Sketches for Design and Design of Sketches

Barbara Tversky, Masaki Suwa, Maneesh Agrawala, Julie Heiser, Chris Stolte, Pat Hanrahan, Doantam Phan, Jeff Klingner, Marie-Paule Daniel, Paul Lee, and John Haymaker
Stanford University, Stanford, CA, USA
Chukyo University, Toyota, Aichi, Japan
Microsoft Research, Redmond, WA, USA
LIMSI, Orsay, France
NASA-Ames, Mountain View, CA, USA

Sketches for and by Design

It is said, though not without controversy, that what distinguishes design from art is function. Design is for a purpose, usually a human one. As such, design entails both generating ideas and adapting those ideas to intended uses. This occurs iteratively. Form and function. Studying how people go about both these tasks gives insights that can facilitate the design process. Two relevant projects will be described. The first investigates how designers and novices get ideas from sketches and applies those insights to suggestions for promoting generation of ideas. The second seeks to develop computer algorithms for designing individualized visualizations, algorithms that are informed by cognitive design principles.

Insights from Sketches

Why do designers sketch? The simple answer is that they are designing things that can be seen. But this simple answer underestimates the contributions of sketching to the cognition underlying design. After all, designers could construct things in their minds in three dimensions, and to varying extents, they do. But the mind rarely has sufficient capacity to contain an entire object of design; sketches can overcome this limitation. The mind may not notice inconsistencies or incompleteness; sketches demand some consistency and completeness. The mind may not have the capacity to construct, hold, and evaluate a design; sketches hold the constructions in view of the designer, freeing the mind to examine and evaluate. Thus, sketches, like other external representations, relieve short-term memory, demand consistency, and augment information processing. They are also public representations of thought, so they can be shown to others and reasoned on collectively. What the mind does in evaluating sketches to promote design has fascinated designers and cognitive scientists alike. Our own investigations have included experts and students of architecture and design as well as laypeople.

They have included analyses of the spontaneous, detailed, step-by-step reports of the thoughts of designers as they designed a building complex as well as experimental manipulations of interpretations of sketches. We review some of those studies and their results here.

Role of Sketches in Design Ideas. In contrast to other visualizations, such as diagrams and graphs, sketches, especially early ones, are replete with ambiguities. They are, after all, "sketchy;" that is, vague, committing only to minimal global arrangements and figures. Rather than inducing uncertainty or confusion, ambiguity in design sketches is a source of creativity, as it allows reperceiving and reinterpretating figures and groupings of figures. A designer may construct a sketch with one arrangement in mind, but on inspection, see another arrangement enabling a new, unintended interpretation (e. g., Goldschmidt 1994; Schon 1983; Suwa, Gero and Purcell 2000; Suwa and Tversky 1997). Both beginning and experienced designers are facile in making new inferences from their own design sketches. However, experienced designers are more adept at making functional inferences than novices, whose inferences are primarily perceptual (Suwa and Tversky 1997). A functional inference is seeing the flow of pedestrians in a sketch of a plan whereas a perceptual inference is seeing new spatial relations among structures. The facility of seeing function in structure is a hallmark of expertise in numerous domains from chess (Chase and Simon 1973; de Groot 1965) to mechanical devices (Heiser and Tversky, submitted).

What enables designers to see new implications in sketches, especially their own? The analysis of the protocol of one experienced architect as he designed a building complex is instructive. After perceiving new perceptual configurations in his sketch, he was more likely to get a new design idea than after interpreting the sketch in the same way. Getting a new 'design idea in turn led to perceiving new perceptual relations in the sketch, and so on, a productive cycle (Suwa, Gero and Purcell 2000).

Stimulatingng New Design Ideas.

Can the strategy used by the expert architect to enable new design ideas be explicitly adopted by others to same end? To see if searching for new perceptual relations could be used purposefully to enable new interpretations by a larger population, we gave undergraduates the ambiguous sketches shown in Figure land asked them to come up with as many interpretations as possible for each, a procedure adapted from one used by Howard-Jones (1998; Suwa, Tversky, Gero and Purcell 2001). Participants generated ideas for four minutes for each drawing. About two-thirds of the undergraduates, either spontaneously or by suggestion, adopted a strategy of attending to the parts of the sketch, either focusing on different parts or mentally rearranging the parts of the sketch, in order to see new interpretations. Participants attending to parts produced more interpretations, on average, 45 for the different parts group and 50 for the rearrange parts group, than the others, who did not adopt that way of interacting with the sketch and who generated on average 27 interpretations in the four minutes.

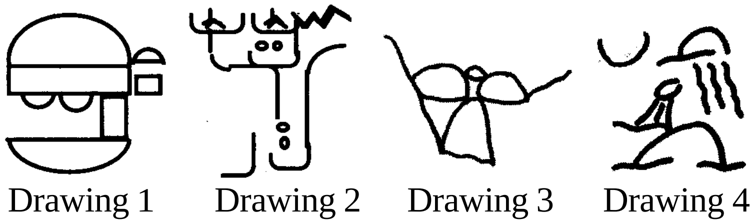

Fig. 1. Four Ambiguous Drawings

One factor that plagues designers and problem solvers in general is fixating on old ideas. Early in the design process, designers generate a flurry of ideas, but later in the design process, they find it harder and harder to see a design differently and generate new ideas. Adopting one of the parts strategies also provides protection against fixation. Undergraduates who adopted one of the parts focus strategies for generating new ideas produced relatively more ideas in the second half of the session than those who did not adopt a parts focus strategy.

Comparing Experts and Novices in Generating Interpretations of Sketches.

We replicated this experiment on groups of practicing designers, design students, and laypeople (Suwa and Tversky 2001). The practicing designers produced more interpretations and were more resistant to fixation than any of the other three groups, design students and laypeople, who did not differ from each other. Participants reported in detail the strategies they used to generate new interpretations. Primary among them were regrouping parts and changing reference frames. Participants also reported reversing figure-ground relations in the service of generating new ideas, but used this strategy less often. Both experienced designers and novices of all types used the same strategies, but the designers succeeded in generating more interpretations and resisting fixation. Perceptual reorganization is only half the process of generating ideas; the second, critical half is finding meaningful interpretations, a process which is conceptual in nature. This suggests that what separates experienced designersfrom novices and laypeople is the process of linking perceptual reorganizations to conceptual interpretations. This conclusion echoes the results of the protocol analyses of experienced and novice architects discussed earlier (Suwa and Tversky 1997). In that study, a major difference between practicing and novice architects was in facility of seeing functional implications of designs.

Constructive Perception

Designers appear to deliberately adopt perceptual strategies for reorganizing parts of ambiguous sketches in the service of generating ideas, a process we call ***constructive perception*** (Suwa and Tversky 2001). We believe that constructive perception can be fostered, and are experimenting with how to do it. Can constructive perception serve as a model for creativity in other domains? It seems likely. Even abstract domains that cannot be sketched have parts, which can be reorganized into new configurations and reconceived from new points of view.

Cognitive Design Principles

For design, beauty is not sufficient. The ideas must serve a user. Teapots should be easy to fill and easy to pour, and they should not bum the **user.** Instructions should be easy to apprehend and follow. To design a better teapot, we need to study how people use them. Similarly for instructions. Careful investigations into human cognition can provide guidelines for effective design. The domain we have chosen is visual instructions. Within those, we have selected two common and familiar cases: route instructions and assembly instructions. Visual instructions are a challenging domain because realism is not paramount. Effective visualizations omit irrelevant information and highlight, even distort, the relevant information. What is relevant depends on how people think of the task. To design effective visualizations for routes or assembly, we must know how people think about routes or assembly. Cognitive experimentation can elucidate people's mental models of routes or assembly or other domains. Cognitive experimentation can also elucidate how people perceive and interpret visualizations of these procedures and explanations. For these reasons, the contributions of cognitive experimentation go beyond traditional user testing. The cognitive experiments give insights into how people conceive of routes and assembly and how depictions and language can compatibly convey those conceptions. The conceptions as well as their diagrammatic and linguistic expression are principled. These principles serve as design principles. Let us illustrate how this happens in practice.

Route Maps

In order to design effective maps for guiding someone from one location to another, the first step is to know how people conceive of routes. From this understanding, design principles for the automatic construction of route maps can be inferred.

How do People Think About Routes?. A number of years ago, just before dinner, we approached students outside a dormitory and asked them if they knew how to get to a nearby fast food restaurant (Tversky and Lee 1998). If they did, we gave them a sheet of paper and asked them to either sketch a map or write instructions how to get there. We analyzed both sketch maps and route directions according to a scheme developed by Denis (1997) for the structure of route directions. He found that route directions consist of sequences of four kinds of segments: start point, reorientation, path progression, and end point. For example: you leave the station, you turn right, you go down Bahnhofstrasse, until you come to the cathedral. We found that this scheme, which had been developed to account for verbal directions, also characterized sketch maps. The similarities of syntax and semantics of route maps and directions suggest that both derive from the same underlying cognitive structure. Both route maps and route directions took a number of liberties with the Euclidean world. Degree of turn was approximate, around 90 degrees. Curves in roads were straightened. It turns out that these distortions of the Euclidean world also occur in memory for environments, maps, and spatial arrays; they are a consequence of normal perceptual organizing principles used in establishing and retrieving mental representations (e.g., Tversky, in press). In the sketch maps, long distances with no turns were shortened and short distances with many turns were enlarged, so scale was used to reflect the spatial information needed about the world rather than the spatial information of the world. Simply put, people think of routes as paths and nodes, where the nodes typically indicate change of direction.

Designing Route Maps. The sketch maps we obtained were typical of those that people draw for one another for navigation. Sketch maps such as these have undergone generations of informal user testing. They are quite different from highway maps or from the maps that can be downloaded from popular websites. Those maps suffer from clutter, too much extraneous information, and also from uniform scale, so that some important details may not be discernable. Agrawala and Stolte (2001) instantiated the design principles derived from cognitive research in the construction of computer algorithms that produce sketch-like route maps on demand. These maps, which users have praised, can be found at mapblast.com (Linedrive maps).

Assembly Instructions

Assembly instructions are the bane of do-it-yourselfers, who bring home boxes with enticing photos of barbeques or desks and contain dozens of parts. The instructions typically consist of a single detailed exploded diagram of the desired object. Consequently, the small parts are usually hard to distinguish, as is how to attach them. The order of assembly is typically not indicated. It is no wonder that not only is assembly frustrating, but at the end, do-it-yourselfers sometimes find themselves with extra parts.

How Do People Design Instructions? Users know better. Designing effective assembly instructions entails knowing how people think about the object to be assembled, how they think about the assembly process, and how visualizations can effectively convey both. To uncover cognitive design principles for assembly instructions, we ran a series of experiments, using a TV cart as a paradigm case (Heiser, Tversky and Daniel, in preparation; Heiser, Tversky, Agrawala and Hanrahan 2003). In the first experiment, participants assembled a TV cart using only the photograph on the carton as a guide. Afterwards, they generated instructions to assemble the TV cart. The visualizations produced varied widely across individuals. Those lower in spatial ability, as assessed by mental rotation performance, tended to produce 2-D menus of parts. Some also produced structural diagrams, showing the parts assembled, but without using perspective. The diagrams constructed by high ability participants were dramatically different. They typically produced step-by-step action diagrams in 3-D perspective. The steps corresponded to the major parts to be assembled. The action indicated the manner of assembly, typically using arrows and guidelines. The perspective chosen was that the showed the parts and how to assemble them. These diagrams went beyond structure to show construction, often by using extra-pictorial, diagrammatic devices such as arrows.

The characteristics of the diagrams constructed by high ability participants are good candidates for cognitive design principles. Their efficacy was tested in two further experiments. In the next, a new group of participants assembled the TV cart, and then rated the previous instructions for quality. Highly-rated instructions in fact had the qualities characterizing the diagrams of the high spatial participants: they presented one step at a time; they produced 3-D perspective views showing the assembly; they enlarged the small parts to be discemable; they used extra-pictorial features such as guidelines and arrows to indicate manner of assembly. A third group of participants used instructions varying in rated quality to assemble the TV cart. For high ability participants, instructions made no difference; in fact, those participants could and often did rely on the photograph on the carton to guide assembly. For low ability participants, however, the quality of instructions had the expected effects: good instructions enabled assembly that was faster and more accurate. Note that the participants were students at a highly-selective university, so that the low ability participants who benefited from effective visualizations are probably more representative of the general population.

Applying Cognitive Design Principles. These qualities of superior instructions were instantiated as design principles for automatically generating visualizations for assembly. The algorithms have produced elegant step-by-step visualizations for the assembly of furniture, including our paradigm TV cart, Lego, and other objects (Agrawala, Phan, Heiser, Klingner, Haymaker, Hanrahan and Tversky 2003). The algorithm decomposes a model of the object into assembly parts, and selects views that maximize the visibility of the parts to be assembled. Order of assembly is normally only partially constrained by the mechanics of assembly, that attaching some parts must be done before others. An innovation of the present approach is that the algorithm further constrains assembly order by selecting an order that maximizes the visibility of the assembly steps. Planning the procedures is thereby intertwined with presentation of the visualization. More generally, the ease of comprehending and implementing instructions should constrain order of assembly. This has general implications for design: to increase user ease, products should be designed in concert with instructions for their assembly or their use.

Summary and Implications

Cognitive research can inform and facilitate design. Studies of the kinds of design ideas that experts and novices generate from sketches have shown that new design ideas are frequently a consequence of reorganizing, then reinterpreting, the parts of a design. Using reorganization strategies in the service of generating new design ideas, or constructive perception, has two components, seeing a new configuration and connecting it to a new conceptualization. Experts seem to do this better than novices, suggesting that constructive perception may be cultivated. Constructive perception may have generality beyond design of visual objects.

For visualizations such as route maps and assembly instructions, even novices create visualizations that simplify and distort the visual information in ways that increase their usefulness by streamlining their message, for example, by enlarging small but critical elements and regularizing uninformative irregularities. The simplifications and distortions suggest cognitive design principles that can be implemented in algorithms to automatically generate visualizations. Such algorithms enable rapid inexpensive production of individualized visualizations.

Cognitive science has provided two messages for designers. Sketches benefit design. Design benefits sketches

Acknowledgements:

We are grateful for the encouragement and support of the following grants: Office of Naval Research, Grants Number N00014-PP-1-0649,
N000140110717, and N000140210534 to Stanford University.

References

Agrawala, M., Phan, D., Heiser, J., Klingner, J. Haymaker, J., Hanrahan, P. and Tversky, B. (2003) Designing effective step-by-step assembly instructions. ***Proceedings of SIGGRAPH '03.***

Agrawala, M. and Stolte, C. (2001). Rendering effective route maps: Improving usability through generalization. ***Proceedings of SIGGRAPH '01,*** 241-250.

Chase, W. G. and Simon, H. A. (1973). The mind's eye in chess. In W. G. Chase (Editor), ***Visual information processing. N.Y.:*** Academic Press.

de Groot, A. D. (1965). ***Thought and choice in chess.*** The Hague: Mouton.

Goldschrnidt, G.: 1994, On visual design thinking: the vis kids of architecture, ***Design Studies,*** 15(2): 158-174.

Heiser, J. and Tversky, B. (submitted). Mental models of complex systems: Structure and function.

Heiser, J., Tversky, B., Agrawala, M., and Hamahan, P. (submitted). Cognitive design principles for visualizations: Revealing and instantiating

Heiser, J., Tversky, B., and Daniel, M.-P. (in preparation). Constructing instructions.

Howard-Jones, P. A.: 1998, The variation of ideational productivity over short timescales and the influence of an instructional strategy to defocus attention, ***Proceedings of Twentieth Annual Meeting of the Cognitive Science Society,*** Hillsdale, New Jersey, Lawrence Erlbaum Associates, pp. 496-501.

Jansson, D. G. and Smith, S. M.:1991, Design fixation, ***Design Studies,*** 12(1), 3-11.

Schon, D. A. : 1983, ***The Reflective Practitioner,*** Harper Collins, USA.

Suwa, M., Gero, J. and Purcell, T.: 2000, Unexpected discoveries and S-invention of design requirements: Important vehicles for a design process, ***Design Studies,*** 21(6): 539-567.

Suwa, M. and Tversky, B.: 1997, What do architects and students perceive in their design sketches?: A protocol analysis, ***Design Studies,*** 18(4): 385-403.

Suwa, M., & Tversky, B. (2001). Constructive perception in design. In J. S. Gero & M. L. Maher (Eds.) ***Computational and cognitive models of creative design*** *V*, Sydney: University of Sydney, pp.227-239.

Suwa, M, Tversky, B, Gero J. & Purcell, T. (2001). Regrouping parts of an external representation as a source of insight. Proceedings of the 3rd International Conference on Cognitive Science (pp.692-696). Beijing, China: Press of University of Science and Technology of China..

Tversky, B. (In press). Functional significance of visuospatial representations. In P. Shah & A.Miyake (Eds.), ***Handbook ofhigher-level visuospatial thinking.*** Cambridge: Cambridge University Press.

Tversky, B., & Hemenway, K. (1984). Objects, parts, and categories. ***Journal of Experimental Psychology: General, 113,*** 169-193.

Tversky, B., & Lee, P. U. (1998). How space structures language. In C. Freksa, C. Habel, & K. F. Wender (Eds.), ***Spatial cognition: An interdisciplinary approach to representation and processing of spatial knowledge*** (pp. 157-175). Berlin: Springer-Verlag.