Do we see within-subject change?
Four cases of engineering student design processes

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Abstract

Engineering design is a key facet of engineering practice and engineering education. Our goal in improving engineering education is to understand what contributes to design knowing and learning. Our study focuses on changes in student design processes over time and explores this issue through a within-subject experimental design. Eighteen engineering students solved three engineering problems as freshmen and later as seniors; the students provided a verbal protocol while doing so. We present case studies of four students who represent four distinct patterns of change in design process based on our analysis of these 18 verbal protocols. This work contributes to design research community efforts to understand the nature of design cognition and design expertise.
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Introduction
Understanding design cognition represents an important direction for the design research community. Research questions involving design process, knowledge and communication strategies can and have been asked. Such fundamental knowledge of design is critical to those responsible for developing design education, designing tools that support design activity and creating design methodologies that work. Fortunately, much research already exists that sheds light on design cognition.

Frameworks for studying expertise provide a useful means for organizing much of that work. Ericsson and Smith provide one such framework in their 1994 book on expertise (Ericsson and Smith 1994). They identify three important elements critical to research into the nature of expertise (1) identifying tasks that will elicit the expert performance, (2) determining what contributes to expert performance by analyzing performance on the tasks, and (3) focusing on the acquisition of expertise (Ericsson and Smith 1994).

How far has the design research community come relative to this framework? In terms of the first element – identifying tasks that will elicit the expert performance – a variety of tasks have been used to probe design expertise. For example, researchers have asked participants to rate activities on a master list as important and unimportant in overall design activity (Newstetter and McCracken 2001) and identifying factors that they would take into account in solving a design problem (Bogusch, Turns and Atman 2000). In general, the most common task has been to have participants simply design a process or product relative to given requirements (e.g., design a bicycle, design a playground, etc.). Researchers have chosen tasks for their familiarity, their novelty, and/or their complexity. For example, Adelson and Soloway (1985) and Schraggen (1993) have conducted studies using tasks of varying levels of familiarity and complexity.

In terms of the second element, the design research community has also made clear progress in understanding the nature of expert design performance through research using the tasks described above and a wide variety of research design and data collection methods. For example, in a series of expert-novice studies, Atman and her colleagues found that more experienced designers as compared to less experienced designers (1) spent more time engaged in design, (2) had a different distribution of time across design steps (e.g., problem definition, data gathering, evaluation, etc.), (3) progressed farther in the design process (4) transitioned more frequently among design steps, (5) considered a wider variety of design criteria, and (6) created solutions of higher quality (Atman and Bursic 1996; Bursic and Atman 1997; Atman, Chimka, Bursic and Nachtmann 1999; Mullins, Atman and Shuman 1999; Atman and Turns 2001). Concerning progression, these findings suggest that more experienced designers utilize not only the earlier steps of the design process (e.g., defining the problem, analysis) but also those steps that come later in the process, such as making final design decisions and communicating that design (Atman et al. 1999). Moving up a level, Cross has comprehensively reviewed studies in which participants completed design tasks while providing verbal protocols (Cross 2001). In that review, Cross identifies problem formulation, solution generation, creativity, sketching, and opportunism as key areas where researchers have reported on expert design behavior.

The third element of the expertise framework, understanding the acquisition of expert design performance, represents one of the current challenges in research on design cognition. In contrast with the first two elements of the framework, little research has focused on understanding the
acquisition of design expertise. Issues in studying design acquisition include how processes change over time, what range of changes exist, and what types of processing of experiences contributes to growing design expertise. Fortunately, the existing research on design cognition provides a good foundation for understanding the acquisition of design expertise.

In this paper, we present data that contributes to understanding the acquisition of design expertise. Our contribution stems from a within-subject study of student design abilities using a verbal protocol analysis methodology. Specifically, we have analyzed the design behavior of specific engineering students at different points in time (at the beginning and at the end of their course of study). This within-subject approach allows us to gain a deeper understanding of the change in design processes within specific students. Our goal is to explore the general question of how individual student design ability changes over the four-year period of an education in engineering. Our questions include:

- What does change look like for individual students?
- Do all students exhibit a change in design process?
- Is an individual student’s change in design process consistent across different problems?
- Is an individual student’s change in design process consistent across different measures of design performance (i.e., time spent, number of transitions, and progression)?
- Can various patterns of change be identified?

The paper is organized as follows: in the next section, we describe our experimental design, data collection methodology, and analysis approach. In the subsequent results section, we present both summary results concerning the patterns of change that we identified and case studies illustrating each of the change patterns. The discussion is devoted to addressing each of the above questions in light of the results.

**Method**

Our current study of engineering student design processes uses a within-subjects design. Eighteen subjects participated as freshmen and then later as seniors. We also collected data from an additional 14 freshmen and 43 seniors so that we could address issues such as pre-test effects and the extent to which the within-subject participants represent the entire population of engineering students. This paper focuses only on the within-subject data.

**Part one: Problem definition and data collection**

Each participant was asked to complete three problems and to provide a concurrent verbal protocol (a “think-aloud” protocol) while completing the problem. In the first two problems, participants were asked to design a solution for a stated set of requirements. The first problem asked the participants to design a ping pong ball launcher that would function as part of a game. This problem, which we refer to as the “Ping Pong Problem”, was stated as follows: “In an attempt to avoid boredom at Benedum Hall, creative engineering students developed a challenging new game. A ping-pong ball is to be launched at a bullseye target, and points are awarded according to the accuracy of the landing. However, the ping-pong ball cannot be thrown at the target. It is up to you to design a device which will lift the ping-pong ball into the air and land it at the target. An accurate landing is desired while also maintaining a long flight time. Given that the center of the landing area is 5 meters away from the launch site, and the entire launching assembly must not be greater than 1m x 1m x 1m in dimension, design a ping-pong ball launcher for this game.”

In problem two, participants were asked to design a method for crossing a busy street at their university. The “Street Crossing Problem” was selected so that the participants would be more familiar with the context of the problem, and thus possibly utilizing a different design process. It read: “College campuses are often overcrowded with pedestrians crossing the streets, since walking...
is a popular form of transportation for college students. One busy intersection at Pitt is the crossing of Fifth Ave. in front of the bookstore. Dangers at this intersection include heavy traffic and busses which run against the general traffic flow. The University would like to design a cost effective method to cross Fifth Ave. which would reduce the possibility of accidents at this intersection. Your work should contain a detailed description of your design and should include any relevant diagrams and calculations. Estimate both the costs and the benefits associated with your design. Please clearly state all assumptions which are needed in your analysis and try to keep your design simple yet effective.”

The third problem asked the participants to identify important factors to be addressed in designing a retaining wall for the Mississippi River. The results of this analysis are presented in (Rhone, Atman, Turns, Adams, Chen and Bogusch 2001).

**Part Two: Analysis of product and process data for each problem**
We analyzed the participants’ products and processes for each problem. To assess the product quality, two scorers evaluated the solutions to each problem using a rubric developed by a team of five engineering professors. The scorers first classified each solution (e.g. bridge, tunnel, crossing guard) and achieved an inter-rater reliability level of 93%. They then applied the appropriate rubric to the solution. For this portion of the scoring they agreed at a 94% inter-rater reliability level. To explore design process, we analyzed the protocols provided by the students as they solved the design problems. To do this, the protocols were transcribed and then segmented into idea units. Two coders then independently coded each segment according to a coding scheme representing steps associated with design activity. The coded design activities were: problem definition (PD), gathering information (GATH), generating ideas (GEN), modeling solutions (MOD), feasibility analysis (FEAS), evaluation of alternative solutions (EVAL), making decisions (DEC) and communicating the design (COM). After coding a transcript the two coders met to compare results, record the initial reliability of the coding and, if an initial 70% reliability level was met, negotiate disagreements to consensus. If the initial inter-rater reliability level for a transcript was below 70%, the transcript was recoded. The coders achieved an average reliability of 81% on the Ping Pong problem protocols and 83% on the Street Crossing protocols.

We entered the codes into a software package called MacSHAPA (Sanderson, Scott, Johnston, Mainzer, Watanabe and James 1994). Using the software we then printed timelines of the coded data for each of the subjects. This enabled us to compare how different subjects spent their time. Example timelines are included in Figure 1 in the results section.

**Part Three: Classify subjects in terms of extent of change**
By comparing the timeline representing the freshman performance to the timeline representing the senior performance, we investigated changes in participants’ design processes. In a number of the comparisons, we observed a multifaceted pattern of change in that the senior performance differed from the freshman performance on a number of dimensions (e.g., number and frequency of transitions, extent of progression to the later design activities, and amount of time spent solving the problem). We called this pattern simply “change.” In other cases, the process changed but primarily because the amount of time increased dramatically. We labeled this pattern “more of the same.” We also noticed instances where the senior design process looked remarkably similar to the freshman design process. We labeled this pattern “no change.” Finally, for one participant we noticed a pattern of “simplification,” characterized by fewer design activities or fewer and less frequent transitions in the design timelines provided by the participant as a senior. The quality of product score was not used in this classification of change.
Using these four categories of change, we categorized each freshman-senior pair of timelines. Because our data consists of 18 subjects each solving two problems, we ultimately categorized 36 pairs of timelines. The process of categorization began with four coders classifying each pair of timelines. The initial inter-rater reliability was 72%. We arbitrated the cases where only one coder disagreed (three of the four coders had assigned the same category) by negotiating the coding until consensus. For the other cases, two coders reclassified the timelines and then discussed them until an agreement was reached on the classification.

### Results

Table 1 shows the distribution of participants in the change categories. In the table, C represents change, M represents more of the same, N represents no change, and S represents simplification. As the data in the table suggest, we found that the design processes of most participants changed from the freshman to the senior year. We also found that some participants displayed change on one problem but did not display change on the other. We identified only one instance of simplification.

In the remainder of this section, we illustrate the patterns of change through case studies. Figure 1 presents results from four participants that illustrate each of the four patterns of change. The freshman results are presented on the left and the senior results are presented on the right. In addition to including the timelines, the figures include actual values for the quality score (maximum score is 3.618), the number of transitions, and the total time engaged in design. All timelines in Figure 1 represent participant performance on the Ping Pong problem.

#### Case study 1: Change

The timelines in Figure 1a represent a participant whose senior design process differs from the freshman design process on many dimensions. The participant as a senior (a) received a higher quality score, (b) spent more time solving the problem, and (c) had more transitions among design steps. Additionally this participant as a senior progressed farther into the design process, specifically by spending much more time addressing issues of feasibility and spending some time in the decision and communication steps. While the amounts of time that this participant spent in the final two steps was very small it is still notable that the participant reached these steps. Only 16% of the participants from the full dataset spent time in decision, and only 15% spent time in communication. For these participants who did spend some time in these steps, the average amount of time spent in decision was 11.5 sec and the average amount of time spent in communication was 6.6 sec. Finally, the participant for Case Study 1 also demonstrated explicit “generating” (GEN) behavior, behavior that was absent from the freshman design process.
Case study 2: More of the same
The timelines in Figure 1b represent a participant who spent dramatically more time as a senior, but whose design process did not seem qualitatively different from his/her process as a freshman. In looking at the figure, we see that this participant as a senior (a) received a slightly higher quality score, (b) spent more time solving the problem, and (c) had more transitions among design steps. However the frequency of transitions did not change. Additionally, this participant did not progress any farther into the design process. It is as if this participant is simply repeating the same general process used as a freshman, but spending much more time.

Case study 3: No change
The timelines in Figure 1c represent an instance of no change. As a senior this participant (a) received a higher quality score, but (b) spent the same amount of time solving the problem, (c) had the same number of transitions among design steps, and (d) did not progress any farther into the design process. Concerning the progression finding, the participant displayed more feasibility behavior as a freshman than as a senior but displayed more gathering behavior as a senior than as a freshman.

Case study 4: Simplification
The timelines in Figure 1d represent an instance where the design process seems to have simplified over time. We note that the participant as a senior (a) did receive a higher quality score and (b) spent more time solving the problem, but (c) had fewer transitions among design steps, and (d) did not progress any farther into the design process than he/she had as a freshman. While the participant displayed more decision behavior as a senior than as a freshman, the participant also displayed more evaluation as a freshman than as senior. Overall, the participant spent time in more design steps as a freshman than as a senior.

Discussion
Our over-arching goal is to understand what contributes to design knowing and learning in engineering. With our current study we are trying to understand the acquisition of design expertise in engineering students. Earlier we identified several specific questions that interest us. Based on our results, we offer some tentative answers.

What does change look like for individual students? These results suggest that change may look quite different for individual students. In our analysis, we found that five participants’ design processes changed on multiple dimensions on our first problem while eleven participants’ design processes showed this kind of change on the second problem. We were also able to distinguish three other patterns for characterizing freshman to senior change in design processes.
Figure 1: Example Timelines Illustrating Patterns of Change. From top to bottom, the figures illustrate (A) change, (B) more of the same, (C) no change, (D) simplification. In these timelines, the x-axis represents time and the y-axis corresponds to design activities used in the coding scheme. The location and width of each tick mark indicates the starting time and duration of an activity, respectively.
Do all students exhibit change in design process? Twelve of the eighteen participants displayed multi-dimensional change on at least one of the two problems, and most participants had some form of change. We are intrigued by the one instance of simplification. However, we also found that three participants had design processes characterized as “no change” for both problems.

Is individual student change in design process consistent across problems? These results suggest that design performance may be different across design problems, and also that change may differ across problems. As Table 1 shows, half of the participants displayed the same pattern of change for each problem while the other half had different patterns of change across the two problems (for example, participant M displayed a pattern of “more of the same” on both problems whereas participant F displayed two different patterns—“more of the same” on Ping Pong and “change” on Street Crossing). This is consistent with our analysis of the full dataset (all 65 participants). For example, we found that more students engage in evaluation behavior on the second problem than on the first (Cardella, Atman, Adams and Turns 2002).

Is individual student change in design process consistent across different measures of design performance? In our work, we have used a variety of measures to characterize design performance. These measures have included final quality, total time, number of transitions among design steps, and progression to later stages of design. As our coding scheme suggests, student change may not be uniform across these different measures. For example, in the instance of “more of the same” described in case study 2, the participant’s performance changed in terms of quality score and amount of time spent on the problem, but not in terms of complexity of the process. These results suggest that the different measures may provide different insights into change in design ability.

Can various patterns of change be identified? As our coding scheme illustrates, it is clearly possible to identify various patterns of change. Our codes of “change”, “more of the same”, “no change” and “simplification” represent such patterns. In our upcoming work, we will be gaining increasing precision with such efforts to categorize and characterize the change exhibited by these subjects. This work will put us one step closer to understanding what contributes to the acquisition of design expertise.

Concluding remarks
This study attempted to characterize levels of change in engineering design expertise. We see this as a first step in understanding the acquisition of design expertise. We saw that most students acquired some expertise as a result of their engineering education as evidenced by change in their design process behavior. We were able to answer our initial questions regarding change and identified features associated with skill acquisition in design—an increased amount of time devoted to solving the design problem, an increase in number of transitions between design activities, progression into the latter steps of the design process and an increase in product quality. These features are consistent with our findings from previous studies.

The results from this study suggest the need to unpack overall change into compact dimensions for further analysis. We still need to address the question of why some students exhibited change on some measures but not on others. Another question that is raised is how some students were able to invoke a sophisticated design process as part of their freshman performance. How did some students acquire some level of expertise prior to their engineering education?

While the current analysis does not clarify how an engineering education may have contributed to the acquisition of design expertise, we have shown that student design processes do change after that education. As future studies further explore the acquisition of design expertise, we may begin to see the answers to these questions.
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