, T. W. (1995). Trends in non-response rates. *International Journal of Public Opinion Research, 7*(2), 157–171. http://dx.doi.org/10.1093/ijpor/7.2.157

Snijders, T., & Bosker, R.J. (1994). Modeled variance in two-level models. *Sociological Methods & Research*, *22*, 342–363. http://dx.doi.org/10.1177/0049124194022003004

Terenzini, P. T., Cabrera, A. F., Colbeck, C. L., Parente, J. M., & Bjorklund, S. A. (2001). Collaborative learning vs. lecture/discussion: Students' reported learning gains. *Journal of Engineering Education, 90*(1), 123–130. http://dx.doi.org/10.1002/j.2168-9830.2001.tb00579.x

Terenzini, P. T., & Reason, R. D. (2005). *Parsing the first-year of college: A conceptual framework for studying college impacts.* Paper presented at the Annual Conference of the Association for the Study of Higher Education. Philadelphia, PA.

Terenzini, P. T., & Reason, R. D. (2010). *Toward a more comprehensive understanding of college effects on student learning*. Paper presented at the Annual Conference of the Consortium of Higher Education Researchers (CHER), Oslo, Norway.

U.S. Department of Education (2006). *A test of leadership: Charting the future of American higher education.* Report of the commission appointed by Secretary of Education Margaret Spellings. Washington, DC: Author.

Van Horn, P. S., Green, K. E., & Martinussen, M. (2009). Survey response rates and survey administration in counseling and clinical psychology: A meta-analysis. *Educational and Psychological Measurement*, *69*, 389–403. http://dx.doi.org/10.1177/0013164408324462

Von Hippel, P. T. (2004). Biases in SPSS 12.0 missing values analysis. *American Statistician, 58*(2), pp. 160–64.

Wright, S. (1992). Fostering intellectual development of students in professional schools through interdisciplinary coursework. *Innovative Higher Education*,*16*, 251–261. http://dx.doi.org/10.1007/BF00917811

(1)Authors

Lisa R. Lattuca is professor of higher education and integrative systems and design at the University of Michigan, 610 University Avenue, Ann Arbor, MI, 48109-1259, llatt@umich.edu.

David B. Knight is an assistant professor of engineering education at Virginia Tech, 614 McBryde Hall, 225 Stanger Street, Blacksburg, VA, 24061; davidknight@vt.edu.

Hyun Kyoung Ro is assistant professor of higher education at Bowling Green State University, Bowling Green, Ohio, 43403-0001, hro@bgsu.edu.

LTC Brian J. Novoselich is an assistant professor of civil and mechanical engineering at the United States Military Academy, Bldg. 752 Thayer Road, West Point, NY, 10996, brian.novoselich@usma.edu.