The influence of prior industry experience and multidisciplinary teamwork on student design learning in a capstone design course

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This study compares the design process knowledge of students before and after a capstone design course. The influence of having prior industrial experience or being on a multidisciplinary capstone project on design process knowledge is also investigated. To assess design process knowledge, students critiqued a proposed design process; their responses were evaluated with a rubric that focuses on seven traits of design process knowledge. Results indicate that a capstone experience increases students' understanding of needs identification, the overall layout of a design process, and relative time allotments of different design activities. A capstone course also reduced the differences seen before this study between students with and without prior industrial experience. Students in multidisciplinary and single disciplinary capstone courses performed similarly.

Keywords: engineering design, design education, design knowledge, interdisciplinarity, capstone

Even though engineering design is a core knowledge area for all disciplines within engineering, it is not known exactly what engineering graduates know about design and where they learn it. To begin learning about design, introduction to engineering courses for first-year students are becoming more common. Other experiences thought to increase design process knowledge are capstone experiences in a student's senior year and industry internships held by students during the summer.

In a recent study by Bailey (2007), the design process knowledge of students entering their senior year without any industrial experience was shown to be no different than that of first-year students at the end of an introduction to engineering course. Seniors with industrial experience, however, showed some differences compared to the first-year students: they were more aware of documentation's role throughout design, less aware that idea generation is an important part of design, and less able to allot time to different design activities.

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In this work, we follow students to the end of the capstone design course and reassess their design process knowledge. The long-term goal of this project is to evaluate what engineering students know about engineering design, when they learn it, and how. The specific aim of this study is to compare the design process knowledge of students after an engineering capstone course to their knowledge before the course. More specific goals are to evaluate the correlation between prior industrial experience or multidisciplinary design projects (such as a first-year design experience) and the change in design knowledge during a capstone course.

1 Background

Existing literature on assessing the impacts of capstone experience, industry experience, and multidisciplinary team experience ranges from anecdotal evidence to more rigorous qualitative quantitative studies.

Koen (1994) hypothesizes the necessity of a capstone design course by arguing design is a type of behavior, and students can only learn through behavioral experience. From this, Koen asserts that experiencing a design process (i.e., through a capstone project) has a positive effect on students' design process knowledge. Koen's conclusions are based on his experiences more so than on a study in which this hypothesis is tested.

Dutson et al. (1997), of Motorola, conducted a study presenting that since World War II, engineering education has evolved to rely more on theory and less on practical skills. He claims that capstone design courses act as a mechanism for students to understand the practical skills that modern engineering education lacks. Industries now demand capstone coursework experience from engineering schools.

Todd et al., at Brigham Young University (BYU) (1995) analyzed the effects of a capstone project on students. Although the projects required much faculty involvement, they were highly beneficial to students in gaining professional experience. In response to the effectiveness of such a course, professors rated the capstone course an 8.6 on a 10-point scale. BYU conducted 96 of these industry-sponsored projects over the course of five years and saw a marked improvement in the real-world experience of its students.

Literature related to how internships affect college students suggests that internships are a valuable experience for the student. A study at the Georgia Institute of Technology (Parsons et al., 2005), suggested that students with industrial experience had a higher average GPA and were offered higher salary upon graduation. Additionally, Wessels and Pumphrey (1996) found that students with co-op experience advanced in their field more quickly once employed. These studies showed that internships have positive effects on the students, but whether or not they affected their learning or retention of the design process has not been studied.

A study conducted at the University of Florida (Knechel and Snowball, 1987) further illustrates the benefits of internships for business majors. This study matched students with co-op experience to students who did not have a co-op experience based on similar academic performance before the internship program. Both students' performance was then compared after the internship experience. Internships were found to increase 'exposure to accounting techniques and problems not encountered in a classroom environment,' enhance 'understanding of the business world,' and improve the 'ability to evaluate and assimilate classroom experiences' (p. 800).

Much of the relevant literature related to the differences between multidisciplinary and single disciplinary capstone courses qualitatively addresses advantages of the multidisciplinary courses. Hanlon et al. (2004) at the US Military Academy noticed advantages of the multidisciplinary course over the single disciplinary capstone course. One advantage of the multidisciplinary course was that it introduced students to 'the capabilities and limitations of other disciplines' (p. 1). Additionally, it was found that 'they more closely model real work engineering projects where no group of engineers from a single discipline could actually affect a design because of the depth and complexity of the design space' (p. 2). The study at the US Military Academy recognizes the need to evaluate the success of capstone projects with short-term feedback (end of semester feedback), intermediate feedback (3 years later), and eventually long-term feedback from alumni. Findings in this study reflect student and faculty perceptions. At this point, however, no attempt has been made to directly identify differences in knowledge attained from multidisciplinary and single disciplinary courses.

At Clemson University, Dixon (2002) explored the differences of single disciplinary and multidisciplinary capstone projects at a single university and multi-university level. This study identified a multidisciplinary capstone course at a single university level as the most successful of the four options. The advantages of a multidisciplinary course included recognizing differences in engineering terminology between different disciplines and being introduced to new design methodologies from students of different technical backgrounds. Although this study determined that the multidisciplinary course was the superior capstone course, there was no data assessing the differences in what students learned in the different approaches. Conclusions were based on the perceptions of industrial representatives, faculty, and students who participated in the different courses.

Bailey and Aronson (2005) at the University of Arizona quantitatively assessed the differences between the engineering design knowledge of students in a single disciplinary course and students in a multidisciplinary course. This study used several measures to compare students between the two courses. The first measure was students' performance on a design skills assessment similar to the one used in this study (the assessment approach has been significantly refined since the 2004 study). Students were assessed based on how well they critiqued a proposed design process. Students in the multidisciplinary course scored significantly higher on their critiques than did the students in the mechanical engineering senior design class. Students in the multidisciplinary class were better at 'identifying needs and using them throughout a design process to guide decisions, understanding the importance of documenting throughout a design process, and seeing the big picture of how a design process fits together' (p. 11). Another feature of this study was a comparison of course evaluations by students in the multidisciplinary course and students in the mechanical engineering senior design course. In both Fall 2003 and Spring 2004, students in the multidisciplinary course felt they were more able to 'design a system to meet a set of needs' (p. 12). Although this study lacked enough data to conclusively determine if a multidisciplinary course provides a better educational experience, it certainly suggests that this is the case.

In *Engineering and the Mind's Eye*, Ferguson (1992) discusses the importance of practicing design rather than solely learning principles of engineering sciences. In the late 1950s and 1960s, a transition to analysis-heavy engineering programs lacking a design component resulted in engineers less equipped to look at the entire problem and solve real-world problems. For successful design, engineers must possess the 'intuitive feel of experience' along with formal knowledge. Additionally, while newly developed analysis techniques are an asset, they can provide students with an answer that they do not fully understand. Thus, asserted Ferguson, students need to incorporate the knowledge and analysis tools with design experiences. Industry visits and experiences are valuable for engineers to increase their knowledge. Based on research such as Ferguson's, design courses are now routine and industrial experiences encouraged. The work presented here investigates the effect of both of these on the engineering design knowledge of students.

1.1 Purpose of this study

In light of the prior work, we are investigating the change in engineering design knowledge of students by analyzing this knowledge before and after a capstone engineering design course. This study will also investigate if this change is related to previous industrial experience or participation in multidisciplinary design projects. In experimental design terms, there is one primary dependent variable, engineering design knowledge, which, as described in the following section, is divided into seven sub-areas of knowledge. There are three independent variables: prior industrial experience (yes or no), multidisciplinary capstone project (yes or no), and a repeated measure, completion of a capstone project (before project and after project).

Core Research Question: How is student knowledge of engineering design different after a capstone course compared to before?

As discussed in the literature review, studies show that capstone courses have a positive impact on design process knowledge. We are specifically interested in determining which areas of design process knowledge are affected by a capstone design course.

Due to the applied nature of engineering design, we are interested in understanding the impact of prior industrial experience on the effect of a capstone course on a student learning about engineering design.

Question 2: Is the change in design process knowledge for students with prior industrial experience different than the change for those without prior industrial experience?

Additionally, with the growing number of multidisciplinary teams working together on design projects in capstone courses, we are interested in understanding the impact of such projects on the effect of a capstone course in student learning about engineering design.

Question 3: Is the change in design process knowledge for students on multidisciplinary design projects different than the change for those on single disciplinary projects?

2 Methods

2.1 Participants

A group of 103 engineering students enrolled in the mechanical or multidisciplinary senior design courses during the 2005–2006 academic year at the University of Arizona participated in the study. These two courses were nearly identical in that all students attended the same classroom sessions and completed the same assignments. Perhaps the only relevant difference is that the multidisciplinary team reports were graded by the course instructors (ensuring that the teams used tools introduced in class correctly) while the single disciplinary team reports were graded by their team mentor (who in most cases was not intimately familiar with the design tools introduced in class).

Participants self-selected by enrolling in either the mechanical or multidisciplinary design course. Students in the multidisciplinary course worked on teams composed of engineering students from several majors that were matched to projects with certain needs in terms of technical skills. Students in the mechanical course worked on teams composed of all mechanical engineering majors that were matched to projects with a strong need for mechanical technical knowledge. Materials science and optical engineering students were required to enroll in the multidisciplinary class, mechanical students could choose either one of the two courses, and other majors could select either a capstone class within their own discipline (not in this study) or the multidisciplinary course (in this study). Forty-five participants were in the single disciplinary mechanical design course, of which 28 had prior industrial experience and 17 did not. Fifty-eight participants were in the multidisciplinary course, of which 40 had prior industrial experience and 18 did not. All subjects were assessed at the beginning and end of the course. Only the assessments from students who agreed to participate in the study and who completed both the pre- and post-tests were analyzed. Of 119 students completing pre-tests, 103 completed post-tests and are in this study, 10 did not complete post-tests, and six completed post-tests but elected not to be in the study.

2.2 Apparatus

Subjects' critique of a proposed design process provided an approach to measure each student's design process knowledge. A former study (Bailey, 2007) of the effects of different first-year projects and sophomore and junior coursework on design process knowledge successfully used the same evaluation approach to create a practical scale for comparison. The Gantt chart shown in Figure 1 visually represents the critiqued process.

Students critique the process by identifying its pros and cons in a written response. A seven trait rubric created and evaluated by Bailey and Szabo (2006) provided a scale for scoring the responses. The seven traits of the rubric assess the response according to the following learning objectives.

Trait 1. Needs/requirements identification
Explain why needs must be gathered and *analyze* the effectiveness of techniques for gathering needs. This trait is focused on measuring if students know that early in the design process it is important to accurately define the problem by determining the parameters and criteria of the problem.

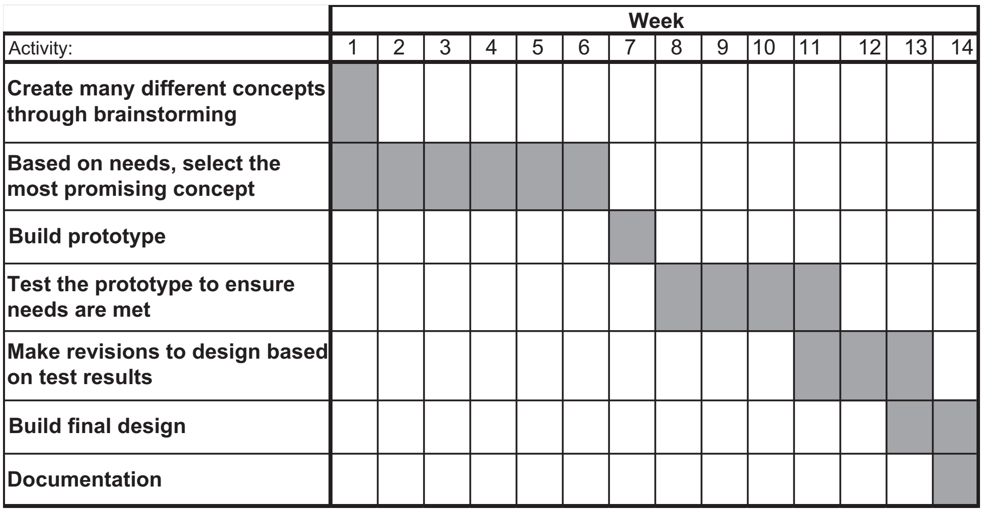

Figure 1 Gantt chart of design process that students critiqued

Trait 2. Idea generation
Explain why multiple alternatives should be generated before developing a single alternative in depth.

Trait 3. Analysis and decision-making
Explain that a combination of analysis and decision-making (based on the needs of the project) is required to eliminate ideas before building them.

Trait 4. Building and testing
Explain that built designs should be tested to determine if they meet the needs.

Trait 5. Overall layout of a design process and iteration
Explain the overall layout of a design process, including iteration.

Trait 6. Time allotments
Analyze how much time is necessary for each step.

Trait 7. Documentation
Explain that documentation occurs throughout a design process.

For each of the seven traits, a set of ordinal scores is specified by the rubric. For instance, on Trait 1, the scores on the rubric are as shown in Table 1.

The rationale for choosing this instrument is based on the trade-off between depth of assessment and sample size. The data obtainable through ethnography or through verbal protocol analysis is much richer and deeper than the data obtained from the design process critique. While such depth and richness can be useful, much can be learned about a student's design process knowledge with other methods such as the design process critique used here. That is, assessing design process knowledge is not 'all-or-nothing' — interesting information about design knowledge can be learned with less time-intensive methods than ethnography or verbal protocol analysis.

On the other hand, the design process critique gathers much richer and deeper information on student design knowledge than a close-ended instrument, such

Table 1 Example of ordinal scoring of rubric: Trait 1

Points	*Trait 1: needs identification*
0 Points	No mention of needs identification
1 Point	States that gathering needs/requirements is important or should be included in the design process.
2 Point	States that needs/requirements should be gathered *before brainstorming* in the proposed design process.
4 Points	In addition to stating that needs/requirements should be gathered, gives a suggestion as to how to find needs/requirements

as a Likert or multiple choice survey. For a concept as complex and adaptive as engineering design, close-ended surveys would be too shallow and blunt to gain significant insight. In summary, the design process critique instrument is used to obtain a larger sample size than would be possible with ethnography or verbal protocol analysis while maintaining sufficient openness to assess some of the complexities of engineering design knowledge.

Information on prior industrial experience was obtained from a survey given to students on which they were asked, 'Have you had any experience working in an engineering job?' Further details about the prior experiences were requested, including if the job was a summer job and how much of the job involved design.

2.3 Procedure

Students critiqued the design process on the first day of their senior design class and provided information about prior industrial experience. Near the end of their two-semester capstone experience, the students critiqued the design process a second time.

3 Results

3.1 Rater reliability

Two raters scored the pre-tests and two teams of raters scored the post-tests. In each case, intra-rater reliability and inter-rater reliability were evaluated. In addition, inter-rater reliability between the pre-test raters and the teams of post-test raters was checked. Both Pearson's and Spearman's correlation coefficient were evaluated, with target values of 0.8 or better for intra-rater reliability and 0.7 or better for inter-rater reliability. In most cases, values near 0.9 or higher were obtained.

3.2 Structure of the statistical analyses

To address the three research questions, three corresponding comparisons must be made with the collected data:

1. pre-test scores compared to post-test scores for the entire population (for the core research question),
2. the change in score (from pre-test to post-test) for students with prior industrial experience compared to the change in score for students without prior industrial experience (Research Question 2), and
3. the change in score (from pre-test to post-test) for students on multidisciplinary teams compared to the change in score for students on single disciplinary teams (Research Question 3).

For all three cases, scores on each of the seven traits and the total score (i.e., the sum of scores on all seven traits) were studied. The statistical tests used to make each of these comparisons are shown in Table 2.

Table 2 Statistical tests

	Groups compared		*Statistical test*
I	Pre-test scores	Post-test scores	Wilcoxon test for the seven traits (ordinal variables) and paired T test for the total scores (interval variables)
II	Difference in pre-test and post-test scores for students *with* industrial experience	Difference in pre-test and post-test scores for students *without* industrial experience	Tests of proportions looking at the interaction between prior experience (yes or no) and completion of capstone (pre-test or post-test) Factorial ANOVA with one repeated measure, looking at the interaction between prior experience (yes or no) and completion of capstone (pre-test or post-test)
III	Difference in pre-test and post-test scores for students on *multidisciplinary teams*	Difference in pre-test and post-test scores for students on *single disciplinary teams*	Test of proportions looking at the interaction between team type (multidisciplinary or single disciplinary) and completion of capstone (pre-test or post-test) Factorial ANOVA with one repeated measure, looking at the interaction between team type (multidisciplinary or single disciplinary) and completion of capstone (pre-test or post-test)

The Wilcoxon test was a natural fit for comparing the repeated measure of pre- and post-test ordinal scores. Similarly, the paired T test was a natural fit for comparing the repeated measure of pre- and post-test total scores, which are interval variables.

A statistical tool for evaluating interactions between ordinal variables, however, was more elusive. Hence, two statistical tests were performed for the comparisons based on interaction effects. A factorial ANOVA with one repeated measure and two between-subjects measures (team type and prior experience), which would be the appropriate test for parametric variables, was performed. In addition, a test of proportions (a non-parametric test) was performed for each trait. For the test of proportions, responses were coded as a binary variable (as either receiving points for a certain trait or not); *how many* points are earned on a certain trait could not be analyzed with this test. The test of proportions, because it is non-parametric, was a more appropriate statistical analysis for each of the seven traits of ordinal data. The drawback of the test of proportions was that the data had to be reduced to a binary response. The factorial ANOVA was the appropriate test for the total scores (which are parametric variables), but was also calculated for each trait's score (which are ordinal) because the complete data (not reduced to binary responses) could be analyzed.

3.3 Comparison I: results for the core research question

Compared to before the capstone experience, seniors near the end of their capstone projects showed greater knowledge about the role of needs identification

(Trait 1), the overall layout of activities in a design process including the role of iteration (Trait 5), and relative time allotments of different design activities (Trait 6). In addition, the total score for seniors at the end of the capstone experience was significantly higher than that of seniors before the capstone. All statistical tests used an alpha of 0.05. These results are shown in Table 3 and Figure 2.

3.4 Comparison II: results for research question 2

In studying whether prior industrial experience affects what someone learns during a capstone project, only one trait of the rubric was significant. On Trait 6, which concerns the relative time allotments of design activities, the test of proportions showed that the change (from pre- to post-test) in the percentage of students who understand relative time allotments for students with prior experience is greater than that change for students without prior experience ($p < 0.05$). The factorial ANOVA indicated a $p = 0.066$ for the interaction between prior experience and capstone experience completion on Trait 6. The interaction plots for the test of proportions (percent of students scoring on Trait 6 as the dependent variable) and for the ANOVA (Trait 6 average score as the dependent variable) are shown in Figure 3.

3.5 Comparison III: results for research question 3

In studying whether being on a multidisciplinary design team affects what someone learns during a capstone experience, only one trait of the rubric was significant. On Trait 1, which concerns understanding the importance of need identification at the start of a project, the test of proportions showed that the change (from pre- to post-test) in the *percentage of students* that understand the importance of need identification for students on multidisciplinary teams is greater than that change for students on single disciplinary teams ($p < 0.05$) (Figure 4). Results from the factorial ANOVA, however, showed no significant interactions at $\alpha = 0.05$ – indicating that *how much* a student learns about need identification does not change significantly between multidisciplinary and single disciplinary teams.

Table 3 Descriptive statistics: pre- and post-test scores

		N	*Mean*	*Std. Dev.*	*Wilcoxon*
Trait 1 needs identification	Pre	103	0.27	0.77	$Z_{obt} = -2.188$, $p = 0.029$
	Post	103	0.55	1.12	
Trait 5 overall layout/iteration	Pre	103	1.24	1.38	$Z_{obt} = -3.180$, $p = 0.001$
	Post	103	1.83	1.51	
Trait 6 time allotment	Pre	103	1.50	0.86	$Z_{obt} = -2.054$, $p = 0.040$
	Post	103	1.73	0.69	
		N	*Mean*	*Std. Dev.*	*t Statistic*
Total score	Pre	103	7.15	3.20	$t(102) = -2.692$, $p = 0.008$
	Post	103	8.25	3.47	

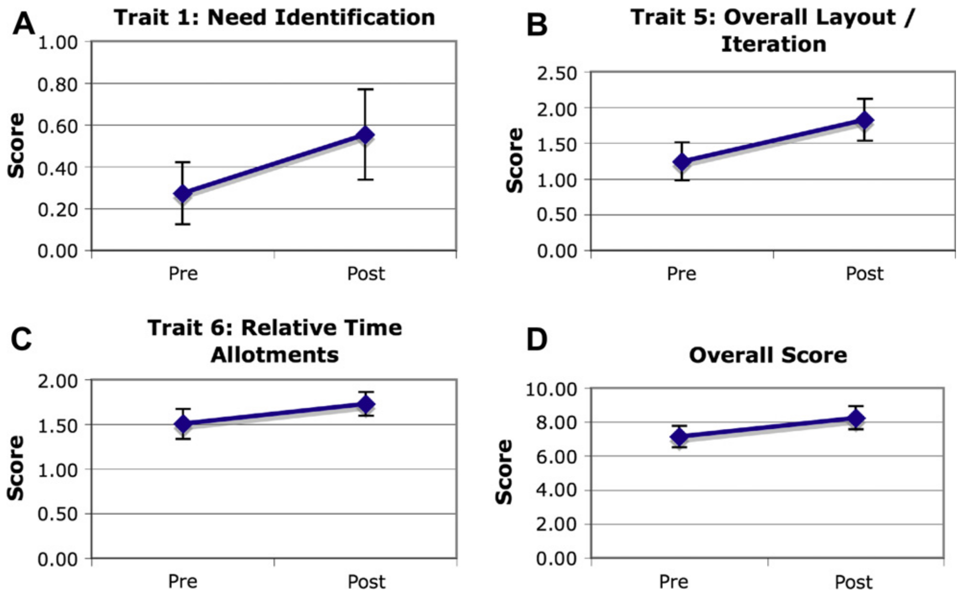

Figure 2 Pre- versus post-test with significant differences

To control for differences between majors (44 out of 45 students in the single disciplinary class are aerospace or mechanical engineering majors, while the multidisciplinary sample has a wider array of majors), analysis was also run between the single disciplinary class students who were aerospace or mechanical (AME) majors (44 of 45) and the multidisciplinary students who were AME majors (14 of 58). Of the AME students, those on the multidisciplinary teams showed larger increases in scores for Trait 1 (185% increase for multidisciplinary versus 46% increase for single disciplinary) and for the total scores (34% increase for multidisciplinary versus 15% for single disciplinary) than did those on single disciplinary teams (see Figure 5) but the two samples were not statistically significant (due largely to the small sample size of AME majors on multidisciplinary teams). Similarly, the percent of AME students scoring on Trait 1 increased from 23 to 54% on multidisciplinary teams while no change was observed on the single disciplinary teams.

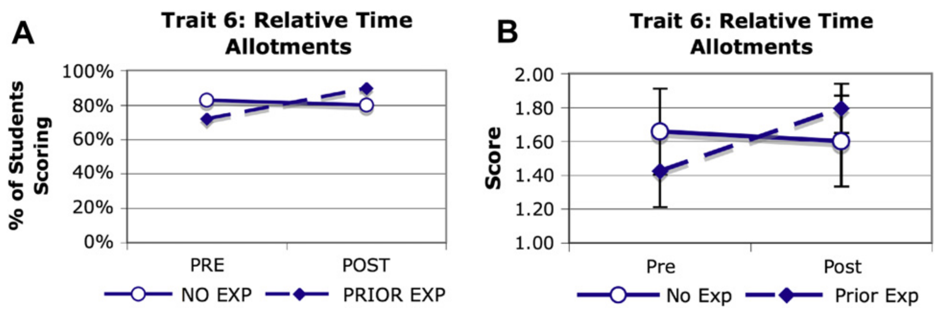

Figure 3 Interaction plots: capstone project completion × prior experience. (A) Proportions, (B) means; 'Exp' = experience

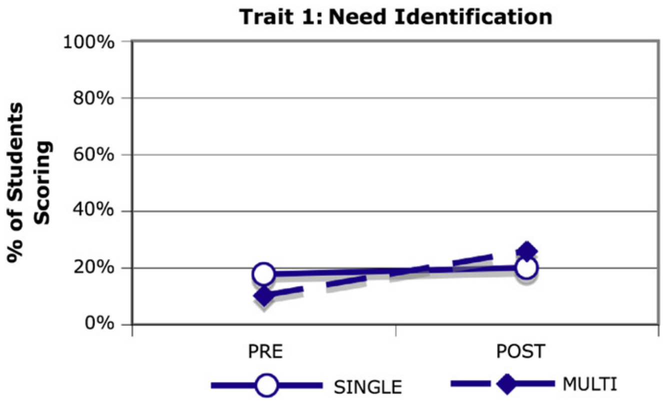

Figure 4 Interaction plot for test of proportions: capstone project completion × multi or single disciplinary design team. Single = single disciplinary, multi = multidisciplinary

4 Discussion

The results presented here are more clearly understood when compared to design process knowledge assessment results for first-year students both before and after a hands-on, introduction to engineering design course that involved two six-week design projects (Ernst et al., 2006).

4.1 Core research question: impact of capstone course

Two areas in which students made significant gains during the capstone course were understanding the role of needs identification and the overall layout of design, including iteration. Students showed no change in knowledge in these two areas during the first-year course or between the end of first-year course and the start of the capstone course (Ernst et al., 2006; Bailey, 2007). Plausible reasons for these differences are (1) first-year students are not ready to learn these higher-order skills, and (2) the shorter projects in the first-year course are not long enough for students to learn these skills. A single capstone project completed over an entire year would give students a greater time frame to fully explore the overall layout of design and have the time necessary to perform multiple iterations.

With respect to understanding time allocation among design activities, first-year students showed significant increases during the introduction to engineering design course. By the start of the capstone course, knowledge in this area had declined to levels observed before the introduction to engineering design course. During the capstone course, students showed an increase in their knowledge of relative time allotments of design activities that paralleled gains during the first-year course. This leads to the conclusion that knowledge of relative time allotments is not retained without practicing design.

There is a lack of improvement in knowledge with respect to design analysis and the role of building and testing in design. While analysis is incorporated into the capstone projects as necessary, analysis is not a core focus of the

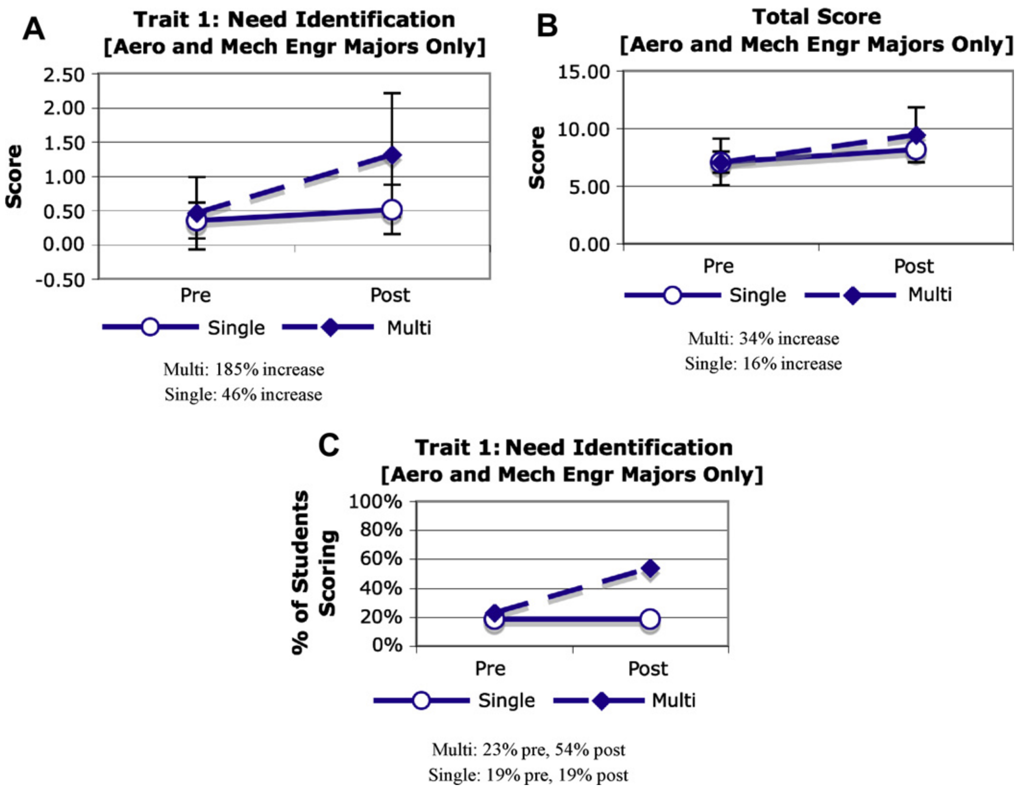

Figure 5 Comparison of mean scores [(A) and (B)] and proportion of students scoring [(C)] for aerospace and mechanical majors in the single disciplinary course versus the multidisciplinary course (these differences were not *statistically significant at $\alpha = 0.05$)*

course. Building and testing, however, is a central aspect of the capstone course. Therefore, the lack of improvement for building and testing is unexpected.

4.2 Research question 2: impact of prior industrial experience on design knowledge learning during capstone

Three areas of design knowledge measured in this study warrant discussion with respect to how engineering experience prior to the capstone affects this knowledge.

With respect to idea generation, prior studies (Ernst et al., 2006) show large gains are made during a first-year hands-on engineering design course. For those students with experience prior to the capstone project, these gains are all lost before the start of the capstone. It is theorized that this is related to most students not having a significant role in the idea generation aspect of a project during their industrial experiences. A capstone course allows these students to regain these skills. At the end of the capstone course, students with prior experience have closed the gap with their peers without engineering experience (they are statistically equivalent). Both groups, however, show slightly less knowledge about the role of idea generation in design at the end of their capstone project compared to at the end of the first-year class where this knowledge peaked.

In terms of understanding relative time allotments for design activities, gains are made during the first-year design class. These gains are lost during analysis-heavy sophomore and junior years, especially for students with engineering experience prior to their senior year capstone course (Ernst et al., 2006). During the capstone project, students without experience did not show any change in this knowledge area, while students with experience showed strong improvements.

With respect to understanding the role of documentation in a design process, students with engineering experience have shown strong gains between their first-year course and the start of the capstone course while those without engineering experience showed no change from their first-year course (Bailey, 2007). After the capstone course, however, students without engineering experience had increased their understanding of documentation's role such that they are equivalent to the students with experience at the end of the capstone course (whom did not see significant change from before the capstone course).

The strongest trend concerning prior industrial experience was for the capstone course to reduce the differences between students with and without engineering experience present before the capstone course. While this trend is most prominent in terms of knowledge about idea generation and documentation, it is present in nearly all aspects of design knowledge measured. Additionally, the capstone course did not significantly increase the difference between students with and without experience in any case.

4.3 Research question 3: impact of multidisciplinary capstone team on design knowledge learning

In the matter of a multidisciplinary background affecting the design knowledge of a student, it was found that the students who completed the multidisciplinary course scored similarly to the students from a single disciplinary course. Given the attitude present within many departments that a multidisciplinary experience negatively affects what students learn about *XX* design (where *XX* can be replaced with *mechanical*, or *electrical*, etc.) it was especially encouraging to find that both groups of students scored similarly on Traits 3 and 4 (which include analysis and testing) since these traits tend to be more focused on disciplinary material.

The data also *suggested* (but not at an $\alpha \leq 0.05$) that multidisciplinary students performed better at developing certain design skills such as needs identification (Trait 1). This agrees with previous studies including the 2004 study at the

University of Arizona conducted by Bailey and Aronson, reinforcing anecdotal evidence that multidisciplinary capstone provides a better experience for students.

4.4 Closure

The key results from this study are

- a capstone experience increases students' understanding of needs identification, the overall layout of design including iteration, and relative time allotments of different design activities,
- the total score of students' design knowledge after a capstone experience is greater than before the capstone,
- a capstone course reduces the differences between students with and without previous industrial experience, and
- students from a multidisciplinary course scored similarly to students from a single disciplinary course.

A capstone course is effective at helping students learn certain design skills. With regard to design knowledge, industrial experience is not critical if students complete capstone design before graduation. Furthermore, no evidence suggests that multidisciplinary design experiences are inferior to single disciplinary design experiences.

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