Title
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Coping with the Complexity of Design: Avoiding Conflicts and Prioritizing Constraints

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Abstract

Design is a complex cognitive task that pushes the limits of human information processing. How do expert designers handle this complexity? Professional and student architects solved a real-world diagram construction task that required satisfying multiple, sometimes conflicting, constraints to achieve an acceptable design. Professionals' initial designs were more consistent with task constraints and remained more consistent throughout problem solution. Students restructured their designs more often in their unsuccessful attempts to satisfy the multiple constraints imposed by the task. Analysis of subjects' verbal and action protocols suggests that one aspect of professionals' superior performance is their early recognition of the critical constraints on a design. Professionals handle these constraints before others to structure the remaining, more negotiable, constraints. By properly ordering constraints, professionals effectively minimize constraint conflicts. As conflict resolution has high processing costs, constraint prioritization may be one way that professionals cope with the complexity of design.

Introduction

Design is a complex cognitive task that pushes the limits of human information processing. A design task may require satisfying multiple, sometimes conflicting, constraints in order to achieve an acceptable design. For each design decision, designers must be sure not to contradict previous decisions—resolving such a conflict may require extensive redesign. How do expert designers make design decisions that take into account all necessary information? This paper describes an expert-novice study investigating the strategies experts use to cope with the complexity of design.

The architectural design process generally consists of three phases: preliminary design, refinement, and detailed design (Akin, 1986). Preliminary design involves an initial exploration of the design problem, resulting in a general plan that is embellished during later phases. Results of preliminary design may be more reflective of designers' intentions than are later phases (Ervin, 1990). Compared with later phases in which designers' decisions will have narrowed a design problem, the effects of design complexity should be clearest during preliminary design. This investigation therefore focuses on a task that falls within the preliminary design phase of a typical architectural project.

The Block Diagram Task

Before beginning a detailed drawing, architects may employ analysis techniques in which relatively simple diagrams are constructed to explore certain aspects of an incomplete design specification such as spatial or functional constraints (de Vries & Wagter, 1990). For example, in constructing a block diagram, an architect arranges a set of rooms[1] (e.g., the lobby and customer service area of a bank) onto a building site, specifying the spatial arrangement of rooms as well as the building's location on the site.

In this experiment, subjects constructed block diagrams on computer, using a dual-screen system. One screen (called the "workscreen") provides a site plan, a set of blocks representing the rooms of the building, and tools for constructing the design (similar to a computer-aided design package). A second screen provides background information and design specifications for the task—the graphic and text documents typically available to architects for constructing a block diagram in actual practice.

Figure 1 shows the workscreen from one subject's partially completed block diagram. Initially, all the blocks are provided at the top of the screen; the sizes of the blocks represent the relative square footage of each room. Down the left side of the screen are buttons that allows subjects to perform various design actions (e.g., move block, rotate entire current design). The second screen (not shown) provides a menu-based interface for viewing task documents one page at-a-time.

The documents specify the spatial constraints[2] on rooms that an arrangement of blocks must satisfy. Constraints include pair-wise adjacencies between rooms (e.g., "The teller line must be immediately accessible by the bank lobby") as well as adjacencies between parts of the site and parts of the building. An example of the latter constraint is "The drive up teller window may be located in...the [staff] workroom," which implies that the workroom must be

[1] Strictly speaking, in addition to rooms, the entities in a block diagram can represent any distinct area of a building. Architects use the more inclusive term "functional space," but for brevity we refer to all spaces as rooms.

[2] Constraints other than spatial constraints also affect the design of a block diagram (e.g., cost). However, in the analyzed task, the majority of constraints are spatial, and reported results pertain only to spatial constraints.

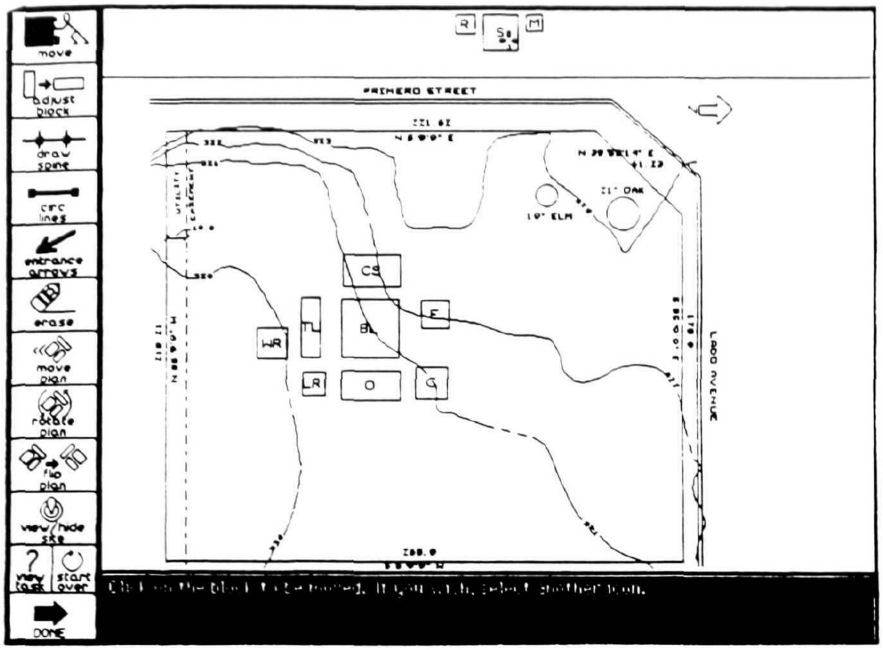

Figure 1: Sample workscreen from a partial design

immediately adjacent to the drive-up teller lanes (where ever the designer decides these lanes should be).

While not as time-intensive as a full-scale design problem, block diagram construction nevertheless shares many features distinguishing design problems from more puzzle-like problem-solving tasks (Goel & Pirolli, 1991). The task is relatively ill-structured: no definitive series of steps will necessarily result in an acceptable design. Problem solving involves finding a design that satisfies the multiple requirements, or constraints, specified in the task documents. Thus, alternative solutions are described in terms of better/worse designs rather than correct/incorrect—the issue is not whether a particular design was achieved but how well a design satisfies the requirements of the task. The task specifications are often implicit and/or negotiable; an important part of design is recognizing and trading-off conflicting constraints (Descotte & Latombe, 1985; Gross, 1987).

Constraint conflicts are a source of complexity in the block task. As an example, assume that the subject has arranged several blocks on the site and intends next to place the "staff workroom" block. The task documents specify that the workroom must be immediately adjacent to the teller line. If there are already other blocks surrounding the teller line (the other rooms that must also be adjacent to the teller line) such that the workroom cannot fit, then this conflict must somehow be resolved—the designer must rearrange the blocks around the teller line. Of course, rearranging already-placed blocks may lead to other constraint conflicts or may result in a design that violates a previously satisfied constraint.

In this report, I compare performance of professional architects with architecture students, seeking the unique methods professionals use to cope with the complexity of design. Analyses of subjects' designs first establish that professionals solve the block task (at least moderately) better than do students. The next set of analyses demonstrate that students redesign relatively often compared with professionals, suggesting that professionals avoid constraint conflicts that lead to redesign. Finally, verbal protocol analyses seek the source of professionals' success in avoiding redesign while nevertheless producing designs that meet the task constraints.

Method

Subjects

Eight volunteers were recruited from the students and faculty of the Boston Architectural Center (BAC). Two experience groups were recruited: (1) students half-way through the BAC program (equivalent of a recent B.Arch. graduate) and (2) professional architects in practice at least 10 years (BAC faculty members). There were four subjects per group.

Materials and design

All subjects were asked to create block diagrams for two "projects": a library and a bank. The limited number of subjects available made a counter-balanced design unfeasible, so all subjects were presented with the two tasks in the same order (library, then bank). This report will discuss results pertaining only to the bank task.

Procedures

Subjects participated individually in sessions lasting approximately 2.5 hr. Each subject received verbal instructions and practiced using the computer system on a demonstration problem. The subject then completed the two tasks on his/her own, although an experimenter was available to answer questions about the system or to clarify the task materials.

Along with the final designs produced by each subject, two types of process data were collected as subjects solved the tasks. First, all subject interactions were automatically recorded by the data collection system, producing an interaction log for each subject. The logs contain the time and location of each mouse click, with a short description of the click's semantics (e.g., "Begin adjust block BL," "Click move icon"). These logs provide detailed chronometric data on subjects' solution processes that would be otherwise difficult to obtain. Second, half of the subjects (2 students and 2 professionals) provided concurrent verbal protocols (cf. Ericsson & Simon, 1984) while solving the tasks; subjects were instructed not to explain their reasoning, but to say aloud anything they would normally "say" to themselves while generating a design. During problem solving, each subject's workscreen was videotaped, with verbalizations recorded on the audio track of the videotape.

Table 1: Percent of verbalizations in each category

Experience Group	Read	Evaluate/Plan	Design	Miscellaneous	Non-task
Students	18%	16%	23%	26%	17%
Professionals	21%	33%	19%	27%	0%

Results

General Results

Overall, subjects spent an average of 41 min to complete the task, with students taking 37 min and professionals taking 43 min. On their final designs, professionals were slightly more consistent with the task constraints (98% consistency[3]) compared with students (88%). However, within the first 2.5 min of designing, professionals' designs were consistent with 62% of the specified constraints, compared with 31% for students' designs. This difference is partially due to professionals' quicker placement of blocks onto the site and to students' violation of specified constraints in their early designs.

Effects of experience

Professional evidenced fewer constraint conflicts as indicated by their relative lack of redesign—blocks were rarely moved once placed. Students changed their designs more often. When initially placing blocks onto the site, an indication of constraint conflicts would be if the inclusion of a new block requires the reshuffling of already-placed blocks. An "interruption" is defined as any rearrangement of blocks on the site while other blocks have still not been placed. More interruptions indicate that subjects rearranged part of their design to accommodate a newly placed block. All professionals had one interruption in an otherwise straightforward placement of blocks onto the site. In contrast, 3 of 4 students had more than one interruption ($\chi^2(1)$=4.8, p<.03).

Students made changes to their design throughout problem solving as well. Subjects' interim designs at 2.5 min intervals were individually scored. A "design change" is defined as occurring when successive interim designs differ in whether a constraint is satisfied or violated (i.e., a constraint is satisfied at one point but violated in the subsequent design interval, or vice-versa). Professionals averaged only 0.07 design changes per minute compared with students' average of 0.19 changes per minute (design changes ranged from 0 to 0.30 per minute).

Sources of expert performance

Analyses of the subjects' verbal protocols provides further insight into the nature of professionals' problem-solving approach. Four subjects (2 students and 2 professionals) provided verbal protocols concurrently as they designed. Five categories of verbalizations were identified: (1) verbatim reading of task documents, (2) comments on the current design or design intentions (i.e., evaluative or planning statements), (3) comments made while performing design actions (e.g., the motivation for an action), (4) miscellaneous task-related comments (e.g., regarding navigation among task documents), and (5) non-task comments. Each verbalization was assigned to one of these five categories. To control for subjects' differing tendency to verbalize, Table 1 lists the percent of all verbalization that fall into each category.

The differences between students and professionals focus on two categories: Non-task and Evaluate/Plan statements. Only students made comments unrelated to the task (e.g., comments about the computer system). More importantly, professionals generated proportionally twice as many evaluative or planning statements compared with students.

At what points in designing do these evaluative or planning episodes occur? When subjects contemplate their interim designs, it is reasonable to expect that they are not performing overt design actions on the computer. That is, between two design actions, longer pauses may indicate a subject considering the design or planning the next steps to take before performing an action; shorter pauses may indicate that an action did not require prior contemplation. To identify the points at which planning or evaluation occurs for each subject, a bar graph of the pauses made before each design action (one bar per design action) was created based on the computer logs. The length of each bar represents the amount of time between successive actions. Thus, the graph for a particular subject may show the degree of planning or evaluation of a design and where that thinking occurs over the course of completing the design. In interpreting the graphs, the stringent criterion of 60 sec pauses (or longer) is taken as an indication of planning or evaluation.

Consistent with the verbal protocol analysis, 3 of the 4 professionals demonstrated relatively long contemplation throughout their problem solving (Figure 2a shows the latency graph for one professional). Only 1 of the 4 students showed this pattern; the remaining students showed almost no long pauses during their design (Figure 2b shows one student).

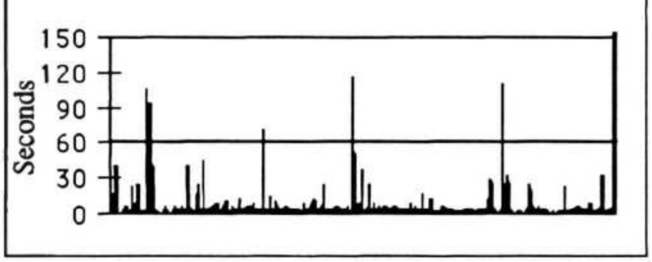

Figure 2 (a): Latency graph of a professional

[3]To achieve an objective design score, we enumerated the 17 inter-room adjacency constraints explicitly stated in the task documents. The consistency of a design is the percent of these constraints satisfied (i.e., the appropriate rooms are adjacent).

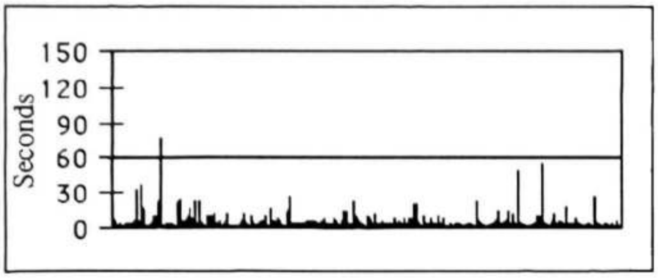

Figure 2 (b): Latency graph of a student

What happens during the long pauses? Do these pauses actually reflect evaluation or planning episodes? The next section presents informal "case studies" of three subjects who evidenced the pattern of long pause episodes throughout problem solving.

Case studies

Of three professionals and one student with longer pauses during problem solving, verbal protocols were available from all but one professional, allowing us to observe what sorts of verbalizations occurred during these pauses. Although there were slight differences in the total number of long-pause episodes, professionals verbalized directly about their design on proportionally more of the long-pause episodes compared with the student (Table 2).

Table 2: Character of verbalizations made during pauses of greater than one minute

Subject	No. long pauses	Pauses with evaluation	% evaluative pauses
Professional A	6	5	83%
Professional B	11	8	72%
Student	6	3	50%

For the student, longer pauses occurred primarily while reading (or rereading) one of the task documents. Half of the episodes consisted of reading a document verbatim, without other comments. In the other three episodes, the subject commented on how he planned to complete his design, focusing on low-level problems with the design, such as the relative positioning of two rooms.

The two professionals demonstrated planning and evaluative behaviors during their long-pause episodes. Earlier episodes reflected subjects' initial reading of the task documents, but not merely a verbatim reading of the documents. One professional verbalized information that went beyond the information in the document, drawing implications not explicitly stated in the documents. For example, after reading that the bank must front on a street (i.e., be visible from the street), the subject notes "but they don't say which street it has to front on." The subject also took special note of the requirements for vehicular circulation (i.e., specifications for parking and the drive-up teller window), choosing satisfaction of those requirements as a primary objective of the design. The other professional paraphrased documents and checked the document specifications with the provided site details (e.g., the subject often looked back and forth between the task documents and the initial workscreen). For both subjects, other long-pause episodes occurred while evaluating their design as a whole, making sure that the design satisfies the requirements for vehicular circulation (e.g., Professional B saying "we drive in...we turn, a hard turn...we go out" while using his finger to trace the path of an imagined car on the site).

These case studies suggest that professionals investigate the task documents more closely than do students, even before beginning their design. Perhaps as a result of this careful reading, the professionals identified a key constraint of the task: the location of the drive-up teller lanes.

Two between-group measures suggest that these results generalize to the remaining subjects. First, compared with students, professionals spent (marginally) more time between the start of the task and when they began to design (professionals: 626 sec; students: 350 sec; two-tailed $t(6)=-2.28$, $p<.07$). This result is consistent with the notion that students merely read through the task documents, while professionals more carefully consider the constraints specified in each task document before committing to a design. Second, professionals' early focus on drive-up constraints is revealed in how quickly the block containing the drive-up window—the staff workroom—was placed onto the site. For professionals, the staff workroom was always among the first blocks placed; for students, the workroom was always among the last blocks placed (perhaps because the staff workroom was among the last rooms described in the task documents). Professionals incorporated the staff workroom into their designs within, on average, 1.5 min of placing their first block. In contrast, students placed the workroom on average 6 min after placing the first block (two-tailed $t(6)=2.95$, $p<.03$).

Why do professionals treat the drive-up lanes as a high-priority constraint? In retrospect, there are several properties of this constraint that suggest its importance for the bank task. First, because of the size of the site and location of nearby streets, there are only a few possible paths the drive-up lanes can reasonably take. In contrast, most of the room constraints are defined relative to other rooms, not to the site. As a result, a particular room's location on the site is quite unconstrained (at least until more rooms are placed). Thus, at the beginning of a design process, drive-up lanes have few possible locations while each room has relatively many possible locations. Second, decisions about the drive-up lanes can drastically affect the building's location on the site and even its internal structure (because only certain rooms may contain the drive-up teller window). Thus, professionals' early attention to the drive-up lanes may sufficiently limit the remaining decisions such that only acceptable designs are generated.

Discussion

Professionals rearrange their designs less often, yet produce superior designs compared with students. While professionals design linearly, placing rooms onto the site with minor rearrangements, students often rearrange their designs to incorporate each room. These results are consistent with the notion that professionals successfully avoid constraint conflicts, which might force redesign.

The results suggest that professionals avoid constraint conflicts through appropriately prioritizing constraints.

Professionals identify the constraints affecting the entire design task (e.g., accommodation of a drive-up teller window), focusing on those constraints before attempting to satisfy any less important constraints (such as individual rooms' adjacencies). Students do not prioritize constraints; this lack can lead to conflicts because to incorporate a new constraint into the design, students may need to violate previously satisfied constraints.

In terms of information processing costs, handling constraint conflicts can be expensive. Resolution may involve backtracking (replacing parts of the design with alternatives), which in turn may lead to further constraint conflicts; witness the greater number of design changes made by students. This recursive descent may create memory overload as more and more conflicting constraints are discovered and need to be resolved. Thus, avoiding constraint conflicts should reduce the processing demands of a design task.

If there is a clear ordering of constraint priority (e.g., it is acceptable for some constraints to be satisfied less than optimally while other constraints are not negotiable), addressing constraints in that order should minimize conflicts (Darses, 1990; Mackworth, 1987). When each new constraint is considered (e.g., by placing a block on the site), the previous constraints will all be of greater or equal importance. Most conflicts will therefore have a clear "winner"—the already-satisfied constraints. In the current task, professionals attend to those constraints with limited alternative solutions, postponing the constraints with wider possibilities.

How do experts recognize the critical constraints of a task? Other researchers have noted experts' ability to treat provided constraints differently than constraints imposed on the task by the expert (Darses, 1990; Eastman, 1970). However, all of the constraints discussed in this work were explicitly provided in the task documents, yet professionals somehow knew which constraints to focus on constraints before others. These critical constraints were not explicitly identified in the text, so how did professionals detect them? There are at least two possible explanations. First, professionals may recognize certain types of constraints as likely candidates for early consideration. Professionals may know, for example, that constraints involving the site typically drive the remaining design. This knowledge may even be more specific: professionals may know that drive-up window considerations are important for a bank, while lighting is important for a library, for example. Second, professionals may focus on those constraints that are unusual or not recognized. A block diagram task typically specifies room adjacencies; the details of what rooms are available and how they relate to one another would, of course, change for different block diagram tasks. Similarly, design tasks may have various unique constraints, such as specifications of parking or drive-up lanes. Professionals may focus on those constraints that differ from task to task and are dependent on the specific building being designed. Thus, professionals' early focus on the drive-up lanes may reflect that constraint's uniqueness rather than professionals' explicit recognition that it is a critical constraint.

By properly ordering constraints—by attempting to satisfy those constraints with fewer alternatives first—professionals effectively minimize constraint conflicts. Reduction of unnecessary conflicts frees professionals to attend to the most challenging aspects of a design task—satisfying constraints of equally high priority. Thus, constraint prioritization may be one way that professionals cope with the complexity of design.

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