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Development of Verification and Validation Engineering Design Skills through a Multi-year Cognitive Apprenticeship Laboratory Experience

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Abstract:

In this study, a sophomore-level Biomaterials and Biomechanics laboratory, junior-level Biotransport laboratory, and senior-level Professional Elements of Design course were modified or created in order to integrate components of the cognitive apprenticeship model to teach experimental design. To assess the influence of the cognitive apprenticeship model on student ability to design experiments we evaluated the quality of verification and validation protocols between students who matriculated through traditional, technique driven laboratory experiences (traditional group) and students who participated in cognitive apprenticeship inspired inquiry-based laboratory experiences (experimental group). Student work was assessed using a modified EDAT rubric[9] to evaluate 19 elements of experimental design. Student work from the experimental group showed gains greater than 15% in four experimental design competency areas: independent variable identification, experimental control identification, published protocol identification, and appropriate statistical analysis. In summary, our data suggests that the vertical implementation of a cognitive apprenticeship strategy enhances student ability to design effective experiments.

Introduction:

Verification and validation testing protocols demonstrate that a design solution meets the design specifications and addresses the problem. Unfortunately, designing sufficient testing protocols is challenging for most undergraduates, even at the capstone design level. In our experience we have observed that the students can design, develop, and build a solution to a medical or healthcare problem but struggle with the process of evaluating their design. The students' abilities to pose and design effective verification and validation tests were limited. How did our students get to their senior year without developing this essential laboratory skill despite having required laboratory experiences since freshman year?

Traditional laboratory experiences follow step-by-step procedures and we believe this cookbook approach limits students' development of testing skills. Historically, we found that our students were performing the predefined steps of the laboratory exercises while taking minimal responsibility for the outcome and intended knowledge to be gained from the experience. This observation is consistent with prior research that has found students do not make cognitive connections between doing a procedure and the intended result from a single laboratory experience[1-4]. The material needs to be supplemented for students to fully understand the experiment and its design. Furthermore, these predefined experiments were perfected and do not adequately prepare students for real-life experiences in which incorrect, useless, or contradictory results may be produced from an investigation[3, 5]; thus, students are ill-prepared to evaluate, design, or debug a testing protocol. To address these shortcomings, we altered our required laboratory courses to better foster our students' cognitive ability to progress from an objective to formulating an appropriate experimental question and designing an effective experimental approach to address that question.

The cognitive apprenticeship model has been proposed to help students transition from a lower-level competency to that of a higher level[6, 7]. We explored this pedagogy to better develop our students' experimental design skills. Cognitive apprenticeship consists of four phases: modeling, scaffolding, coaching, and fading. During the modeling phase, students observe how experts employ processes to solve a problem. To facilitate student growth during the modeling phase, instructors must identify and articulate invisible processes that are employed to solve complex problems. In the scaffolding phase, students are provided a guided framework to promote the imitation of the processes that they observed by the experts. The scaffolding phase helps to build skill competency by providing a learning environment that provides concrete and authentic experiences. Next, the coaching component facilitates student understanding of skill limitations and actions that may be implemented to improve competency. During the fading phase, the scaffolding component is removed, while the coaching phase remains in place in order to continue to build complex understanding of concepts[6-8]. For this study, we implemented a multi-year cognitive apprenticeship within our required laboratory courses to improve our students' abilities to design an experiment.

To assess the effectiveness of this pedagogical strategy on developing our students' experimental design abilities, we adapted a previously validated assessment tool: the Experimental Design Ability Test (EDAT)[9]. EDAT was originally developed to assess the ability of students to develop an experiment that investigates a scientific claim[9]. We found that this tool in its original version does not assess all experiment types and formats used for the verification and validation testing that accompanies the design process. Thus, we adapted the EDAT to better help us assess student mastery of the testing process in our capstone design course.

Materials and Methods:

Cognitive apprenticeship phases: For our purposes, we defined the four phases of the cognitive apprenticeship within the context of experiment design as:

> *Modeling*: Course instructors provide an explicit discussion of all aspects of an experiment design that the students perform to address a scientific question. Emphasis is placed upon showing students why decisions are made in regards to selection of experimental design constraints and variables.
>
> *Scaffolding*: A guided activity where the students design their own experiments to answer a question. This guidance may be represented in many formats such as a recommended protocol for which they have to define variables and conditions or simply some questions to prompt them through the design process.
>
> *Coaching*: Students design their experiment to answer a question without any formal guidance; in advanced stages, they practice posing their own experimental question to support a scientific statement. The students get feedback on their design before implementing their experiment.

Fading: Students pose their own experimental questions and design and conduct their experiments independently; instructors serve as consultants during the process but unless asked by the students they only look over results and provide feedback on the design and results after the students have conducted the experiment.

Course adaptation: Three courses: a sophomore-level Biomaterials and Biomechanics laboratory, a junior-level Biotransport laboratory, and a senior-level Professional Elements of design lecture course were modified or developed to enhance student ability to design experiments using a cognitive apprenticeship pedagogy. A progressive refinement of student experimental design abilities was embedded throughout the three course series (Figure 1). With respect to the cognitive apprenticeship model, in the sophomore-level course there was a major emphasis on modeling and a minor emphasis on scaffolding to provide a strong framework for students to build their experimental design skills. In the junior-level and senior-level courses there was more emphasis placed on the scaffolding and coaching elements of cognitive apprenticeship.

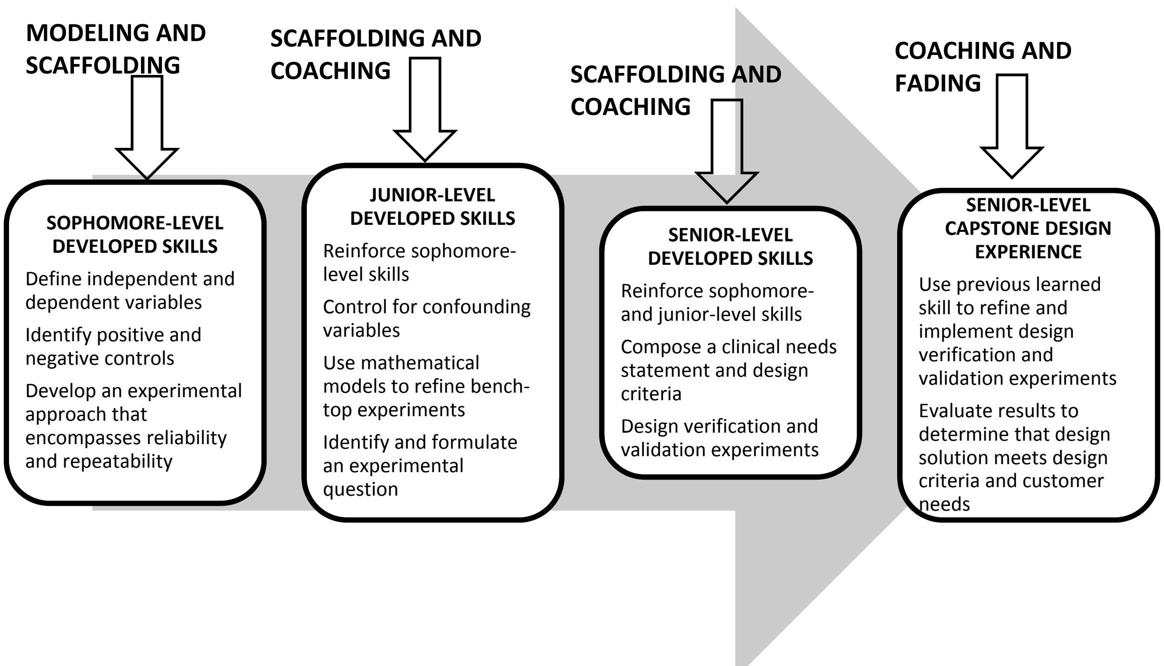

Figure 1. Expected experimental design skill development at the sophomore-, junior-, and senior-level

Using elements of a cognitive apprenticeship pedagogy: The modified sophomore-level Biomaterials and Biomechanics laboratory was first taught in Spring 2010. The laboratory was modified from 10 separate experiments following step-by-step instructions to a tiered challenge approach in which students are stepped through the experimental design process by first having students watch an instructor perform the skills needed to answer a scientific question (modeling), then having the students mimic the observed skill (scaffolding), followed by the students adapting the skill to address a similar open-ended question. A detailed example of this process is provided in the results section. A majority of the original course content remained in the modified, tiered challenge approach. For example, in the original laboratory sequence students learned in three separate laboratories how to use a mechanical tester to run compression, tension, bending, and fatigue tests. To update to the challenge sequence the original compression and tension exercise remained unchanged while the bending and fatigue laboratories were updated so that the step-by-step procedure was substituted with an investigation question for the students to address. Overall, in order to accommodate the new course format, two original laboratories were removed and one new laboratory was added.

In Spring 2011, the junior-level Biotransport laboratory course was altered from a traditional laboratory with students following step-by-step procedures to an inquiry-based learning style laboratory to scaffold and provide coaching on the experiment design process[10]. While updating this course there were significant content changes; however, the content changes reflected the instructors' decision to expose students to a wider range of biotransport problems rather than trying to modify the laboratories to fit the new model. In the new course, students work on teams to answer three open-ended problems by designing and implementing an experiment and analyzing their collected data. For each problem, the students are expected to articulate their experimental approach and results through oral presentations and a written scientific report.

In Fall 2010, a studio-style course on Professional Elements of Design was created to support the co-requisite Capstone Senior Design laboratory experience. The Professional Elements of Design course facilitates student skill development in articulating and documenting a design solution with short topical lectures and in-class activities that are performed within students' senior design teams[11, 12]. Coaching and fading were employed within this course and the associated capstone senior design laboratory. Additional details on the implementation of this vertical distribution of the cognitive apprenticeship pedagogy to teach experiment design are provided in the results section.

Data collection: Data collection and analysis procedures were approved by Purdue University's institutional regulatory board (IRB 1007009505). Data was collected from biomedical engineering seniors taking the Professional Elements of Design companion course to our senior design capstone laboratory. For this study, our experimental group consisted of 58 students that participated in the multi-year cognitive apprenticeship embedded within our required laboratories. Our traditional group contained 51 students who took the sophomore and junior level laboratory courses in their original, traditional laboratory format. Data acquired for the traditional group was collected from the 2010 course offering. Data acquired for the experimental group was collect from the 2012 course offering. Both the traditional (2010) and experimental (2012) course offerings were taught by the same course instructors. For both groups, students completed an in-class assignment that required the identification and description of a verification or validation test for their senior capstone design solution (Figure 2).

Data analysis: Using the rubric (Figure 2), student work was independently scored by two raters. On the rubric, raters gave a score of 1 if the item was articulated in student work and a 0 if it was absent from the work. Subset questions (alphabetical designation) were evaluated by raters only when a score of 1 was given to the main question (numerical designation). The percentage of students correctly addressing each item of the rubric was computed for both the traditional and experimental groups by each rater, and the difference between the traditional and experimental group percentages for each rubric item were computed. Differences in the percentages that exceeded 15% for rubric items and were independently identified by both raters were considered significant. Positive differences demonstrate an improved experimental design skill for the experimental group while negative differences demonstrate a lack of improvement by the experimental group, i.e. the traditional group performed at a higher level. Pearson's Correlation Coefficient was calculated to assess inter-rater reliability.

Verification/Validation Experimental Design Scoring Rubric

Experimental Method

1. ____ Was an experimental question was present?
    a. ____ Proposed experiment verified or validated the design solution?
2. ____ Should an independent and dependent variable be identified for the experiment?
    a. ____ Was an appropriate independent variable defined?
    b. ____ Was/were appropriate dependent variable(s) defined?
3. ____ Do confounding factors exist in this experimental design?
    a. ____ Were confounding factors identified?
    b. ____ Did the experimental design control for confounding factors?
4. ____ Should controls/baseline be used for this experiment?
    a. ____ Were appropriate controls/baseline identified for the experiment?
5. ____ Should a standard have been used in the experiment?
    a. ____ Was an appropriate standard cited?

Data Collection Process

1. ____ Was sample size presented in the protocol?
2. ____ Should this experiment have repeated samples?
    a. ____ Were repeated samples indicated in the protocol?
3. ____ Should this experiment have replicates?
    a. ____ Were replicates presented in the protocol?

Data Interpretation

1. ____ The type of data that would be acquired from the experiment was defined?
2. ____ The correct data analysis method was presented?

Figure 2. Scoring rubric used to score student experimental design abilities.

Results:

Implementation of cognitive apprenticeship: The sophomore-level laboratory course delivery format was modified in a manner to have the students repeatedly experience modeling and scaffolding with immediate instructor feedback. During the modeling phases students are provided an experimental question and follow step-by-step, experimental procedures. At the start of these laboratory sessions the instructor explicitly reviews the experiment design: they explain how the procedure will result in the production and analysis of data that will answer the experimental question. Following a modeling laboratory experience the students are challenged with an open-ended investigational question laboratory. During an investigational laboratory, scaffolding is used to encourage students to follow one pathway to a solution using previous knowledge. Prior to conducting their self-planned experiments, the experiment design is reviewed with instructors for immediate feedback and correction. The types of investigational questions explored at the sophomore-level promote the identification of dependent variable(s), an independent variable, positive and negative controls, and sample size. Additionally, the investigational question laboratories are intentionally constructed such that the appropriate data analysis would be either a student t-test or a one-way Analysis of Variance (ANOVA).

Table 1 illustrates a three stage modeling and scaffolding process in the sophomore-level laboratory around evaluating cellular responses to biomaterials. During stage 1, the cell culture laboratory, students observe an instructor executing the steps required to grow and plate cells for an experiment. During the demonstration the instructor provides verbal explanations for the steps involved. Following the demonstration students repeat the process by following a step-by-step protocol. Instructors are present during the laboratory to provide correction and guidance. In stage 2, the cytotoxicity laboratory, students continue to refine skills learned at the previous stage by applying them in a new context. At this stage students have already acquired the knowledge on how to plate cells for an experiment; therefore, the modeling component for this laboratory is focused upon experimental design. The instructor provides in-depth reasoning citing examples in peer-reviewed journals and ISO standards for experimental design choices such as, cell type selection, cell to biomaterial plating ratios, amount of time to run the experiment, positive control, negative control, sample size, method to evaluate cell death, and how to analyze the data. Following the modeling component students follow an abridged laboratory procedure in which learned skills from stage 1 are omitted, thus, requiring the students to review previous work for the methodology. The third stage in this series, cellular response to biomaterials laboratory, requires students to create an experimental approach that will determine if the presence of a biomaterial elicits an inflammatory cellular response. To address this question students' are given the types of biomaterials and cells available for experimentation. Using this information students are expected to employ the research processes modeled in stage 2 to identify appropriate cell to biomaterial plating ratios, timeline to run the experiment, positive control, negative control, sample size, method to evaluate an inflammatory cellular response, and how to analyze the data.

This pattern of building skills and then challenging students to reinforce and adapt the skills is implemented a total of 3 times in the semester. In addition to the cellular responses to biomaterials challenge module, students complete challenge modules that explore biomechanics of human and rodent models, and mechanical properties of tissues and biomaterials. A term experimental design project is also included in the sophomore-level lab to help gauge how well the students have bridged the concepts learned in the challenge series modules. In the term project, students work in teams to identify a medical condition that can be treated with the use of a biomaterial. Once the medical condition and targeted biomaterials are defined students must design and implement experimental protocols to demonstrate the validity of their claims.

Table 1. **Example of the modeling to scaffolding process in the sophomore-level laboratory.**

Laboratory	Content	Modeling Component	Scaffolding Component	Nature of Instructor Feedback
Cell Culturing	Learn how to grow and plate cells	Students follow a protocol on how grow cells in a sterile environment		
Cytotoxicity	Learn how to plate cells to evaluate cytotoxic response to materials	Students are shown how to design experimental conditions, identify and create appropriate positive and negative controls, and mange experimental errors related to reliability and repeatability issues	Students are provided with a standard cytotoxicity assay. They must adapt, plan and conduct the cytotoxicity assay to determine cellular response to biomaterials.	Students verify with instructors prior to experiment cell plating densities and experimental and control conditions.
Cellular Response to Biomaterials	Develop and employ a method to determine if a cellular inflammatory response is elicited when macrophage are cultured in the presence of different types of biomaterials		Students must design an experiment that combines skills and protocols learned in the cytotoxicity lab.	Students verify experimental design with course instructors prior to starting experiment. They must be prepared to defend their choices.

For the junior-level laboratory, instructors designed course materials and assignments to align with the scaffolding and coaching components of the cognitive apprenticeship model (Table 2). As such, the course consisted of three experimental design modules in which the scaffolding (guiding details and prompts) provided by course instructors within the problem statement were progressively reduced over the semester (Table 3).

During the second week of each module, each team orally presents their experimental plan and receives feedback from instructors. Student teams modify their experimental design to address the feedback and follow-up with an informal meeting with the instructors to discuss their revised experimental design. Informal coaching continues during the experiment implementation and data analysis phases of the module in order to guarantee a good experimental design is being implemented. To reinforce prior concepts from the sophomore year, a primer on experimental design was presented in the first lab session[13]. The types of investigational questions explored in this course reinforce prior concepts from sophomore year and introduce (1) the concepts of confounding variables, (2) the use of mathematical models to refine bench top experimentation, and (3) the identification and formulation of appropriate experimental questions from a problem statement.

Table 2. Integration of cognitive apprenticeship into the junior-level Biotransport laboratory[10].

Laboratory Module	Content	Scaffolding Component	Coaching Component	Extent of Scaffolding	Reliance on Coaching
Mass transfer	Static and convective diffusion through gel	Students are provided with a brief problem statement and experimental question about which to design a study	Students present work to class and receive formal feedback from instructors; instructors interact with teams throughout module to ensure correct methods are employed	High	High
Pharmacokinetics	Acetaminophen distribution in body; compartmental modeling			Moderate	High
Heat transfer	Freeze/thaw process for cryopreservation			Low	Moderate

Table 3. Progressive reduction in scaffolding in junior-level laboratory module prompts.

Module	Problem Statement
Convective Diffusion	Understanding how diffusion works is important when designing tissue engineered constructs. Of particular interest is understanding the relationship between molecular size and diffusion, tissue density and diffusion, and convective and static conditions. To better understand both convective and static diffusion, you are asked to design experiments to investigate diffusion. You may explore other variables than the ones mentioned here, but first, get the instructors permission before proceeding
Pharmacokinetics	Your roommate has twisted his/her ankle, and the physician recommended maintaining an acetaminophen plasma concentration of between 8-10 mg/L to be effective. The physician provided your roommate with a prescription and directions for dosing; however, knowing you are a biomedical engineer, the physician challenged you to identify additional methods to achieve/maintain the specified plasma concentration. Please choose a route of administration, dosing amount, and schedule to achieve this goal.
Cryopreservation	What freeze/thaw procedure is best to obtain the most viable cells (3T3 fibroblasts will be used)?

Similar to the scaffolding component of this course there is a progressive reduction in the level of coaching provided by course instructors. For example, in the first module instructors provide answers to questions in regards to correctness of experimental design, supply availability, model parameters, etc. In the second module instructors reduce the level of coaching by encouraging students to define these parameters using literature resources and targeted key words. By the third module the level of coaching has been modified to motivate students to identify the problem and use literature resources to develop an experimental design to further knowledge on the topic.

Finally, in senior year, the evaluation of the ability of students to develop meaningful verification and validation experimental procedures occurred in the developed course, Professional Elements of Design, a companion course to our program's undergraduate Capstone Senior Design laboratory. The Professional Elements of Design course is taught in a studio-style format to allow for the implementation of short interactive lectures on course topics followed by immediate practice of each course topic with respect to the student's senior design project. While students completed the in-class assignment within their senior design teams, instructors circulated to address questions and concerns on the subject matter. Both the traditional and experimental groups participated in a studio-style learning format. For the traditional group, the course topics addressing experimental design occurred during weeks 8 and 9; while, for the experimental group, the course topics were covered during weeks 5 and 6 of the 16 week course. The experimental design topics covered in the course for both groups were definitions of verification and validation experiments and selection of appropriate statistical analyses. These topics were covered during the short lectures using a scaffolding approach through interactive example problems. Coaching was employed as the students worked in teams to independently develop a verification or validation protocol. The traditional group experienced additional scaffolding during the in-class activity time due to the instruction for specific design details embedded within the original course assignment, see Figure 3.

Traditional Group Assignment (Fall 2010)

Choose one of the design requirements of your project. Write an experimental protocol that will verify or validate that your project meets that requirement by addressing the following:

- What are you trying to verify or validate with your protocol?
- How are you going to test this? (Outline the experimental groups, methods, control groups, tools, techniques, etc.)
- What kind of data will your test produce? (qualitative, quantitative)
- What statistical test will you use and how many replicates do you anticipate that you will need?
- What is your acceptance/rejection criterion?
- How will you determine if your protocol results are statistically significant?

Experimental Group Assignment (Fall 2012)

Provide a description of a detailed testing plan for each subcomponent. Include question to be answered, test method and measured outcomes, test groups including relevant positive and negative controls, and gold standards, calibration, and statistical analyses. Cite relevant references to justify your choices for specific methods.

Figure 3. Experimental design assignments for the traditional and experimental group.

Coaching and fading were employed in the Capstone Senior Design laboratory. Verification and validation experiments are an expected component of student's senior design project and documentation. For all project teams, instructors reviewed and provided feedback on at least one experiment within a coaching capacity but the majority of the experiments for the design verification and validation were planned and completed independently by the student teams. Thus, the laboratory predominantly uses a fading phase as instructors are available for consultation but did not actively evaluate experiment designs prior to students completing their experiments unless explicitly asked.

Evaluation of the cognitive apprenticeship approach: Data collected in the Fall 2012 senior capstone design experience reflected the experimental design abilities of the first class of students to experience the multi-year cognitive apprenticeship (experimental group). Table 4 shows the level of improvement based on the average of two independent reviewer's scores (in percent for each group). Positive values in Table 4 indicate the experimental group performed better than the traditional group while negative values indicate the traditional group performed at a higher level. Data indicated that the experimental group demonstrated a higher competency on four components from the rubric (Table 4).

Table 4. Assessment components with significant performance differences between the experimental and traditional groups.

Experimental Design Question	Improvement (%)	Inter-rater reliability
Identified independent variable	19.0	Pearson correlation coefficient = 0.95 (p=0.015)
Identified appropriate controls	33.0	
Used and cited published protocols	17.6	
Indicated appropriate repeated samples	-14.4	
Appropriate statistical analysis	16.8	

Discussion:

This study examines the usefulness of a multi-year cognitive apprenticeship instructional approach to enhance the students' knowledge and skills in experimental design. We are specifically exploring the impact of this approach on the ability of students to design a meaningful verification or validation experiment with respect to their capstone senior design project. Figure 1 shows the progressive increase in experimental design skill from sophomore to senior year through the integration of a cognitive apprenticeship process.

To assess the impact of a multi-year cognitive apprenticeship on student ability to design verification and validation experiments student work collected in the senior-level Professional Elements of Design course was evaluated using a modified version (Figure 2) of the EDAT rubric[9]. The rubric adaption permitted the evaluation of a broader class of experiments that were not constrained to those defined by independent and dependent variables: our data indicated that approximately 20% and 30% of the student derived verification and validation experiments from the traditional and experimental groups did not involve an experiment that required independent and dependent variables, respectively. Also, it was important that the assessment rubric evaluated the significance of the proposed verification or validation tests to ensure they provided meaningful results that supported the students' design project.

Both traditional and experimental groups were exposed to the same concepts in sophomore- and junior-level laboratory courses. In these experiences, students learned about independent and dependent variables, experimental controls, the importance of sample size, and common statistical analysis techniques. Therefore, the difference between the groups was in the delivery format of instructional information. It was expected that success would be demonstrated by both groups for most of the experimental design questions, excluding more complex issues of confounding factors. Since the experimental group participated in an inquiry-based laboratory course, we anticipated that they may exhibit some enhancement of their experiment design skills since this instructional format has been shown to positively affect investigational design and analysis skill abilities of students[14, 15]. This hypothesis was supported by our data analysis presented in Table 4. Each of these significant differences is discussed in more detail below.

Due to the experimental group's inquiry-based learning experience, it was anticipated that the group would perform at a higher level. For identifying published protocols, the experimental group scores averaged 17.6% better than the traditional group which was expected as the experimental group's inquiry-based experience required them to self-identify experimental protocols. In addition, the experimental group demonstrated improvement, 19%, on identifying the independent variable in an experiment and in identifying appropriate experimental controls (positive, negative, or baseline), 33%. Gains of these magnitudes were unexpected because both groups, traditional and experimental, had been exposed to conducting experiments in previous laboratory settings. However, the traditional group was not required to self-identify experimental conditions only employ predefined laboratory exercises. In contrast, the experimental group was required in an inquiry-based laboratory to self-identify experimental conditions and employ experimental controls. The process of learning to self-identify experimental controls requires a student to fully understand what is being tested and the purpose of a control. The improvement shown by the experimental group suggests that self-responsibility introduced in the inquiry-based laboratory enhanced the understanding and self-identification of experimental conditions and controls.

Identifying an appropriate statistical analysis for the experiment was another area of improvement for the experimental group, 16.8%. Both the traditional group and the experimental group had been exposed in previous laboratory courses to standard statistical analyses, mainly t-tests and ANOVA. The traditional group's exposure consisted of performing analyses on experiments conducted from a predefined laboratory exercise while the experimental group who participated in the inquiry-based laboratory designed their own experiments and determined an appropriate statistical analysis for the experiment. The traditional group relied highly on previous experiences as most laboratory exercises dealt with t-tests or ANOVA. However, the experimental group during the junior-level inquiry-based laboratory discussed experimental designs and the associated statistical analyses with the instructional staff; this coaching reinforced statistical concepts, such as MANOVA and factorial design. After interacting with the instructional staff, most students in the experimental group due to time constraints chose to focus their experiments and did not perform full factorial experiments; however, the ideas and purpose of those designs had been introduced, which is in contrast to the traditional group. For analyses requiring categorical data, both the traditional and experimental group were introduced to typical analyses during the Professional Elements of Design course; few students, if any, had previous experience with analyses of categorical data. The improvement shown by the experimental group in identifying the appropriate statistical analysis and in presenting better refined analysis techniques indicates a continued positive trend in improved experimental design skills.

The experimental group demonstrated improvement in all analyzed areas except indicating repeated samples, -14.4%. This lack of improvement is not due to the experimental group incorrectly indicating the need for repeated samples; instead, many students in the experimental group failed to mention sample size when compared to the traditional group. The exercise for the traditional group (Figure 3) was a step-by-step short answer (high level of scaffolding) in which one question focused on sample size. The exercise for the experimental group was a less instructive (low level of scaffolding) and asked the students to provide their experimental design plan and statistical analysis (Figure 3). Regardless of the difference in exercise format, the decreased performance indicates that instruction on inclusion of sample size and collection in a statistical analysis protocol should be further emphasized and iterated in order to foster the transition from novice to expert[16].

While gains of greater than 15% improvement were shown in the four areas discussed (independent variable identification, experimental control identification, published protocol identification, and appropriate statistical analysis), confounding factors identification, which did not meet our threshold for marked improvement, did show modest gains in the experimental group. Understanding the effect of confounding factors in an experiment is important and can make the experiment more robust which ultimately affects the experimental results. However, this topic leads to more complex experimental designs (blocking experiments, factorial designs, etc.) and is rarely covered outside of Design of Experiment courses, to which few students are exposed at the undergraduate level. While the traditional group had not been exposed to any discussion on identifying and controlling for confounding factors, the experimental group was briefly exposed (one laboratory lecture in the junior-level inquiry-based laboratory) to identifying and accounting for confounding factors. Reviewer scores on confounding factors indicate an improvement in the experimental group which is likely due to topic exposure in the Biotransport laboratory. Consequently, while the format of the junior-level component of this cognitive apprenticeship model promotes the development of rudimentary interpretive knowing of experimental design[6], the data suggests that more opportunities should be experienced to reinforce this skill. Therefore, more instruction on confounding factors and abilities about which to control for them needs to be presented. Additional instructional modules on confounding factors in experimental design have been developed and will be implemented using modeling and scaffolding phases in the junior-level Biotransport laboratory[17].

Most individuals learn through practice. Experimental design skills are no exception. Even at the expert level, the ability to solve a problem is an evolving skill, and continual practice is the best option to help students build their skills[3, 18]. Students need to learn skills in order to be able to perform more complex experiments, but perhaps introducing inquiry-based learning earlier (for instance, at the freshman or sophomore level) would allow for introduction of more complex experimental design topics (including confounding factors) at the junior level. Each of these practices would allow students to gain multiple experiences with experimental design on different topics which further enables each student's understanding of key topics in experimental design and how to employ the skills in different settings.

In addition, integration of experimental design skills throughout the curriculum will allow students to practice retrieval[19, 20], which has been shown to enhance long-term learning. Long-term learning and application of experimental design skills is essential for a biomedical engineering career. Options exist and are being explored to provide more modeling opportunities at the sophomore-level laboratory to help engage experimental design choice reasoning.

To further prepare students for a biomedical engineering career, students need to learn experimental design in the context in which it will be used, situated learning[21]. Situated learning has been shown to enhance student's performance, particularly in project work, when compared to traditional instructional methods[22]. Learning the statistical information in the context of a lecture course is insufficient; few, if any, homework sets allow for practical employment of statistical principles.

Conclusions:

Our study indicates that the use of a multi-year cognitive apprenticeship model was effective at enhancing student ability to develop verification and validation experiments in their senior capstone design experience. Furthermore, the assessment of student experimental design skill ability identified instructional areas of improvement to facilitate student learning experiences. Our results suggests that experimental design needs to be incorporated throughout a curriculum to allow students to practice the skills in real-world projects and to continually practice and retrieve previously learned information to further solidify the knowledge gain. Therefore, to enhance our students' experiences and allow us to further assess our techniques, we are in the process of implementing a longitudinal study that will allow us to evaluate the building of student knowledge and skills through the individual cognitive apprenticeship phases.

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