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ABSTRACT

The role of planning in the design of digital circuits was studied in two experiments. One compared the planning-related activities of expert designers and beginning students of design, and the other looked at the effect on circuit-design processes of forcing students to construct a global plan. In experiment 1, five undergraduate students (novices) and two advanced graduate students with outside experience (experts) designed a one-bit full subtracter, taking several design constraints into account. Subject think-aloud protocols were videotaped and analyzed. Only one of the experts formulated a global plan before beginning the problem; undergraduate students did not formulate global plans but did exhibit local planning. More cross-component planning was conducted by students who were deemed more skillful by instructors. In the second experiment, 20 undergraduate and graduate students performed the same problem and a job-skill problem. Analyses suggest that at the group level there is no effect of planning on errors nor on attempts at optimization. Forcing formulation of a global plan does not mean that subjects are able to carry it out. (Contains 13 references.) (SLD)

The Role of Planning in Simple Digital Circuit Design

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Objectives

One characteristic of expertise in digital circuit design is understanding how each part of the design interacts and interrelates to other parts. Instructors in introductory design courses often comment on how difficult it is to get students to think about their designs from this perspective. In other domains, planning often functions to provide problem solvers with a global view of their solution activity. This research investigates the role of planning in the design of digital circuits. In an initial experiment, the planning-related-activity of expert designers and beginning students of design was compared and a lack of global planning was observed. The objective of a second experiment was to look at the effect on circuit design processes of forcing students to construct a global plan.

Theoretical Framework and Overview

The knowledge and problem-solving processes that support the execution of complex cognitive skills and performances have been the subject of cognitive research for several decades. A focus of this research has been on characterizing differences between individuals who are experts and those who are novices. Such contrastive analyses have been undertaken, in part, to elucidate the "end state" performance goals of acquiring cognitive skills and, in part, to understand how to assist individuals in attaining these end states. Researchers have taken this approach in a number of domains including physics, chess, architecture, mechanical engineering and instructional design (e.g., Akin, 1988; Chase & Simon, 1973; Chi, Feltovich, & Glaser, 1981; Foz, 1973; and Goel & Pirolli, 1989).

Characteristics of Expertise

Previous research has resulted in some general characterizations of the attributes of experts and novices in terms of both overall approach and specific strategies (e.g., Ericsson & Smith, 1991; Chi, Glaser, & Farr, 1988; Larkin, 1980). Several differences between expert and novices are noteworthy. For example, Chi, Feltovich and Glaser (1981) found that experts represent problems in their domain at a deeper level than novices; and Paige and Simon (1966) showed that experts spent more time analyzing a problem qualitatively. In addition, Larkin (1980) has shown that an expert first plans the main features of the solution and then elaborates them into the complete solution rather than initially delving into the detailed solution process.

There have been a number of studies of the design process in architecture and in various areas of engineering (e.g., Akin, 1988; Foz, 1973; Goel & Pirolli, 1989; Vandermolen, James, Goldman, Biswas, & Bhuva, 1992). Although design appears to be a highly constructive and possibly idiosyncratic process, there are a number of general principles and heuristics that students of design are taught (e.g., Garrod & Borns, 1991). As in other areas of complex cognitive activity, researchers have attempted to characterize the differences between individuals who have acquired different levels of design skill.

Results in the design domain generally support results found by other researchers. Glaser and Chi (1988) noted that experts spend more time analyzing a problem qualitatively, have strong self monitoring skills, and solve problems faster. Foz (1973) compared novice and expert designers and

concluded that experts employ a breadth-first approach to exploring the design space, do not commit to a solution until alternatives are explored, and use solutions from prior experience to solve new problems. One interesting observation is the fact that experts even consider solutions that have no a priori likelihood to succeed.

The present research investigates the role of planning in designing a complex domain, digital circuit design. Two experiments are reported. The first experiment examined the spontaneous use of planning during the design of a combinational logic circuit. The conclusions from this study are that students did not spontaneously plan before they started solving a design problem. But students did exhibit a great deal of "local" planning, i.e., planning that occurred during the solution process at times when students got confused or needed to stop and figure out what to do next.

The results of Experiment 1 with respect to planning led us to conduct Experiment 2 in which students were forced to generate a global plan before they started to solve a circuit design problem. The purpose of these forced global plans is to have the students think through the solution before beginning. The hypothesis was that such forced planning would foster more expert-like behavior and potentially better solutions.

Experiment 1

The purpose of the Experiment 1 was to extend the characterization of expertise to the area of circuit design. This is an interesting domain because simple design tasks can be executed as a set of standard procedures; however, to achieve proficiency even in simple design tasks, one has to be aware of

trade-offs between different performance parameters. Typical parameters include total area occupied, input-output delay, and total power consumption. As a result, a number of alternative solutions may be possible, each of which satisfies the functional requirements, but only one of which is optimal considering all requirements. Furthermore, most design problems can be decomposed into subproblems that can be solved independently. Doing so, however, ignores the interaction between the parts and often leads to suboptimal solutions.

Experts and students enrolled in their first course in digital design solved a relatively simple combinational logic circuit problem. Think-aloud protocols were taken and provided the basis of analyses of planning that occurred when they were designing the circuit.

Method

Participants. Five undergraduate student volunteers participated in the study. All five students were currently enrolled in a senior-level digital design course. The students had all completed one introductory course in digital circuits, and had very limited design experience. Contrary to much previous research on expertise, the experts were not college professors or instructors in design. The experts consisted of two advanced graduate students in electrical engineering who had experience working outside of the University setting.

Procedure. The problem required the subjects to design a one-bit full subtracter, taking into account several design constraints. The problem was similar to an example often used in class (the adder circuit), but different

enough so that neither novices nor experts could generate the solution from memory. The circuit required three inputs and two outputs, and the specified target representation was a circuit at the gate level. The subjects were provided with a written, functional description of the problem, rather than the desired input-output behavior. They were asked to think aloud during the solution process, which was videotaped. Each subject solved the problem independently and without a time constraint. Immediately following the problem solving session each subject was asked to watch the tape of her/his session and to add additional comments of what they were thinking and why. This retrospective session was also videotaped.

Analysis and Results

The protocol videotapes for the problem were analyzed at two levels: standard components of solution and discrete behavioral episodes. The component analysis reflects the standard sequence of solution components that is taught for doing combinational circuit design: *understand problem, generate Truth table, generate K-map, generate Boolean expression, implement*, and *evaluate*. Behavioral episodes were related to these standard design components. Episodes characterize the nature of the activity the subject was performing at a particular point in the solution. Five types of episodes (out of a total of 12 types) are associated with Planning-Related Activity; these are *evaluate, list, plan, select* and *verify*. The five Planning-Related Activity episodes are related to decision processes and are associated with the direction the problem solving takes (James, Goldman, and Vandermolen, 1994).

Highlights of the results of these analyses are the following:

1. Only one subject, the expert EM, formulated an overall plan which outlined his entire solution, before he began the problem.

2. In general, the students in this study did not formulate a global plan but they did exhibit local planning throughout their solution.

3. The less skilled student subjects had more occurrences of the Planning-Related Activities within the Components, suggesting that they were having problems with the mechanics of the procedures.

4. Students who were rated by their course-instructor as more skilled designers tended to have a greater degree of cross-component Planning-Related Activity than did those who were rated as less skilled. (These rating were independent of performance in Experiment 1.) This suggests that they were evaluating their solution and planning the next step.

Summary and Rationale for Experiment 2

Students who engaged in a great deal of within-component planning appeared to have little idea of the purpose of the design components they were attempting to execute. Even the more skilled students seemed to have some trouble determining what they should do at the conclusion of particular components. Accordingly, we decided to examine whether being forced to explicitly plan out an entire solution would lead to better performance on the design process.

Experiment 2

Students solved two combinational logic circuit design problems. On the first problem we observed the incidence of spontaneous planning-related

activity. On their second problem, students were specifically required to produce a global solution plan prior to beginning to work the problem. Think-aloud protocols were taken during solution of both problems.

Method

Participants. Twenty undergraduate and graduate student volunteers participated in the study. The students had all completed one introductory course in digital circuits and had had very limited design experience. The students were paid for their participation.

Procedure. The subjects were divided into two groups. Each group was matched on performance in their current design course and on gender. Each subject was asked to solve two problems, one per experimental session. Before solving the second problem each subject was asked to formulate an overall plan for solving the problem.

Problem A, the subtracter problem, was the same problem from the first experiment. Problem B, the job skill problem, required the subjects to solve a problem in which the input/output relations were described in words rather than symbols. It is the same type of problem as Problem A - a combinational logic problem. The circuit from Problem B required four inputs and two outputs. The specified target representation for both problems was a circuit at the gate level. Counterbalancing techniques assured that each problem served as the "first" problem an equal number of times across subjects.

The subjects solved the problems using a computer simulation tool. They were asked to think aloud during the solution process which was

videotaped. Each subject solved the problems independently and without a time constraint. After solving the second problem, each subject was asked a series of questions that compared the two problems, probed for problem solving strategies, and elicited a discussion of how useful the subject felt it was to formulate the global plan before solving the second problem.

Analysis and Results

Three methods of analyses were employed: a component analysis, an accuracy analysis, and an optimization analysis.

Component Analysis. The component analysis breaks down the design problem into domain-specific activities like 'generate truth table' and 'generate Karnaugh map'. It could be argued that not all of the subjects knew the standard design algorithm and thus did not include the same number of components in their designs. An ANOVA was performed with group (solved problem B first, solved problem A first) as the between subjects factor, planning (no plan, plan) as the within subjects factor and total number of components as the dependent variable. None of the main effects nor the interactions were significant. Mean number of components was 9.45 for the no plan condition and 8.9 for the plan condition, out of a possible ten components. This result is consistent with our initial assumption that the subjects did know the standard algorithm for solving this class of problems. Each group included the same basic set of steps in solving the problems.

Accuracy Analyses. The accuracy analysis investigates the presence of errors with respect to the planning condition. An ANOVA was performed with group (solved problem B first, solved problem A first) as the between

subjects factor, planning (no plan, plan) as the within subjects factor and total number of correct outputs as the dependent variable. There were no significant main effects nor interactions: mean numbers of correct outputs was .9 and 1.0, with a maximum of two outputs.

The number of errors in the problem solutions were submitted to an ANOVA in which group (solved problem B first, solved problem A first) was the between subjects factor, planning (no plan, plan) was the within subjects factor, and total number errors in each solution was the dependent variable. Again, there were no significant effects. The mean number of errors per solution was 2.7 for the no plan and 4.6 for the plan conditions.

Optimization Analysis. The optimization analysis examines whether planning led to increases in the attempt to optimize the design. Altogether there were only seven subjects who attempted to optimize any of the outputs in either plan condition. In all cases where a subject attempted to optimize a particular solution, both outputs were attempted. There were no circumstances in which a subject tried to optimize one output in a problem and ignored the other. There was only one subject who did not try to optimize in the no plan condition but who did try to optimize in the plan condition. Two subjects attempted to optimize in both the plan and the no plan condition and the remaining four subjects only attempted to optimize in the no plan condition. Thus, being forced to construct a global plan did not generally lead to a greater number of attempts to optimize a solution.

Subject Interviews. In the post-design interviews the subjects were all asked if they felt that formulating the global plan was helped: 60% felt that

the global plans helped and 40% felt that it was not helpful. Of the 60% who felt the planning was helpful, only 16.6% (2 subjects) were able to correctly design more than two of the four outputs required for the entire study. Whereas, of the 40% who did not find planning helpful, 50% (4 subjects) were able to correctly design more than two of the four outputs required for the entire study.

Summary. These analyses suggest that at the group level there is not an effect of planning on errors nor attempts at optimization. There are several possibilities for why the global plans were not associated with more successful designs:

1. The plans were ignored or not followed during the actual design. A plan that was ignored obviously would not have an effect on the solution process.

2. The plans were not correct, or were insufficiently detailed. An incorrect plan could lead to more rather than fewer errors and an insufficiently detailed plan would leave the subject either to replan or flounder.

One of the more successful subjects offered his own suggestion as to why the forced global plan was not helpful:

> It really wasn't too helpful for formulating a global problem, a global plan, because I feel a global plan comes in when the design is much bigger. See if I have this design, and suppose I'm designing something big, a computer of this sort, then I definitely need a global plan. I can say that. I can't just go designing bits and pieces. It would be useless. ...

OK, let me put it this way. The harder. There are two criterions. One is the hardness of the problem and the other is the volume of the design.

Perhaps the planning was not evident because the better designers automatically plan, as shown in this statement from such a subject: "Well, it [planning] didn't help much because I did the same thing on the first one [problem] only I just did not explicitly state it." There is also the possibility that global planning is not useful to less skilled designers, or is only useful at certain junctures in their design problem solving. Forcing someone with insufficient knowledge and skills to formulate a plan does not mean that they are able to adequately flesh out the details to implement the plan. This could contribute to circumstances in which the designer knows the design algorithm but not necessarily how to fully implement each step.

Further Analyses. Further analyses are underway, including an analysis of the protocols of the forced global plans. These analyses include a characterization of each statement in the protocols of the plans and an investigation of individual differences with respect to performance and attempts at optimization.

The forced global planning statements generated by the subjects have been divided into two categories: Planning Statements and Other Statements. The Planning statements include: Action, Evaluative, Explanative, and Problem-Constraint Statements. The Other Statements include: Elaborative, Irrelevant, Repetitious, and Rereading Statements. To be more informative about what sorts of irrelevant activities the subjects were engaged in the

category was subdivided into Interface-Related, Discourse Pacing, and Task Definition Irrelevant Statements.

We anticipate that the nature of the statements occurring in the plans will be related to the designs produced by the subjects. We expect that those subjects who gave more action, explanative, and problem-constraint statements are more likely to be accurate in their solutions. Analyses of the course of the design process are expected to reveal the flow of the solution activities. This flow will be related to the "planned" flow, with more successful designers adapting their plans as necessary.

References

Akin, O. (1988). Expertise of the architect. In *Expert Systems for Engineering Design* (pp. 173-196). Academic.

Chase, W. G., & Simon, H. A. (1973). The mind's eye in chess. In W. G. Chase (Ed.), *Visual information processing* (pp. 215-282). New York: Academic Press.

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, *5*, 121-152.

Chi, M. T. H., Glaser, R., & Farr, M. J. (Ed.). (1988). *The nature of expertise* (1st ed.). Hillsdale, N. J.: Erlbaum.

Ericsson, K. A. & Smith, J. (Ed.). (1991). *Toward a general theory of expertise: Prospects and limits* (1st ed.). New York: Cambridge University Press.

Foz, A. (1973). *Observations on designer behavior in the parti.* In Proceedings of the Design Activity International Conference,

Garrod, S. A. R. & Borns, R. J. (1991). *Digital Logic: Analysis, Application & Design*. Chicago: Saunders College Publishing.

Glaser R., Chi, M. T. H. (1988). Overview. In M. T. H. Chi, R. Glaser, M. J. Farr (Eds.), *The Nature of Expertise*, pp. xv-xxviii. Lawrence Erlbaum.

Goel, V. & Pirolli, P. (1989). Design within information-processing theory: The design problem space. *Artificial Intelligence Magazine*, 10, 18-36.

James, C. M., Goldman, S. R., & Vandermolen, H. (1994). *Individual differences in planning-related activities for simple digital circuit design* (Tech. Rep. 94-1). Nashville: Vanderbilt University, Learning Technology Center.

Larkin, J. H. (1980). Skilled problem solving in physics: A hierarchical planning model. *Journal of Structured Learning, 6*, 271-298.

Paige, J. M., & Simon, H. A. (1966). Cognition processes in solving algebra word problems. In B. Kleinmuntz (Ed.), *Problem solving* (pp. 119-151). New York: Wiley.

Vandermolen, H., James, C. M., Goldman, S. R., Biswas, G., & Bhuva, B. L. (May 1992). *Assessing expertise in simple digital circuit design*. In M. Evans (Ed.), Midwest Artificial Intelligence and Cognitive Science Society Conference, (pp. 47-51). Starved Rock State Park, Ill.