Characterizing Engineering Student Design Processes: An Illustration of Iteration

Robin S. Adams, Cynthia J. Atman
Center for Engineering Learning and Teaching
College of Education / Industrial Engineering
University of Washington

Abstract

Engineering design problems are often ambiguous, ill-structured, and usually have multiple solutions. As a result, a designer's understanding of the problem or possible solutions evolves through a process of iteration. To understand iterative behaviors we need to investigate what information is known by the designer, how that information is acquired and utilized, what kinds of changes to the design problem occurred as a result of these activities, and how these behaviors affect the quality of the final solution and contribute to the efficiency of the design process itself. In our previous work, we developed a cognitive model for capturing both the evolution of these information processing activities and any changes made to the design problem, solution or process. In this paper we present a case study analysis comparing freshmen and senior engineering students. Verbal protocol data and independent measures of the quality of students final design solutions were used to provide illustrative examples of differences in iterative approaches related to experience and performance. An analysis of these behaviors in terms of problem scoping, solution revision, and comprehension monitoring activities will be presented and discussed.

I. Introduction

To compete in an increasingly global economy, the education of tomorrow's engineers emphasizes the solving of open-ended engineering design problems. This theme is evident in the growing level of collaboration among accrediting agencies, industry, and federal funding agencies to support research on the assessment of student learning, and to encourage excellence in curriculum and pedagogy that provide an exposure to engineering practice[1-3]. Also, the implementation of the new ABET EC 2000 criteria[4] makes it necessary for engineering programs to identify, assess, and demonstrate evidence of design competency. Before more effective instructional strategies can be implemented and assessed there is a need to better understand design problem solving behavior.

Engineering design problems are often characterized as ambiguous, ill-defined, and having multiple solutions that can satisfy a problem's requirements. As a complex and often data-driven behavior[5], engineering design differs from mathematics or science problem solving in three primary ways: design is a goal-oriented activity[6], the "stopping point" is neither systematic or definitive, and the process is repetitive in which the designer incrementally advances upon a particular solution[6-7]. As a result, a designer's understanding of the problem or possible solutions evolves through a process of iteration. Iteration is considered to be an integral feature of the design process, and is often a symbolic feature embedded in design process models as loops, cycles and spirals.

The utilization of a cyclic iterative design procedure is believed to increase the efficiency of the design process and lead to better quality solutions[8]. In one study it was found that adopting a systematic and iterative design sequence correlated with the effectiveness of the design product and the efficiency of the designer's process[9]. Similarly, in a large scale study of freshmen and senior design problem solving behavior it was found that seniors had more transitions between design steps, a higher number of transitions per minute, and that transition behavior related positively to the quality of the final design[10]. These studies suggest that iterative behavior may contribute to performance and may be an attribute of expertise.

Previously we developed a cognitive model to operationalize iterative behaviors based on our understanding of how designers transition through steps in the design process[11]. The focus of this paper is to identify how iterative behaviors may contribute to performance. We will provide some illustrative cases of iterative behaviors in engineering design problem solving, and describe how these behaviors may effect the quality of performance. Research on iteration in design problem solving can contribute to our understanding of cognitive processes in design, the assessment of design competency, and help identify more effective instructional tools and pedagogical approaches to teach design.

II. From Transitions to Iterations

Our research questions were motivated by two findings from a large research study comparing engineering freshmen and senior design behaviors[10]. In this study it was found that seniors transition through the steps of the design process significantly more frequently than do freshmen, and that the amount of transitioning was positively related to the quality of the final design. These findings suggest that transition behaviors play an important role in characterizing effective design behaviors. However, it is difficult to develop recommendations for teaching design based on these findings. We don't want to simply direct students to "transition more frequently"!

To understand how transition behaviors may be a measure of expertise and performance, it may help to think in terms of a *sequence* of transitions. Most models of the design process illustrate a sequential progression from clarifying and exploring the design task, to developing and selecting design solutions, to selecting and implementing a design solution[12]. Therefore, a forward sequence of transitions may be indicative of this natural progression of starting with problem scoping and ending with solution realization. On the other hand, a backward sequence of transitions (e.g., transitioning backward from developing solutions to clarifying the design task) may be indicative of what is commonly represented as iterative cycles in the design process. From our own experiences, we refer to these cycles as "another pass", "the next version", or even "starting over". These behaviors suggest that iteration can contribute to clarifying the design task, elaborating design specifications, and refining design solutions[13].

In other words, iterative activities mark a progression through levels of understanding as the designer discovers and responds to new information about a problem or solution. For example, an initial understanding of the problem is not static, but rather reflects the current understanding at that point in time. As a designer searches for and clarifies information about the problem, the designer gains insight that informs the previous conception of the problem. This new understanding may help in the generation or refinement of possible solutions. Therefore, our research was guided by two goals: 1) to develop a model for operationalizing iterative behaviors based on what we know about transition behaviors, and 2) to utilize this model to analyze how iterative behaviors may contribute to performance.

III. Operationalizing Iteration

In an earlier paper we described a model for operationalizing iterative behaviors in cognitive terms[11]. Cognitive models of design problem solving represent how people perform an activity in terms of functional mechanisms or tasks that constitute a skill[14]. These models emphasize that learning is central and inherent to designing. To develop the model, our first task was to synthesize research on complex problem solving in engineering design and other domains to create a working definition of iteration. This working definition would be the foundation for creating the categories for coding verbal data. For our purposes, we defined iteration as: "a goal-directed process that utilizes reasoning processes and strategies to gather and filter information about the problem, monitor progress, and inform the revision of possible solutions"[11]. There are two important features embedded in this definition.

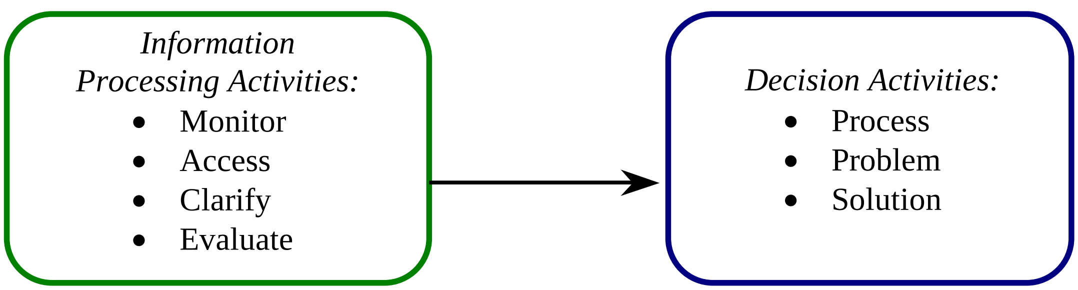


Figure 1. Transition behaviors in design problem solving.

First, it describes iterative behavior as a goal-directed sequence of transition behaviors. Here, goal-directed refers to the purposeful progression through stages of the design process to address or specify design objectives. Secondly, the definition separates transition behaviors into two activities. The first is an information processing activity, and the second is a decision activity (Figure 1). Information processing activities describe how information is being accessed, utilized and generated. Examples of these activities include accessing information about design requirements, monitoring progress, clarifying and examining key design objectives, and verifying how a solution meets design requirements. Information processing activities may be used to justify decisions for making a change to a design state. As seen in

Figure 1, specific activities such as monitoring, accessing, clarifying and evaluating represent coding categories for information processing behaviors.

Decision activities capture what kinds of changes were made to a design state. Therefore, coding categories include changes to a design plan, the problem representation, or a solution representation. These are goal-directed decisions based on utilizing information. Examples of decision activities include redefining a design constraint, modifying a solution to improve performance, and identifying and scheduling design tasks. Both information processing and decision activity codes are described in detail in reference (11). Together, these activities provide a means for measuring transitions behaviors as a function of the number of and amount of time engaged in information processing and decision activities. Similarly, iterative behaviors can be operationalized in terms of the number, kind, and sequence of transition behaviors.

IV. Method

This analysis is part of a larger study of iterative behavior in engineering design problem solving. The research design for this phase of the study has three distinct features regarding the type of research, the sources of data, and the kinds of analyses. The research method for this phase is an exploratory analysis of verbal protocol data to identify and code transition behaviors. In verbal protocol analysis, subjects think aloud as they perform tasks, providing the researcher with rich and detailed data that can be used to describe and empirically analyze problem solving behavior[15]. Verbal protocol studies have been successfully utilized to identify how designers introduce information or knowledge into the design process[16], to quantify differences in approaches[10, 17], and to measure the effectiveness of teaching methods[18].

Secondly, data for this study is drawn from a previous study of student design problem solving[10]. Freshmen and seniors were given three hours to complete an open-ended and complex playground design problem and were encouraged to request additional information from the experiment administrator. The verbal data has been previously segmented, time-stamped and coded for design step, design stage, what information the student is addressing, what the subject is doing such as reading or calculating, and what equipment the subject is working on such as a swing or a ladder. Time stamped transcript data were imported into MacShapa[19], a software program developed especially for the analysis of verbal data. Other data from this study includes an assessment of the quality of individual design solutions, and background information such as gender, age and expected major in engineering.

Finally, this analysis is a case study comparison of transition behaviors across different levels of experience and final design quality scores. For the exploratory phase of this study, 16 subjects (8 freshmen and 8 seniors) out of the original 50 were selected based on three variables hypothesized to be correlated with iterative behaviors: experience level, quality of final design, and the number of transitions. Transcripts were coded using the coding scheme and process described in reference (11). Utilizing this coding scheme provides opportunities to measure the number of information processing activities, the number of changes to a design state, and the time spent engaged in these activities. MacShapa timelines for these 16 subjects were categorized in terms of the amount of specific information processing and decision activities.

Based on these categories, three of the original 16 were selected as illustrative case studies of differences in problem scoping, comprehension monitoring, and solution refinement behaviors.

V. Results and Discussion

A summary of performance scores and the total time engaged in specific information processing and decision activities is provided in Table 1. The first case, Subject A, is a senior who frequently transitioned between steps in the design process, and received a high quality score for the final design. The second case, Subject B, is a senior who had a lower frequency of transition behaviors, and received a higher than average quality score for the final design. And the third case, Subject C, is a freshmen who had a very low frequency of transitioning behaviors, and received a lower than average quality score for the final design.

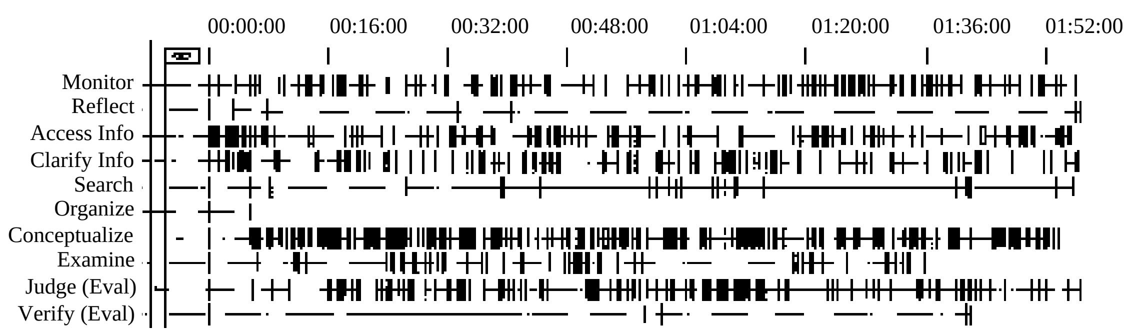
Table 1. Summary of performance scores and of time engaged in information processing and decision activities.

		Subject A	Subject B	Subject C
	Number of Transitions	*402*	*122*	*64*
	Quality Score	*.58 (High = .70-.55)*	*.47 (Med. = .54-.39)*	*.37 (Low = .38-.20)*
	Total Time (seconds)	*4694*	*5713*	*5998*
Monitoring	Self-Monitoring Activities (% time)	12.9	17.0	7.8
Monitoring	*Total Changes to Plan (% time)*	*6.5*	*12.7*	*2.3*
Problem Scoping	Problem Scoping Activities (% time)	30.8	3.6	22.4
Problem Scoping	Identify Problem Elements (% time)	1.7	2.0	1.3
Problem Scoping	Review Problem Elements (% time)	11.4	1.9	2.1
Problem Scoping	Elaborate Problem Elements (% time)	10.9	6.0	3.1
Problem Scoping	*Total Changes to Problem (% time)*	*24.1*	*10.0*	*6.5*
Solution Revision	Examining Activities (% time)	9.1	41.7	47.9
Solution Revision	Evaluation Activities (% time)	11.4	2.9	1.3
Solution Revision	Modify Solution (% time)	1.0	6.7	0.4
Solution Revision	Improve Solution (% time)	3.5	0.0	1.2
Solution Revision	*Total Changes to Solutions (% time)*	*4.5*	*6.7*	*1.6*

As portrayed in Table 1, these subjects are illustrative of different transition behaviors, as well as different levels of performance. Examining the data in Table 1, we can identify some significant differences in transition behaviors across subjects. First, both Subject A and B used more than ten percent of their total time engaged in self-monitoring activities. Monitoring activities are believed to aid comprehension, which may positively effect quality of performance[20]. Secondly, differences across subjects in terms of the amount of time engaged in clarifying, accessing and searching for information is quite diverse. Although subjects A and C exhibit similar levels of these problem scoping activities, Subject C made very few changes to the problem representation. In contrast, Subject B spent the least amount of total time engaged in problem scoping activities (3.6%), yet spent nearly three times as much time (10.0%) making changes to the problem representation. This trend suggests that Subject A may be a good example of effective problem scoping behaviors, whereas Subject B may be a good example of efficient problem scoping behaviors. In other words, Subject B utilized the amount of total time very efficiently to expand and elaborate the problem requirements.

The data on refining solutions is also quite varied. Subject A utilized more total time evaluating solution quality and completeness, and also spent more time improving solutions. In contrast, subjects B and C spent significantly more time examining their solutions, yet only Subject B exhibited a high level of solution modifications to address any design violations. These trends suggest that the quality of solution revisions may be related to the quality of self-monitoring and problem scoping behaviors. Overall, comparing the final quality scores to the transition behaviors data suggests that a high level of monitoring, problem scoping, and evaluating activities contribute positively to performance. To get a more complete picture of the level and frequency of these behaviors, we utilized MacShapa[19] to create timelines of information processing and decision activities.

Subject A: Information Processing Timeline



Subject A: Decision Timeline

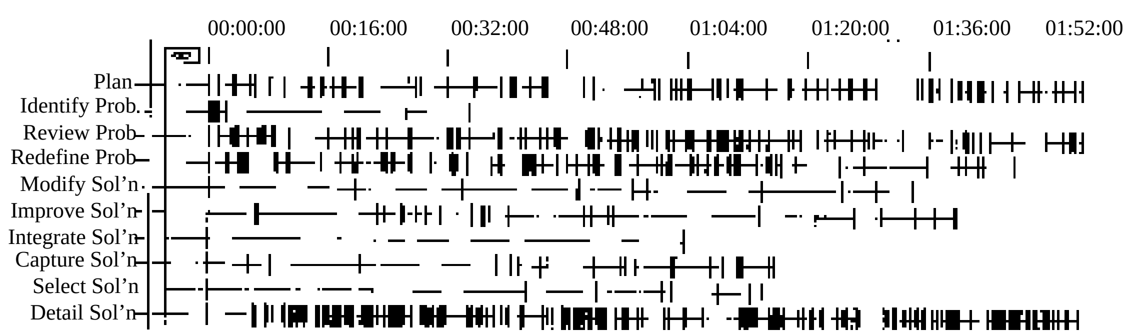


Figure 2a and 2b. Information processing and decision activity timelines for Subject A (senior, quality score = .58).

Figure 2a is the timeline for information processing activities for Subject A. The vertical axis of the timeline represent codes related to information processing activities, such as monitoring and clarifying information. The tick marks on the timelines signify when a student is engaged in a specific activity. Similarly, figure 2b is the timeline for decision activities for Subject A. Here, the vertical axis represents codes related to decision activities, such as redefining problem requirements, selecting or detailing solutions, and modifying solutions.

From figure 2a we can see Subject A displayed a number of behaviors believed to contribute to performance. First, there is a high and relatively constant level of the student self-monitoring their own progress. For this to be an effective activity we would hope to see, and we do see in figure 2b, a similarly high and constant level of planning. Therefore, Subject A is an example of strong monitoring behavior cycles such as setting and meeting design tasks, schedules, and reviewing progress. Subject A is also an example of strong problem scoping behavior cycles. In figure 2a we can see a high and constant level of accessing and clarifying information about the task. Similarly, in figure 2b we see a comparably high and constant level of identifying, reviewing and elaborating problem requirements. It is important to note that many of these problem scoping cycles are occurring throughout the design process in combination with solution revision cycles. In figure 2b we also see periodic cycles in which the student modifies and improves the design solution. These revision cycles are occurring over the duration of the design task, and not just at the end of the design process. This suggests that solution revision cycles early on in the process may be a result of strong problem scoping and monitoring skills.

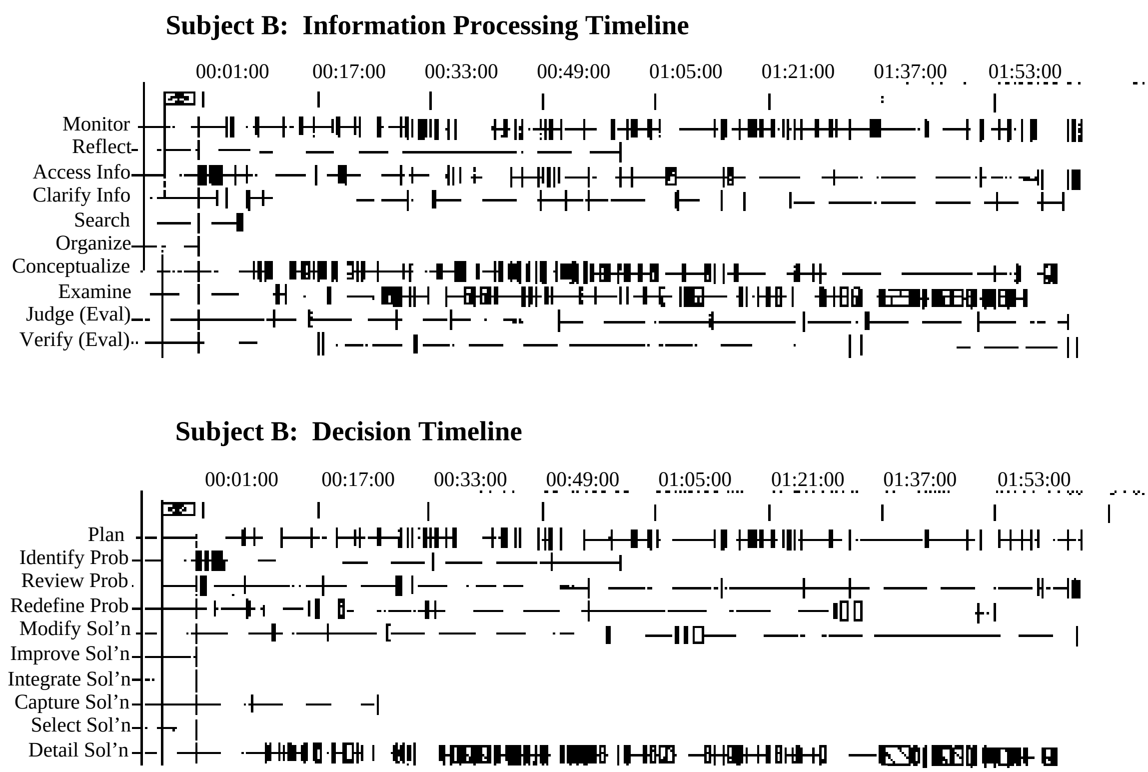
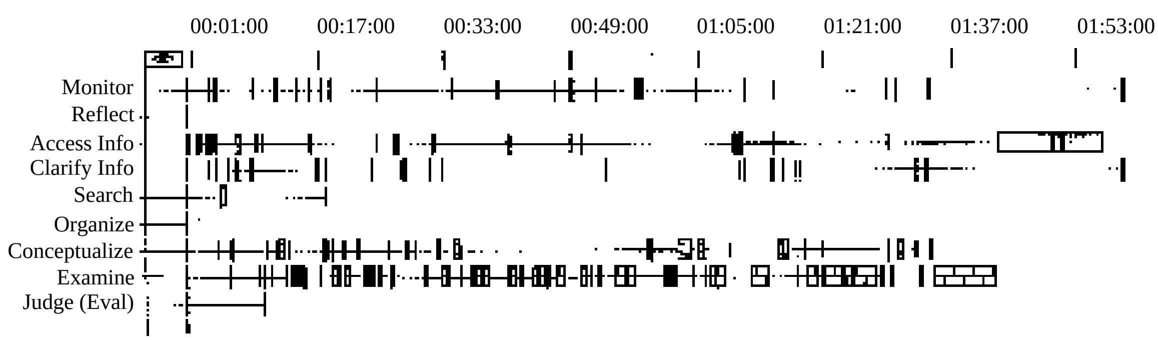


Figure 3a and 3b. Information processing and decision activity timelines for Subject B (senior, quality score = .47).

Figure 3a is the timeline for Subject B's information processing activities, and figure 3b is the timeline for decision activities. Visually comparing figure 3a to figure 2a we can see that although Subject B monitored their progress almost constantly this subject displayed a lower level of monitoring behaviors than Subject A. In addition, the level of activity between monitoring and planning activities for Subject B are comparable (see figures 3a and 3b). Like Subject A, this relationship is indicative of effective monitoring behaviors cycles. This suggests that both Subject A and B are similarly illustrative examples of good monitoring behaviors. Where Subject A and B differ most is in the level and kind of problem scoping behaviors. Given the low frequency of clarifying activities (see figure 3a), the timeline in Figure 3b suggests that Subject B displayed a more efficient use of problem scoping cycles. And finally, both Subject A and B reviewed the problem requirements at the end of the task to evaluate the quality of their solutions. And more importantly, both subjects incorporated solution modifications throughout the design task.

Subject C: Information Processing Timeline



Subject C: Decision Timeline

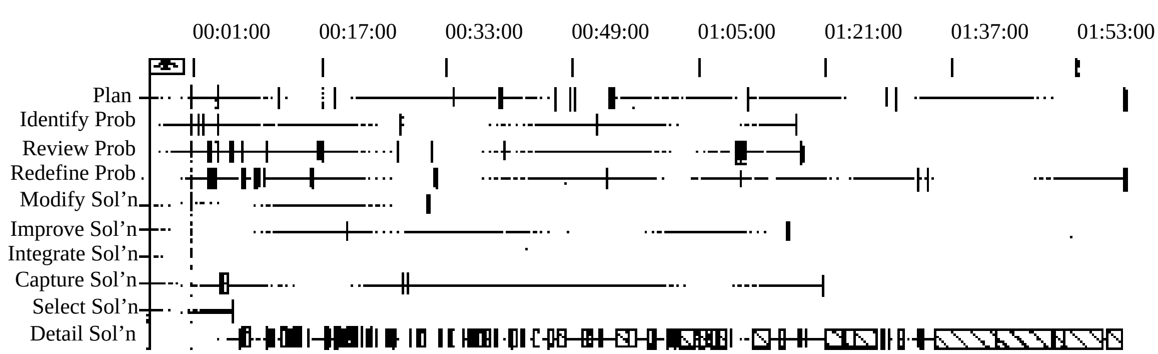


Figure 4a and 4b. Information processing and decision activity timelines for Subject C (freshman, quality score = .37).

Figure 4a is the timeline for Subject C's information processing activities, and figure 4b is the timeline for decision activities. In contrast to the behaviors illustrated in figures 2a and 3a, Subject C sporadically monitored their design progress. Similarly figure 4b illustrates very minimal and sporadic efforts to set and modify a design plan. These monitoring behavior cycles suggest that Subject C is an example of poor monitoring skills. In terms of problem scoping skills, Subject C exhibited a similar level of problem scoping activities as Subject B (see figure 3a and 4a), yet made only minor changes to the problem representation (see figure 4b). This low level of problem scoping cycles suggests that Subject C is also an example of poor or inefficient problem scoping skills. This behavior may be related to poor monitoring skills. And finally, unlike the other subjects, Subject C does not review the problem requirements upon completing the tasks. As a result, we see very few examples of evaluation-revision cycles that may effect the quality of the final solution.

VI. Summary

The kinds of transition behaviors illustrated by these three cases include both high and low levels of problem scoping, monitoring, evaluation and revision cycles. All of these aid the designer in comprehending the design task, the boundaries of the design problem, and the quality of the design solutions. The utilization of these cycles portrays either good or poor monitoring, analysis, evaluation and synthesis skills.

Comparing across the three cases, a high level of monitoring and problem scoping cycles seem to relate positively with performance--both in terms of effectiveness of the design and of efficiency of the design process. Differences between problem scoping cycles for Subject A and B suggest that a designer's efficiency in navigating the design process may relate with specific information processing or decision activities. One hypothesis of efficient behaviors would be interweaving problem scoping cycles with either evaluation or solution revision cycles. At the other end of the performance spectrum, a low level of problem scoping and monitoring cycles seem to relate strongly with poor performance. Also, the level and quality of solution revision cycles may be strongly associated with the level and quality of monitoring and problem scoping skills. And finally, the ability of the coding scheme to differentiate across various levels of performance and kinds of transition behaviors suggests that our model will be lucrative in terms of describing design behaviors and identifying effective guidelines for teaching design.

The data presented in this paper represent transition behaviors. We are still in the process of identifying how a collection or sequence of transition behaviors can be called an "iteration". Even so, the cases illustrated here can help develop some hypotheses about iterative behaviors. Iteration may be a diagnostic process that aids in defining and evaluating design tasks. As a diagnostic process, it provides a means for monitoring progress and comprehension of design tasks. And, iteration may be a transformative process that aids in integrating and synthesizing information. As a transformative process, it provides a means for generating new information. Both of these processes are indicative of monitoring, problem scoping and solution revision behaviors that may correlate with performance.

VII. Future Work

This work is part of a large empirical study of iterative behavior in student design problem solving. Currently we are in the exploratory phase of identifying and analyzing iterative behaviors. The purpose of the larger study is to empirically explore and identify iterative behavior in students' engineering design problem solving, and to develop a model for representing these activities in terms of (1) how these behaviors contribute to analysis, synthesis and evaluation skills, (2) how differences in these behaviors are related to expertise, and (3) how these behaviors may influence performance as a function of process efficiency and the overall quality of the final solution.

VIII. Acknowledgements

This research was made possible in part by the Engineering Coalition of Schools for Excellence in Leadership and Education (ECSEL), a National Science Foundation Engineering Education Coalitions program, National Science Foundation grant RED-9358516, as well as a grant from the GE Fund. We would also like to thank all of the students who participated in this study.

References

1. National Research Council, Engineering Education: Designing an Adaptive System, National Academy Press, 1995.
2. National Science Foundation, Restructuring engineering education: a focus on change, pp. 95-65, 1995.
3. American Society of Engineering Education, "Engineering education for a changing world", Engineering Deans Council and Corporate Roundtable of ASEE October, 1994.
4. Accreditation Board for Engineering and Technology, "Engineering Criteria 2000: Criteria for accrediting programs in engineering in the United States (2nd edition)", Engineering Accreditation Commission, Accreditation Board for Engineering and Technology, 1998.
5. Davies, S.P. & Castell, A.M., "Contextualizing design: Narratives and rationalization in empirical studies of software design", *Design Studies*, 13 (4), pp. 379-392, 1992.
6. Gero, J.S., "Design prototypes: A knowledge representation schema for design", *AI Magazine*, 11 (4), pp. 26-36, 1990.
7. Eekels, J. & Roozenburg, N.F.M., "A methodological comparison of the structures of scientific research and engineering design: Their similarities and differences", *Design Studies*, 12 (4), pp. 197-203, 1991.
8. Bucciarelli, L.L., Designing engineers, MIT Press, 1996.
9. Radcliffe, D.F., & T.Y. Lee, "Design methods used by undergraduate engineering students", *Design Studies*, 10 (4), pp. 199-207, 1989.
10. Atman, C.J., Chimka, J.R., Bursic, K.M. & H. L. Nachtman, "A Comparison of Freshman and Senior Engineering Design Processes," *Design Studies*, Vol. 20, No., 2, pp. 131-152, 1999.
11. Adams, R. & Atman, C.J., "Cognitive processes in iterative design behavior", *Proceedings of the Annual Frontiers in Education Conference*, Puerto Rico, 1999.
12. Pahl, G. & Beitz, W., Engineering design, Design Council Books, 1984.
13. Dym, C.L., Engineering design: A synthesis of views, Cambridge University Press, 1994.
14. Adelson, B., "Cognitive research: Uncovering how designers design; Cognitive modeling; Explaining and predicting how designers design", *Research in Engineering Design*, 1, pp. 35-42, 1989.
15. Chi, M.T.H., "Quantifying qualitative analyses of verbal data: A practical guide, *The Journal of the Learning Sciences*, 6 (3), pp. 271-315, 1997.
16. Mullins, C.A., Atman, C.J., & L. Shuman, "Freshmen engineer's strategies and performance when approaching design problems", accepted to *IEEE Transactions on Education*, October, 1996.
17. Cross, N., Christiaans, H., & K. Dorst, Analysing design activity, John Wiley & Sons, 1996
18. Atman, C.J. & K.M. Bursic, "Teaching engineering design: Can reading a textbook make a difference?", *Research in Engineering Design*, 8, pp. 240-250, 1996.

19. Sanderson, P.M., Scott, J.J.P., Johnston, T., Mainzer, J, Watanabe, L.M., & James, J.M., "MacSHAPA and the enterprise of Exploratory Sequential Data Analysis (ESDA)", *International Journal of Human-Computer Studies*, 41 (5), pp. 633-681, 1994.
20. Chi, M.T.H., Bassok, M, Lewis, M.W., Reimann, P., & Glaser, R., "Self-explanations: How students study and use examples in learning to solve problems", *Cognitive Science*, *13*, pp. 145-182, 1989.