What Does Drawing Reveal about Thinking?

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ABSTRACT. Drawings are an integral part of the dialogue a designer conducts with him or herself during design. They are a kind of external representation, a cognitive tool developed to facilitate information processing. Drawings differ from images in that they reflect conceptualizations, not perceptions, of reality. For a particular domain, sketches use a small set of segments or elements that map the critical elements of the domain. It is proposed that the choice of and representation of elements and the order in which they are drawn reflect the way that domain is schematized and conceptualized. Support for this claim is gathered from research on sketch maps, graphs, and geometric analogy solution.

Design without drawing seems inconceivable. One view of the role of sketching in design is an iterative, cyclical, dialectic view where sketches serve to instantiate design ideas as well as to stimulate new ones. In each cycle, designers express their ideas externally, on paper, and then examine, interpret, and perhaps reinterpret them. This inspection of the drawings may inspire changes in design ideas, which are put down again on paper to be reexamined again, reconceived, redrawn, reexamined, and so on (for expansion of these ideas, see Goldschmidt, 1989, 1991, 1994; Goel, 1995; Purcell and Gero, 1998; Schon and Wiggin, 1992; Suwa, Gero, and Purcell, 1998; Suwa and Tversky, 1996, 1997). In the experienced designer, consideration of the drawings arouses thoughts about visible aspects of the sketches, of the shapes and arrangements of the design elements, as well as thoughts about aspects of the sketches not directly visible, such as functions and activities enabled by the elements and their spatial arrangements (e.g., Akin, 1986; Goldschmidt, 1989, 1991, 1994; Goel, 1995; Suwa, Gero, and Purcell, 1998; Suwa and Tversky, 1996, 1997; Verstinjnen, Hennessey, van Leeuwen, Hamel, and Goldschmidt, 1998).

Drawings are a kind of external representation, one of many cognitive tools invented to facilitate memory and thinking (see discussions by Donald, 1991; Kirsch, 1995 Larkin and Simon, 1987; Norman, 1993; Scaife and Rogers, 1996; Stenning and Oberlander, 1995; Tversky, 1995, in press). Successful external cognitive tools compensate for limitations in human memory and information processing at the same time that they take advantage of them. People are limited simultaneously by the amount of information they can keep in mind and the number of mental operations they can apply to that information. Memory limitations can be reduced by offloading memory to external displays that can be inspected and reinspected. Similarly, mental operations can be facilitated by putting the information relevant to particular operations in spatial contiguity and by taking advantage of people's enormous capacity for recognizing many different patterns (Larkin and Simon, 1987). The way that elements are arranged in space--in groups, orders, or distances--can be meaningful, either iconically or metaphorically (e.g., Kirsh, 1995; Kieras, 1992; Tversky, 1995; in press). These advantages of external cognitive tools are especially available in depictions. Depictions have the added advantage that they can be inspected, discussed, and altered by a group of thinkers, even when distributed over time and space.

Drawings are sometimes regarded as externalizations of images. They are both more and less than that. According to the classical view of imagery (e.g., Kosslyn, 1980, 1996; Shepard and Podgorny, 1978), images are like internalized perceptions. They have qualities like perceptible qualities of objects; they are inspected and transformed in ways analogous to inspecting and transforming objects. Indeed, in elegant research it has been shown that imaging activates some of the very brain structures that perceiving does (Kosslyn, Thompson, Kim, and Alpert, 1995). Like perception of objects, images are regarded as having a single, coherent point of view. Furthermore, certain kinds of drawings, like comics or design sketches or route maps, contain extra information not in perceptions and not necessarily in images, such as arrows to indicate directions or squiggly lines to indicate heat rising or annotations in the form of words. Although drawings can be like images, they frequently contradict many of the properties attributed to images. To put it succinctly, drawings reveal people's conceptions of things, not their perceptions of things.

How might our conceptions of things differ from our perceptions of them? Children's drawings are an excellent case in point (e.g., Goodnow, 1977; Kellogg, 1969). Consider their early drawings of people. All the world over, young children draw people by drawing a circle for a face, with arms and legs extending from it. Does this mean that children perceive that people have 4 limbs and no body, and that the limbs are attached to the head? Certainly not. Rather, a head, arms, and legs are the components of children's early conceptions of the human body, to be enriched by the addition of other body parts. Older children may draw scenes like a ring of children holding hands. One way that many children portray this is by drawing a circle, with an array of children extending from it, feet to the border of the circle, heads outwards. If this were meant to be a drawing from a single point of view, it would be interpreted as children lying on the ground on the perimeter of a circle. But this is not what was intended, nor is it what is understood. Drawings such as these do not attempt to adopt a consistent point of view. Neither the Impressionists nor the Cubists invented mixed perspectives, nor is their use restricted to children. The tourist maps popular today that superimpose frontal views of landmarks onto aerial views of road networks have their ancient counterparts (e.g., Brown, 1949; Noble, 1981; Southworth and Southworth, 1982). Comics provide another common example of drawings that present conceptions of reality (McCloud, 1993); we have become so accustomed to conventions of conveying motion, excitement, and heat that we think we "see" them directly in the drawings.

Drawings, then, are representations of reality, not presentations of reality. Drawings can omit things that are actually there, they can distort things that are there, they can add things that are not there. They need not have a consistent point of view or a point of view at all. As such, drawings are of even greater interest to art critics, designers, and psychologists alike. They can provide insights into conceptulizations not just imaginings.

Segmentation

Depictions of all kinds can be separated into elements and the spatial arrangements of elements. For depictions meant to reflect the real world, elements are the objects in it; for maps, elements may be streets or towns or countries; for data graphs, they may be data points or summaries; for diagrams, they may be conceptual elements. For some of these depictions, the spatial relations may be meant to reflect spatial relations in the real world; for more abstract depictions, the spatial relations may be meant to reflect nonspatial relations, such as money or power. For drawings intended to be realistic, Willats (1997) distinguishes three drawings systems for conveying spatial relations--perspective, oblique projection, and orthogonal projection--and three denotation systems for conveying elements--silhouettes, lines, and optical systems like Pointillism. Design sketches fall into Willats' analysis. The present concern is with representation of elements rather than spatial relations. The issues, however, go beyond those of the physical medium discussed by Willats.

One aspect of drawing apparent to those studying drawings of children and adults, of novices and experts, is that drawings are naturally segmented into elements, that these elements are schematized, that they can be arranged spatially in endless ways (e.g., Goodman, 1968; Goodnow, 1977; Kellogg, 1969, von Sommers, 1984). The particular segments are specialized for content, so the segments of a body are different from the segments of geometric figures or simple objects (von Sommers, 1984), the segments for a an architectural sketch (Do and Gross, 1997a, 1997b) or the segments of sketch map (Tappe and Habel, 1998; Tversky and Lee, 1998, in press), and all differ from the segments used for handwriting (Bar On, 1999). In fact, the segments that make up the sketch vocabulary give insight into the conceptual components of that domain. Bodies, as noted, early on consist of a head, two arms, and two legs; other parts are added later. Handwriting in English consists of about 12-14 strokes that are combined by an individual to construct all of the letters (Bar On, 1999). For handwriting, the elements seem to be motor elements, tied to the different movements of the hand required to make letters.

Sketch maps are an interesting case in point. At one level, sketch maps can be viewed as composed of lines, curved or straight, parallel, or crossing at various angles (Tappe and Habel, 1998). These might be viewed as motor elements of the act of drawing. However, on further inspection, the elements of sketch maps are conceptual elements. Tversky and Lee (1998; in press) asked passersby on campus if they knew how to get to a popular fast food place off-campus. If they said yes, they were asked to either sketch a map or to write directions to get there. We adapted procedures developed by Denis (1997) for decomposing route directions into segments to both our data sets, route sketch maps and route verbal directions. For the most part, maps and directions consisted of the same segments, paths, landmarks, and actions. Moreover, the segments captured the real world schematically. For example, paths were generally portrayed as straight or curved and intersections as X, T, or Y. They did not reflect the exact angles of the actual paths. The verbal segments were similarly categorical: to indicate a straight path, participants said "go" but to indicate a curved path, participants said "follow around." The similarities in segments of depictions and descriptions as well as the similar categorical nature of both suggested that verbal and pictorial toolkits consisting of a small number of units could be used to construct a large set of sketch maps and directions. In fact, this proved to be true; another group of participants used all of the elements in the toolkits to construct new sets of route instructions, finding little need to supplement the toolkits with additional segments (Tversky and Lee, in press). The success of construction of sketch maps and verbal directions with parallel toolkits is encouraging for automatic translation between them.

This leads to a conjecture: Automatic translation between descriptions and depictions ought to be possible when the same conceptual structure underlies each. Another domain where early results encourage such an enterprise is data graphs. Zacks and Tversky (in press) studied students' interpretations of line and bar graphs and conversely, their choice of line and bar graphs in producing depictions of described data relations. Bars are naturally interpreted as containers, as enclosing one set of things and separating that set from other sets. Lines, on the other hand, are naturally interpreted as connectors, as paths interrelating different points. Thus, in the context of representing data, a more natural way to represent discrete quantities is by bars and a more natural way to represent trends is by lines. In fact, participants did exactly that in both interpretations and productions, even when the underlying nature of the data as discrete or continuous contradicted the depiction.

The first way that sketches can reveal thought, then, is that they can reveal the elements or segments of construction or of thought in a particular domain. Notice that this view of drawings as segmented into a small number of elements that can be combined to form an infinite number of drawings is similar to views of language, which is also seen as decomposible into segments that can be combined. It is a digital, categorical, bordering on symbolic (see Goodman, 1968), view of drawings and stands in contrast to an analog view in which lines in drawings might be seen as mapping some continuous aspect of reality, say contours of objects, point by point.

Order

Similarly, the order of drawing the elements of a sketch or design reveals the organization underlying the sketch. The organization revealed can be at any of several levels, at the level of a motor program, at the level of mental construction of the drawing, at the level of the conceptual organization of what is to be drawn. Von Sommers (1984) analyzed the order of copying and drawing geometric designs and simple objects. Motor convenience seemed to account for part of the order of strokes, especially for geometric figures. However, for objects, salience of part also seemed to play a role in order. For example, in drawing a bicycle, the frame and wheels were typically drawn first. Salience, in turn, seems to be related to size or centrality or importance

ORDER OF MENTAL TRANSFORMATIONS. Novick and Tversky (1987) investigated the order in which problem solvers imagined the mental transformations necessary to solve geometric analogies. To solve the geometric analogies required applying two or three mental transformations taken from a larger set consisting of transformations typical to this task, move, rotate, reflect, change size, add part, subtract part, change shading. The order of performing the transformations made no difference in the solution; that is, the same solution would be obtained irrespective of order. Nevertheless, participants typically performed the transformations in the same shared order, that listed above. Moreover, when they were asked to perform them in a different order, their errors and times increased. What accounts for selection of this order?

The data did not support a number of theories for the order of mental transformations. For example, neither the time to perform nor the difficulty of performing the mental transformations correlated with the order of performing them, discounting theories of difficulty of transformation as predicting order of transformation. Similarly, working memory load did not account for order of transformation. Mentally constructing a complex geometric figure is similar to mentally drawing one. We speculated that mental construction is like mental drawing, and should use the same mental constructive processes. Analysis of the task of drawing supported this proposal. The first step in drawing is deciding where on paper to begin. This parallels the "move" transformation. The next step is to decide what direction to move the pencil; this parallels the orientation transformations, rotate and reflect, which are the second and unordered mental transformations applied in solving the geometric analogies. The third decision is how long a line to mark; this corresponds to the size transformations. Finally, small parts and shading can be added to the drawing or the mental solution.

Order of drawing, then, reflects order of mental transformations. Although mental transformations, being mental, are unconstrained in order, they are performed in a stereotypic order. That order follows the constrained order of drawing, suggesting that the mental order internalizes the construction order.

Hierarchical Structure of Knowledge

As the von Sommers' work on drawing order of objects suggests, drawing order can also reflect underlying conceptual structure. The comparison of descriptions and depictions of environments provide a case in point. Taylor and Tversky (1992) asked participants to study maps of simple environments, a small Town, an Amusement Park, or a Convention Center, consisting of 13-17 landmarks. Participants were told that they would either sketch the map or describe the environment. In fact, they did both, in counterbalanced order. Expectation to draw or describe had no detectable affect on performance. Interestingly, elements of both maps and descriptions followed the same order of mention both within and across participants. Moreover, this order reflected the way the environments were mentally organized. Mental organization was hierarchical for each environment. For example, the Town was organized around first large landmarks, mountains and rivers, then major streets and highways, and finally, buildings. The Amusement Park was subdivided into entrance and three thematic areas, and the Convention Center into outer and inner cores. Both descriptions and depictions followed the same hierarchical order for each of the environments. This suggests that environments are mentally organized first, independent of communication medium, and that prior organization is imposed on the communication.

Implications for the Study of Design

As was illustrated in a number of different domains, drawings are a clue to mental conceptualizations of domains. Drawings in a particular domain use a small number of segments or elements in varying combinations to produce a potentially infinite set of different drawings. The segments are appropriate to a particular domain, reflecting the underlying conceptual structure of that domain. The segments here are units of drawings; they may or may not correspond to the "chunks" of design, which also typically include verbal commentary (e.g., Akin, 1986; Goldschmidt, 1989, 1991, 1994; Suwa, Gero, and Purcell, 1998; Suwa and Tversky, 1996, 1997) Moreover they are schematized so that they reflect general, summary properties of the entities that they convey, not detailed, analog properties. As designing progresses and design elements take more specific form, the schematization of elements may be sharpened and refined (e.g. Do and Gross, 1997a, 1997b). Thus, studying the segments of sketches in a design domain should give insight into what conceptual modules are operative and how they are schematized.

The order of production of drawing can also give insights into the conceptions behind the design. Designs are typically too large to be imagined at once. Like other large mental structures, design ideas are then organized hierarchically, with larger units allowing reconstruction of those smaller units contained in them. Mental hierarchies are typically structured in a natural way, by appearance, by function, by significance. Frequently, these seemingly different organizations coincide (e.g., Tversky and Hemenway, 1984). The order of drawing elements reveals the mental organization underlying the design. It is even possible that calling the features of segmentation and ordering of drawing to the minds of designers will promote the dialogue they conduct with their designs.

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