Design of Artifacts from a Cognitive Engineering Perspective

(A Designer's Cheat Sheet of Helpful Hints from Cognitive Science)

by

Annie R. Pearce
School of Civil Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0355

for

Dr. Alex Kirlik
School of Industrial and Systems Engineering
Georgia Institute of Technology
Atlanta, GA 30332

ISyE 6205
Cognitive Engineering
17 March 1994

1.0 Introduction

The purpose of this paper is to set forth some guidelines for the design of artifacts, based on the principles of cognitive engineering. The first part of this paper will explore several theories of design processes, and qualify those theories with a look at some observations from industry. The rest of the paper will address how the principles of cognitive engineering can contribute to existing design processes. The design guidelines proposed in this paper are primarily aimed at the design of artifacts by engineers and other technical types, but it is hoped that they may be extensible to other domains where human needs are met via innovation. After all, we're all designers at heart, aren't we?

2.0 Theories of Design

This section of the paper will present a survey of several theories of design processes for artifacts. First, a systems perspective of the components used to solve design problems will be presented. A two stage design process model, proposed by Newell and Simon (1972), consisting of problem structuring and problem solution phases, will be presented and compared with other design processes discussed in the literature. A discussion of how current design practice differs from the theoretical design processes will conclude this section, and provide a basis for developing guidelines to improve current design practice using the principles of cognitive engineering.

2.1 Components of a Human Problem Solving System for Artifact Design

Goel & Pirolli (1992) postulate a theoretical design process based on the work of Newell and Simon (1972) in the area of information processing for human problem solving. Newell and Simon defined three components of the design problem solving system:

- the human or humans, which Goel and Pirolli call an "information processing system with a problem," (p. 399)
- the task environment, consisting of a problem, a goal and other relevant external factors,
- the problem space, which is the formalized structure used to solve the design problem.

Goel and Pirolli state that traditionally, the problem space is thought to be comprised of the progressive states of the problem solution, the operators which work on the problem to change its state, and evaluation functions which classify the various states of the problem. Additionally, they describe twelve invariants found in Goel's research on the structure of design problem spaces:

- Problem structuring required before problem solving can begin.
- Problem solving is broken down into distinct phases.

- Designer may try to redefine problem to match an existing solution, or to afford a more effective solution
- Problems are decomposed into modules with contingent connections between them
- Artifact designs are developed incrementally, "nurtured"
- Designers use a "limited commitment mode control strategy," enabling generation and evaluation of alternative design components in multiple contexts
- Given time and resource constraints, designers have to make, record, and propagate commitments to design decisions
- Designers must create their own stopping rules and evaluation functions
- Designers make decisions predominately based on memory retrieval and nondeductive inference
- Manipulations and experimentation are performed on models, not the real world
- Orthogonal abstraction hierarchies are created as a result of qualitative differences between input to and output from the design process
- Artificial symbol systems are used in the design process

The human is supposed to work within the problem state to create a solution for the problem which will then be applied within the task environment. The problem solution may be in the form of a physical artifact, a software implementation, a process, or other contribution within the realm of applied science; however, Goel and Pirolli (and also this author) limit their discussion to the design of artifacts. Part of the problem space for design problems (as opposed to non-design problems like puzzles) involves differentiating between the design specification and delivery of the constructed product (Goel & Pirolli, p. 402).

2.2 Phases of the Design Process

Goel and Pirolli identify two main phases in the process of designing an artifact: problem structuring, and problem solving. Other models of design incorporating more steps have been proposed by Hannigan and Herring (1987), Russell and Galer (1987) and others, but the additional steps in these models represent the delivery, construction/production, and implementation of the design specification, and will be excluded from consideration here as discussed earlier.

2.2.1 Phase I: Problem Structuring

Problem structuring involves considering the task environment where the artifact will be used, the people who will be using it, and the resources which will be available to construct it. The primary source of information during the problem structuring phase is (or should be - c.f. Russell & Galer, 1987) the end user (in building construction, the owner) of the product. This view reinforces the point made by Hannigan and Herring (1987) that the designer should not wait until α or β testing of the product to get input from potential users. Simon (1973) defines problem structuring as a process of gathering the knowledge necessary to construct the problem space, specifically identifying the start state, goal state, valid operators, and evaluation functions to constrain the problem solution. A generic design cycle model derived by Hannigan and

Herring (1987), in a study of prescribed design processes of several office product companies, executes the problem analysis and definition, and determines feasibility constraints of the problem in its pre-design phase.

2.2.2 Phase II: Problem Solving

Problem solving, as described by Goel and Pirolli, generally consists of a minimum of three progressive stages: preliminary design, refinement of the preliminary design, and design of details. They concede that these three basic phases may be arbitrarily broken down into many more specific design steps, but believe that these three general stages capture the essence of the design process. Hannigan and Herring, on the other hand, lump design into one step in the artifact development process, and follow it with steps of programming/executing the preliminary design, and testing, evaluation, review, and validation of the design. While specific steps may differ slightly based on the domain of the artifact being designed, the primary goal of developing a robust and usable product specification should be complete at the end of the problem solving phase of design.

Variables over the phases of problem solving include the sources of knowledge, where input from the owner decreases with development of the design, aspects of the design which are considered, beginning with general decisions about functional systems and progressing to decisions about specific aspects or details of each functional system, and the degree of commitment to output, which increases as the design gets refined. In addition, the number of changes which can be made to the design without dramatically increasing cost decreases as design progresses.

2.3 Additional Features of the Design Process

Other features which characterize the design process as described in (Goel & Pirolli 1992) include a variable distribution of information (increasing as the design progresses), significant size and/or complexity of the problem being addressed, many interconnected components within the problem, no “right” or “wrong” answers to the problem but instead “better” or “worse” solutions, both nomological and “negotiable” (i.e. social, political, legal, etc.) constraints on the problem solution, and significant cost of errors. The input to the design process is typically information supplied by the user or owner, including goals for desired behavior using the artifact, and the output is a specification for the construction, production or implementation of the artifact. It is also implicitly desirable that the artifact be able to function independently of the designer.

2.4 How Design Practice Differs From Theory

Hannigan and Herring (1987) found that in the context of office product design, designers stated that “no two products were likely to follow the same development cycles within any of the member companies.” (p. 227) In light of this, it is important to realize that, although designers may endorse a theoretical model of design, what they actually practice may differ dramatically from the model. In fact, Hannigan and Herring reported that their seven stage model (partially described above) "was not discovered as a normal way of designing products." (p. 228) They concur with the view expressed by Whiteside (1986): "The coherent design process...does not exist. The design process is disorderly and radically transformational, bearing little resemblance to the mythical state of affairs portrayed in the orderly stagewise diagrams found in textbooks and engineering manuals." Hannigan and Herring found that when companies used a formal design process at all, it was only as a point of reference or as a way of identifying non-compliance with design constraints. They refer to the "transformational model" set forth by Gardner et al (1986), which adds feedback and return loops to all stages of the linear model described above, and makes constraints at each stage of the process more explicit.

3.0 Guidelines from Cognitive Engineering for Design of Artifacts

This section of the paper will discuss a variety of ways in which the principles of cognitive engineering can be used to enhance the process of designing artifacts. It is hoped that improving the way artifacts are designed may result in better products, which are more usable, task-relevant, and performance-enhancing to the humans which use them. Realistically, design guidelines should be context-specific and should take into account task and user variables, organizational requirements, market requirements, and other ecological factors (Russell & Galer 1987). The design guidelines presented in the following sections have been generalized to the greatest extent possible, but specific examples have been provided to illustrate each guideline and to aid the reader in relating the guidelines to his or her own domain and context.

3.1 Affordances of the Artifact

Gaver (1991) defines affordances as "properties of the world defined with respect to people's interaction with it." (p. 80) He goes on to emphasize that "affordances imply the complementarity of the acting organism and the acted-upon environment...affordances are properties of the world that make possible some action to an organism equipped to act in certain ways."

Gaver gives examples of how affordances and the information available about them may interact to combine to create perceptible affordances, hidden affordances, and false affordances. He emphasizes, as do Michaels (1993), Smets et al (1993), and Leventhal (1987), that attention to the desired affordances of an artifact during design can lead to inclusion of features or cues in the artifact which make its affordances more likely to be correctly perceived by the user. Smets et al discuss the design tools of CAD and virtual reality (see Section 3.5), which seem to be potentially very helpful in simulating the affordances of artifacts which they represent.

The author would like to note that in certain cases, the desire of the designer is to conceal the true affordances of the artifact in order to present some different image to persons not intimately familiar with the artifact. Two architectural examples are given briefly to illustrate this point. First, to reduce cost of materials, "false" or non-structural aluminum decorative columns are often used to ornament entrances or support lightweight roofing. The appearance of these columns is meant to be mistaken for that of solid structural columns, which afford strength and structural bearing, while in reality all the false columns support is their own weight. Second, in certain types of architectural styles, entrances to buildings (typically houses) are disguised using curved entrance paths, overhanging plants, etc., all to lend the impression that the path does *not* afford entrance to the building. In both of these cases (and in many others as well, I'm sure), the intent of the designer is to disguise the true affordances of the artifact. Hence, perceptual information can be used to either exploit or disguise the true affordances of artifacts.

3.2 Information Processing Requirements

Gopher (1987) implies the following guidelines to reduce the information processing requirements of using artifacts when designing the artifacts:

- Structure elements of information so as to permit logical "chunking"
- Incorporate cues in the artifact's representation of the world to help make the connection between the artifact and how it's supposed to act on the world
- Minimize coordination requirements of information processing cognitive elements
- Link task requirements to natural cues in the environment, whenever possible
- Minimize the use of arbitrary representations of the world in the artifact
- If arbitrary representations must be used, give the user the flexibility to select different arbitrary representations, if possible
- Maintain spatial and temporal relationships in the artifact's design which exist in the world it represents.

The context of Gopher's research is in performance of manual skills such as touch typing. The above guidelines may be extended to incorporate cognitive features of other domains (see Section 3.4).

3.3 Memory Management

Goel and Pirolli (1992) suggest that decomposition of problems may provide a way of reducing attentional loads without compromising the "richness" of the problem, and is a useful way of dealing with the size and complexity of design problems. They claim that design problems can have many "leaky" (i.e. interconnected) modules, and yet still be tractable since the interconnections between modules are contingent rather than logical (p. 419f).

Barwise and Etchenmendy (1989) and Zhang and Norman (1994) provide excellent arguments for using external visual representations as reasoning tools, which is supported by Donald's concept of memory management using External Symbolic Storage (1991). Hence, the use of sketches, models and other artifacts as reasoning tools, external memory stores, or representations of the world should be encouraged as a way of managing the demands on internal memory and reducing the need for procedural reasoning (see Section 3.5).

3.4 Looking Critically at Existing Artifacts in a Cognitive Context

Gopher (1987) makes the claim that "significant design improvement and enhancement of skilled performance in manual tasks can be achieved through a detailed evaluation of the cognitive structure of existing control devices, leading to corrective steps based upon the emerging knowledge of cognitive science." (p. 233) The domain Gopher explored in his research was touch-typing, which he criticized in terms of its nonoptimal cognitive requirements. After developing two alternative keying devices which reduced cognitive and motor demands on the operator, comparative testing showed dramatic improvements in performance using the redesigned artifacts.

Gopher claims that critical evaluation of existing artifacts in the context of cognitive science may suggest ways of improving the design of existing artifacts or designing new artifacts to perform similar tasks. Among the factors Gopher considered in his cognitive critique were:

- significance of associations and mappings between the world and the representation
- level of arbitrariness of the representations
- number of motor responses which must be acquired
- degree to which spatial and temporal relationships in the world are maintained in the representation of the world
- structure of elements/information and degree to which structure promotes logical chunking and provides representational cues
- level of coordination required.

This set of factors was particularly relevant to the task of touch-typing, and should be extended or modified depending on the task analyzed.

3.5 Direct Manipulation

The benefits (and costs) of using direct manipulation to reduce the cognitive demands for procedural reasoning are extolled by Owen (1987). Direct manipulation is cited in (Smets, et al 1993) as a particularly effective design technology since, with appropriate sensory feedback from the design system, the designer can effectively simulate his designed artifact with little trouble, and concentrate on how effectively the affordances of the artifact are expressed. Smets et al discuss the uses of Computer-Aided Design (CAD) and virtual reality as design and simulation tools, and convey how being able to directly manipulate computer representations of artifacts at various stages of design is effective not only for evaluating products as they are developed, but also for encouraging the consideration of affordances (see Section 3.1) in the design of artifacts.

4.0 Conclusions

The design guidelines set forth in Section 3 of this paper were developed from a very limited search of the cognitive engineering literature, and are hopefully at least representative of the possibilities for improving current design practices afforded by cognitive engineering and science. Many models of the design process exist in addition to those few discussed in Section 2 of this paper, and perhaps further analysis of these models and their representativeness of actual design practice will suggest additional ways to improve the process of designing artifacts. Design of artifacts is a very complex and domain-specific process, and unfortunately considerable depth was sacrificed in this work in the hopes of generating results which might be significant to a broader audience.

5.0 References

Barwise, Jon, and John Etchenmendy, 1989. Visual Information and Valid Reasoning. Unpublished manuscript.

Donald, Merlin, 1991. *Origins of the Modern Mind*. Cambridge MA: Harvard University Press. pp 308-333.

Goel, Vinod, and Peter Pirolli, 1992. "The Structure of Design Problem Spaces," *Cognitive Science*, v. 16, pp 395-429.

Gardner, A., et al. Human Factors in Systems Design, Naval Engineering Standard, Draft part II, Ministry of Defense (The Netherlands), Controllerate of the Navy.

Gaver, William W., 1991. Technology Affordances. in *CHI'91Conference Proceedings*, New Orleans, LA (1991) pp 79-84.

Gopher, Daniel., 1987. Condition at Your Finger Tips - A Cognitive Approach to the Design of Data Entry Devices. in *Cognitive Engineering in the Design of Human-Computer Interaction and Expert Systems*, G. Salvendy, ed. Elsevier Science Publishers B.V., Amsterdam. pp 233-240.

Hannigan, S., and V. Herring, 1987. Human Factors in Office Product Design - European Practice. in *Cognitive Engineering in the Design of Human-Computer Interaction and Expert Systems*, G. Salvendy, ed. Elsevier Science Publishers B.V., Amsterdam. pp 225-232.

Leventhal, Laura Marie, 1987. Discourse Rules in Program Comprehension: Emergence of a Construct Affordances Rule? in *Proceedings of INTERACT'87*, M.J. Bullinger and B. Shackel, eds. Elsevier Science Publishers B.V., Amsterdam. pp 297-302.

Michaels, Claire F., 1993. Destination Compatibility, Affordances, and Coding Rules: A Reply to Proctor, Van Zandt, Lu, and Weeks. *Journal of Experimental Psychology: Human Perception and Performance*, v. 19, n. 5, pp 1121-1127.

Newell, Alan, and Herbert A. Simon, 1972. *Human Problem Solving*. Englewood Cliffs, NJ: Prentice-Hall.

Owen, David, 1987. Direct Manipulation and Procedural Reasoning. in *Cognitive Engineering in the Design of Human-Computer Interaction and Expert Systems*, G. Salvendy, ed. Elsevier Science Publishers B.V., Amsterdam. pp 349-356.

Russell, A. J., and Margaret D. Galer, 1987. Designing Human Factors Design Aids for Designers. in *Cognitive Engineering in the Design of Human-Computer Interaction and*

Expert Systems, G. Salvendy, ed. Elsevier Science Publishers B.V., Amsterdam. pp 289-296.

Simon, Herbert A., 1973. The Structure of Ill-Structured Problems. *Artificial Intelligence*, v. 4, pp 181-204.

Smets, G.J.F., C.J. Overbeeke, and P.J. Stappers, 1993. Perception Theory and Imaging Systems. in *Advanced Technologies*, M.R. Beheshti and K. Zriek, eds. Elsevier Science Publishers B.V., Amsterdam. pp 405-410.

Whiteside, J. A., 1986. Classifying Users: A hard look at some controversial issues. Panel in *CHI'86 Conference Proceedings*, Boston (1986) pp 84-88.

Zhang, J., and D.A. Norman, 1994. Representations in Distributed Cognitive Tasks. *Cognitive Science*, in press.