What do Sketches say about Thinking?

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Abstract

Sketches are produced in many domains to communicate with self or others. They are a kind of external representation serving as a cognitive tool to augment memory and information processing by relieving the mind of some of those burdens. Sketches schematize. They do not portray reality; rather they convey conceptions of reality. Sketches use elements and spatial relations on paper to represent elements and spatial or abstract relations in the domain of interest. They incorporate relevant information and omit irrelevant. As such, they reveal people's conceptions of domains.. An analysis of sketches of routes, for example, reveals that they segment routes around action points, typically turns. Order of drawing reflects mental organization of the domain. From sketches, novices extract structural information about the spatial relations among elements. Experts are also able to extract functional information, information that must be inferred from rather than directly extracted from sketches.

Why do People Sketch?

Sketches are a way of externalizing ideas, of turning internal thoughts public, of making fleeting thoughts more permanent. Of course, written language can do the same, but sketches have the advantage of conveying visuospatial ideas directly, using elements and spatial relations on paper to convey elements and spatial relations in the world. This may explain their ubiquity; maps and architectural plans have been found incised in stone, etched on leather, impressed in clay, and drawn on paper in diverse cultures scattered over the world. Sketches can also convey abstract ideas metaphorically, using elements and spatial relations on paper to express abstract elements and relations. Expressing ideas in a visuospatial medium makes comprehension and inference easier than in a more abstract medium such as language. The externality of sketches and similar cognitive tools promotes memory, providing a record that does not rely on unreliable human memory. They also provide a token for the contents of working memory, relieving the dual burden of holding the content and also simultaneously operating on it. Instead, computations and inferences can be made on an external representation. (e. g., Kirsch, 1995; Tversky, 2001) The public nature of sketches allows a community to observe, comment on, and revise the ideas, and enact those revisions in the external representation.

Like spoken and written language, sketches are a form of communication. More than talking, sketches often serve as communications for self. One role of a sketch is to check the completeness and internal consistency of an idea, especially a spatial idea. A sketch is a literal model of an idea, an existence proof. Another role of sketches for self is to see new relations and figures. These newly seen objects and relations can promote new ideas (e. g., Goel, 1995; Goldschmidt, 1991, 1994; Shon, 1983; Shon and Wiggins, 1992; Suwa, Gero, and Purcell, 2000; Suwa and Tversky, 1996, 1997; Suwa, Tversky, Gero, and Purcell, 2001). Sketchers make sketches with certain ideas and goals in mind, but fortuitously, may see new objects and configurations in their sketches. These encounters produced welcome but unintended discoveries, and may be a fruitful source of new design ideas.

What do People Put in Sketches?

Schematic Structure

Let's begin with maps, the most ubiquitous of sketches, produced by novices and experts, adults and children across the world and over the millennia. Two broad classes of maps can be discerned: those that convey regions (e. g., Taylor and Tversky, 1992), and those that convey routes (e. g., Tversky and Lee, 1998, 1999). In both cases, maps schematize. They include information important to their purposes, eliminating the irrelevant. More than that, map sketches simplify, even distort, the information included to conform to the structure to be conveyed. The structure captured by sketches is not the structure of the environment, but rather, the conceptual structure of the information. Evidence for this comes from an analysis of route sketch maps by Tversky and Lee (1998, 1999).

Students were approached outside a dorm and asked if they knew how to get to a local fast food restaurant. If so, they were asked to either sketch a map or to write directions to the restaurant. These were analyzed by a system developed by Denis (1997) for decomposing route directions into a sequence of segments consisting of start points, reorientations, progressions, and end points. The analysis held for route sketches as well as route directions. In the case of route sketches, each segment was represented by stylized elements. Start and end points were depicted as blobs, irrespective of their actual shape, or names. Reorientations were depicted as T's, L's, or +'s depending on the configuration of the intersection, but irrespective of the actual angles. Progressions were depicted as straight lines or curves, again, irrespective of the actual curvature.

Sketch maps could be analog, unlike language. Instead, they are quite language-like. They are segmented into elements. They consist of language-like strings of stylized figures, lines, curves, and blobs (Zacks, Lee, and Heiser, 2000). These elements can be combined in different ways to create different meanings, again, like language (Goodman, 1968). The parallels to language go further. In fact, the meanings of the depictive elements can be mapped onto the meanings of the linguistic elements. Reorientations were two types, "go down" for straight paths and "follow around" for curved paths. Actions at intersections, regardless of angle or type, were described as "make a" or "take a" or "turn" followed by a direction. Long distances with no actions are truncated, and short ones with many actions enlarged.

A survey of these maps as well as those produced across ages and cultures (Tversky, 2000) illustrates yet other features of sketches. They often include depictive elements that are not present in reality, such as boundaries and arrows. They also include symbolic elements such as names, populations, distances. They may mix perspectives, for example, portraying a road system from above and salient landmarks from within. This allows travelers to find a route to a landmark and to recognize the landmark when they arrive.

Both route sketches and route directions, then, reflect the same conceptual structure. Routes are conceived of as sequences of start points, reorientations, progressions, and end points. The sketch elements are sufficient to convey that structure, but insufficient to convey the exact configuration in the world. In fact, they may severely distort the configuration of the world. These distortions do conflict with their purpose, of getting a traveler from one point to another. The environment itself can correct the distortions. Even if a 60 degree turn is depicted as 90 degrees, the traveler has little choice but to turn 60 degrees. Similarly, if a road is more or less curved than depicted, the traveler again has little choice but to follow the road's curvature, whatever it is.

Route sketches, like spoken and written language, are an ancient and well-practiced form of communication, so it is not surprising that they have become stylized, indeed, language-like, consisting of a small set of schematized elements that can be combined in different ways to convey different meanings. They have advantages over spoken and written language in that the elements themselves are spatial, and can be readily interpreted in context, straight lines on paper as straight paths in the world.

Other Domains

Sketches from other domains have the same character; that is, they consist of a small set of stylized elements that are combinatoric. Children from all over the world sketch people as circular blobs for heads and later for bodies, sticks for arms and legs (Goodnow, 1977; Kellogg, 1969). Handwriting can be decomposed into 12-14 stroke types that are used to compose all letters (Bar On, 1999). The graffiti interface to PDA's is based on combing a small set of diagrammatic elements. Japanese and Chineses calligraphy is composed of a small set of strokes, combined in different ways. Architectural sketches, too, can be decomposed into a small set of elements that can be combined to create large structures (Do and Gross, 1997a, 1997b). Sketches of statistical data and mechanical devices are also composed of simple figures that have meanings easily interpreted in context. Arrows, for example, are asymmetric lines. They suggest an asymmetric connection. As such, they have many uses, among them, to label, to indicate direction, to indicate motion, to indicate order.

Hierarchical Structure

Sketches of regions reveal other characteristics of sketches. The order in which people draw regional maps reflects the conceptual structure of the maps (Taylor and Tversky, 1992). Participants read descriptions or studied maps of regions. Later, they were asked to produce sketches and descriptions of the regions. The order of sketching elements of the regions and the order of mentioning them in descriptions correlated. For regions that had features on different environmental scales, the large features, such as rivers and mountains, were depicted or described before the smaller ones, such as road structure or buildings. This suggests that people impose a hierachical structure on even flat regions, and use that structure to organize the environment.

Sketches in many domains are not presentations of reality, they are representations of reality (Tversky, 1999). They differ from reality in important ways: they omit information, they add information, they distort information. As such, they are not externalized images, at least not in the "classic" sense of images, as internalized perceptions (Kosslyn, 1980). Sketches can be, however, externalizations of ideas. As such, they can convey ideas, especially visual spatial ones, effectively. They can also facilitate discovery of new objects and relations, foster new ideas. Let us now turn to what people extract from sketches.

What do People Extract from Sketches?

It is not trivial to say that people can extract from sketches what sketchers intended. How often have we returned to our own sketches, and writings, only to be bewildered by what was meant to be conveyed. Across a number of domains, including maps and diagrams of devices, what is meant to be conveyed is structure. In fact, from well-composed accurate route maps, the structure of the route can be communicated accurately enough for a traveler to arrive at the proper destination. Similarly, from a well-constructed diagram of a device, the structure of the device can be conveyed (Heiser and Tversky, 2002).

Sketches can also provide a rich source of new ideas for design. ideas (e. g., Goel, 1995; Goldschmidt, 1991, 1994; Shon, 1983; Shon and Wiggins, 1992; Suwa, Gero, and Purcell, 2000; Suwa and Tversky, 1996, 1997; Suwa, Tversky, Gero, and Purcell, 2001). Sketchers make sketches with certain ideas and goals in mind, but fortuitously, may see new objects and configurations in their sketches. These encounters produced welcome but unintended discoveries, and may be a fruitful source of new design ideas.

Extracting the Unseen from the Seen

Sketches and diagrams can be useful for conveying more than structure. They can also be effective in conveying certain abstractions that may be inferred from the structure presented in the sketch but are not directly conveyed by the sketch. Consider mechanical devices such as a bike pump, car brake, or pulley system. All of these devices move; what's more they move to accomplish certain ends. How they move and what they accomplish is usually not directly conveyed in sketches. The small addition of an arrow to sketches of mechanical systems changes their interpretation. When asked to write descriptions of what is portrayed in the diagram, participants viewing simple diagrams of a car brake, pulley system or bike pump write structural descriptions. When arrows were added to the diagrams, participants write functional descriptions of the devices, explaining what they do, step-by-step. The arrows convey temporal order, allowing viewers to mentally animate (Hegarty, 1992) the device. Inferring causal sequence from temporal order is apparently an inference undergraduates make immediately (Heiser and Tversky, 2002). The converse also holds. When presented with a structural description of one of the systems and asked to construct a diagram, participants produced sketches without arrows. However, when provided with a functional description, participants produced sketches with arrows (Heiser and Tversky,, 2002).

Ability

Ability affects the kinds of inferences participants are able to make from sketches. Participants with high mechanical ability were better at making functional inferences from sketches than participants with low mechanical ability (Heiser and Tversky, 2002).

Expertise

Expertise is another quality that affects the inferences that can be made from sketches. Suwa and Tversky (1996; 1997) asked trained architects and students of architecture to design a museum under certain constraints. Afterwards, the participants saw videos of their sketching sessions and reported what they were thinking as they drew each line of the sketch. Practicing architects made more functional inferences from their own sketches than students of architecture. For example, practictioners were more likely to "see" patterns of movement and patterns of light in their sketches than students. These functional attributes are not directly conveyed in the sketches, but can be inferred from them. The presence of corridors connecting high and low use structures allows inferences about traffic flow, just as the presence of windows and skylights along with knowledge of cardinal directions allo inferences about light.

In another experiment, trained designers and laypeople were shown abstract, ambiguous sketches and asked to generate as many different interpretations of the sketches as they could. Expert designers generated more interpretations than laypeople.

Structure is readily acquired from well-formed sketches. Unseen information, such as motion, can also be inferred from sketches, though these inferences from the seen to the unseen may depend on expertise and ability.

Nature of Sketches

Sketches are a useful tool for checking and conveying ideas, for self and others. They also serve as an external display to facilitate inference and discovery., to go from the intended to the unintended, to go from the seen to the unseen. Sketches for design or for diagrams are structured. They consist of elements or segments that can be combined to create a wide range of meanings. The elements are often simply schematic figures such as lines and blobs whose meanings are readily interpretable from their geometric and Gestalt properties. Such sketches have some of the structure of spoken language. Unlike language, however, sketches convey figural and relational properties directly, facilitating memory, inference, and discovery. Nevertheless, there are intriguing parallels between sketches and language, between depictions and descriptions at two levels: at an abstract level, in the very existence of segmentation and combination, and at the level of content of a particular domain, in the particular segments and combinations, most notably in route maps and directions. Under the proper light, analysis of each, descriptions and depictions, can reveal thinking.

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References

Bar On, E.: 1999, Personal communication.

Denis, M.: 1997, The description of routes: A cognitive approach to the production of spatial discourse, *Cahiers de Psychologie Cognitive*, 16, 409-458.

Do, E. Y-L and Gross, M. D.: 1997a, Computatbility of design diagrams: An empirical study of diagram conventions in design, in R. Junge (ed.), *CAAD Futures*, pp. 171-176.

Do, E. Y-L. and Gross, M. D.: 1997b, Inferring design intentions from sketches: An investigation of freehand drawing conventions in design, in Y-T Liu, J-Y Tsou, and J-H Hou (eds), *Proceedings of the Second Conference on Computer Aided Architectural Design Research in Asia*, Taiwan, pp. 217-227.

Goel, V.: 1995, Sketches of Thought, MIT Press, Cambridge, MA.

Goldschmidt, G.: 1991, The dialectics of sketching, *Design Studies*, 4, 123-143.

Goldschmidt, G.: 1994, On visual design thinking: The vis kids of architecture, *Design Studies*, 15, 158-174.

Goodman, N.: 1968, Languages of Art: An Approach to a Theory of Symbols, The Bobbs-Merrill Company, Inc.

Goodnow, J.: 1977, *Children's Drawing*, Open Books, London.

Hegarty, M. 1992. Mental animation: Inferring motion from static displays of mechanical systems. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 18, 1084-1102.

Heiser, J. and Tversky, B. 2002. Descriptions and depictions of complex systems: Structural and functional perspectives, submitted.

Kellogg, R.: 1969, *Analyzing Children's Art*, National Press, Palo Alto, CA.

Kirsh, D.: 1995, The intelligent use of space, Artificial Intelligence, 73, 31-68.

Kosslyn, S. M.: 1980, *Image and Mind*, Harvard University Press, Cambridge, MA.

Kosslyn, S. M.: 1996, Image and Brain, MIT Press, Cambridge, MA.

Schon, D. A.: 1983, *The Reflective Practitioner*, Basic Books, New York.

Schon, D. A. and Wiggins, G.: 1992, Kinds of seeing and their function in designing, *Design Studies*, 13, 135-156.

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, 539-567.

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, 539-567.

Suwa, M. and Tversky, B.: 1996, What architects see in their sketches: Implications for design tools, *Human Factors in Computing Systems*: Conference Companion, ACM, NY, pp. 191-192.

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

Suwa, M., Tversky, B., Gero, J., and Purcell, T. (2001). Seeing into sketches: Regrouping parts encourages new interpretations. In J. S. Gero, B. Tversky and T. Purcell (Editors). *Visual and spatial reasoning in design, II.* Pp. 207-219. Sydney, Australia: Key Centre of Design Computing.

Taylor, H. A. and Tversky, B.: 1992, Descriptions and depictions of environments, *Memory and Cognition*, 20, 483-496.

Tversky, B. (1999). What does drawing reveal about thinking? In J. S. Gero and B. Tversky (eds), *Visual and spatial reasoning in design.* Sydney, Australia: Key Centre of Design Computing and Cognition pp.93-101.

Tversky, B. (2000). Some ways that maps and diagrams communicate. In Freksa, C., Brauer, W., Habel, C., and Wender, K. F.(eds). *Spatial cognition II: Integrating abstract theories, empirical studies, formal models, and practical applications*. Springer-Verlag, Berlin, pp. 72-79.

Tversky, B.: 2001, Spatial schemas in depictions, in M. Gattis (ed.), *Spatial Schemas and Abstract Thought*, MIT Press, Cambridge, MA, pp. 79-111.

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

Tversky, B. and Lee, P. U. 1999, Pictorial and verbal tools for conveying routes In C. Freksa, and D. M. Mark, (eds). *Spatial information theory: cognitive and computational foundations of geographic information science*, Springer-Verlag, Berlin, pp.51-64.

Tversky, B, Zacks, J., Lee, P. U., & Heiser, J. (2000). Lines, blobs, crosses, and arrows: Diagrammatic communication with schematic figures. In M. Anderson, P. Cheng, and V. Haarslev eds.,*Theory and application of diagrams*. Springer-Verlag, Berlin, pp. 221-230.

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