SEMANTICS, SYNTAX, AND PRAGMATICS OF GRAPHICS

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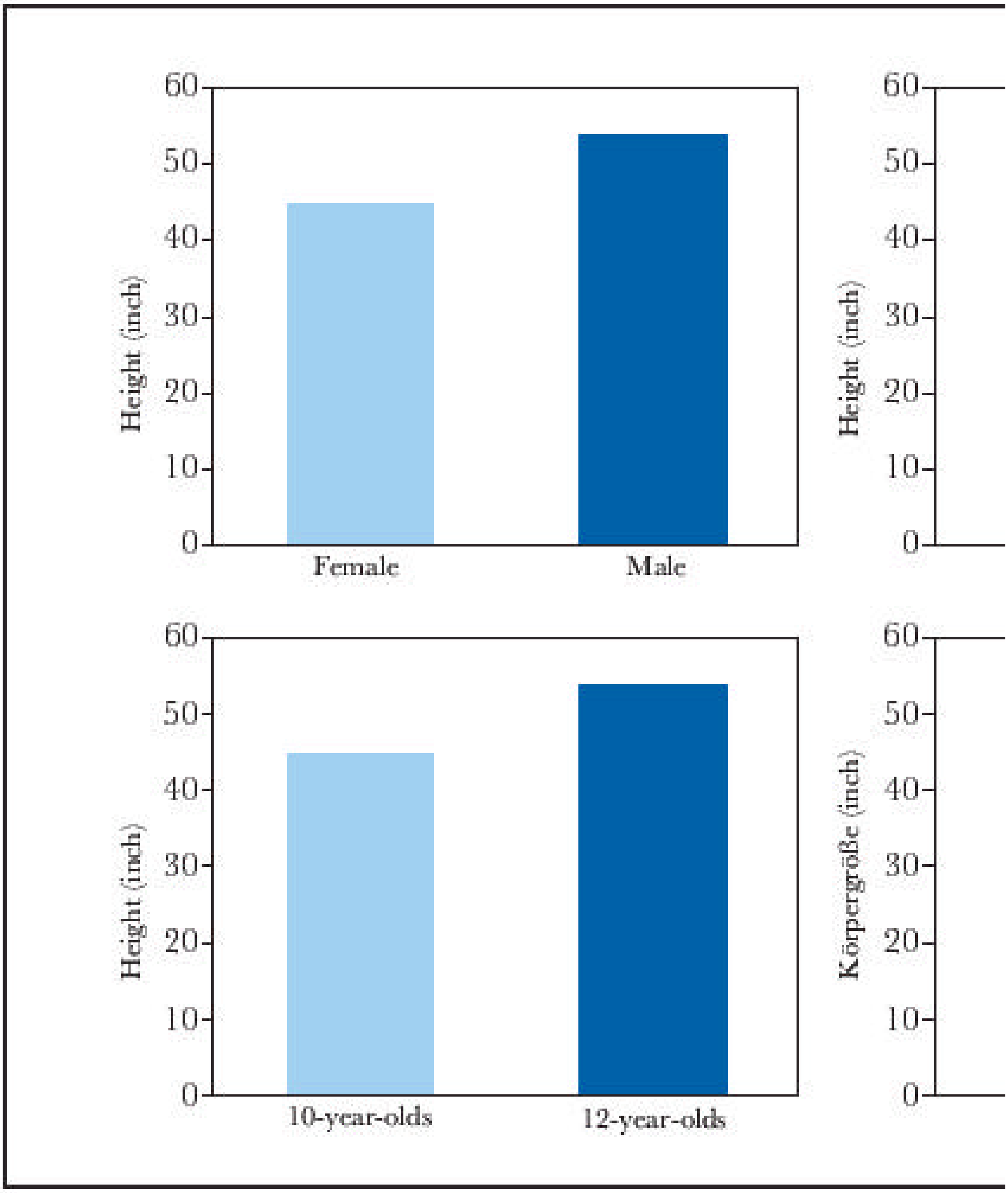
Height (inch)
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Female
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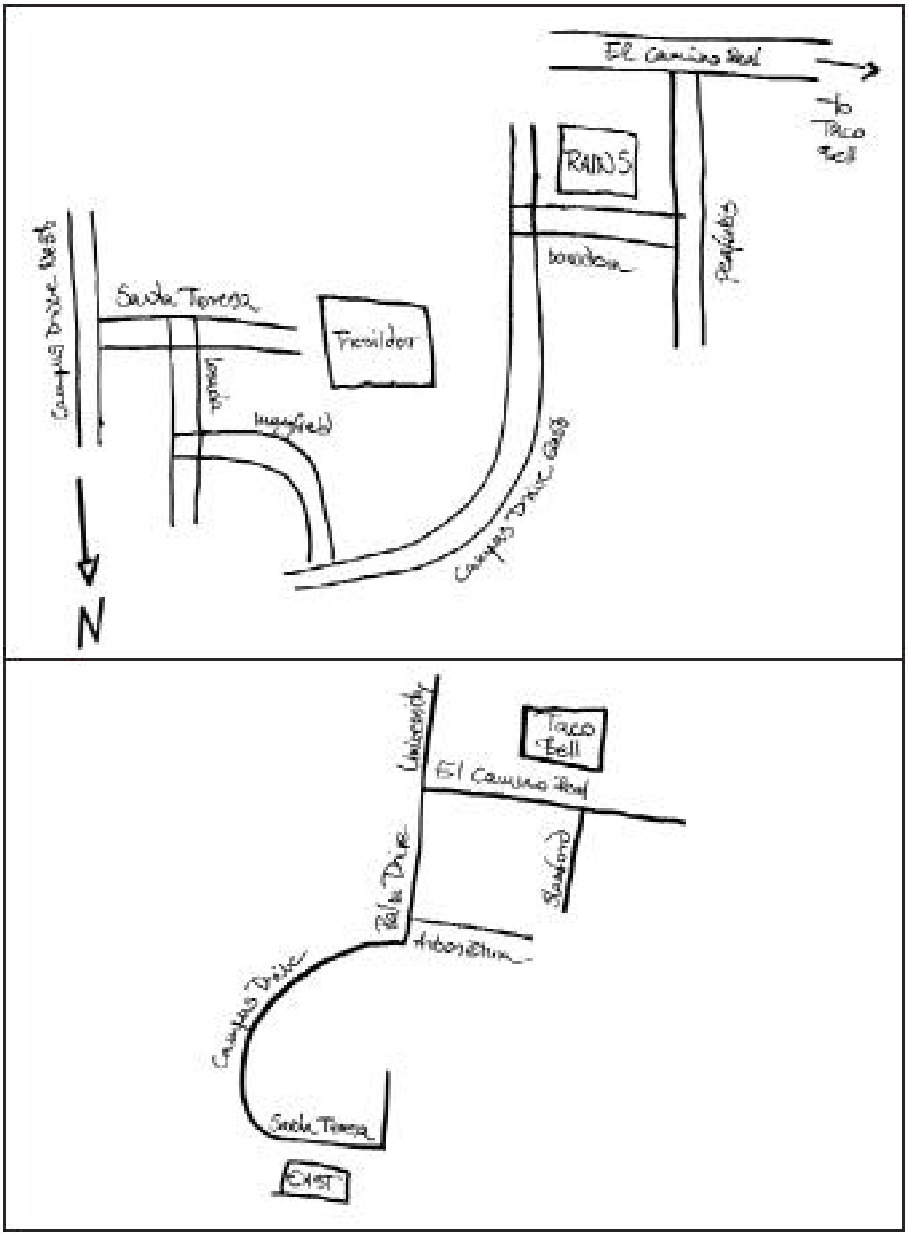
EL Camino Real
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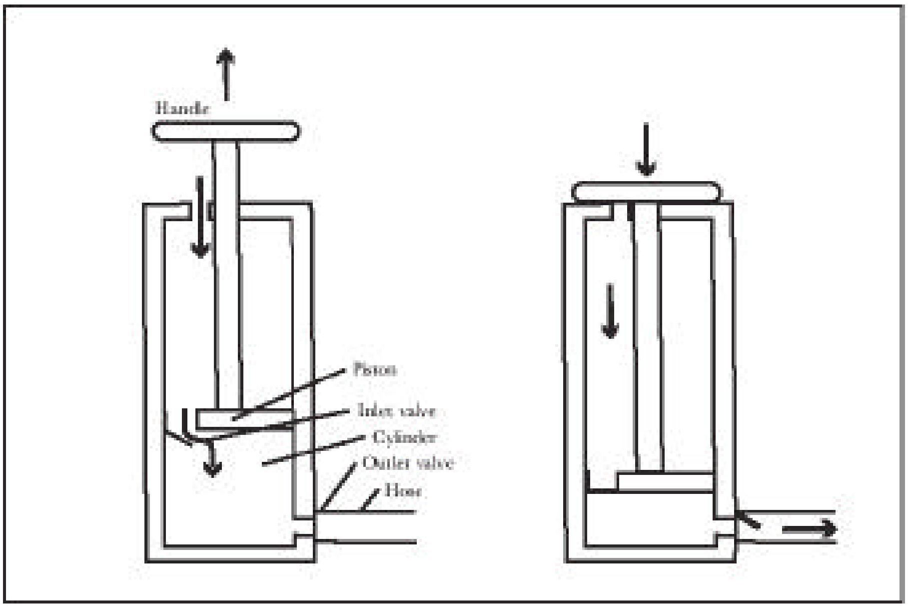

Graphics count among the oldest and newest forms of communication. Maps, for example, have been drawn in the sand or incised in stone or imprinted in clay for millennia. Maps now appear on PDAs or are downloaded from websites or are updated in car navigation systems. Ancient maps and modern ones, maps produced by professionals and those created by novices, by children and by adults, share many features. They schematize the information, eliminating some of it and simplifying other (Tversky, 2000). Long distances with little of importance are shortened, curves are eliminated, turns are simplified to 90 degrees. Maps also display information not present in the terrain, names of landmarks, icons for churches or markets, and boundaries. Maps may present perspectives not possible in the world, showing overviews of networks of roads and frontal views of salient landmarks. These distortions and embellishments of actual space seem to facilitate the uses for which maps were intended. An aerial photograph doesn’t generally make a good map.

Space of graphics

Using diagrammatic space to represent real space.

Maps use space to represent space, as do architectural sketches, engineering designs, and instructions to operate devices. Such diagrams are ancient, and have appeared in many cultures. Other graphics use space to represent concepts and relations that are metaphorically spatial, for example, organization charts, flow diagrams, and economic graphs. Graphics using space to display metaphorically spatial concepts and relations began to appear in the late 18th century (Beniger and Robyn, 1978; Tufte, 1983). Interestingly, the early uses of such graphs are still the most common of graphs, plotting change over time (Cleveland and McGill, 1985).

Using diagrammatic space to represent metaphoric space. Using space to represent space has cognitive immediacy, is readily comprehended. Yes, there is the issue of scale; except for Borges' mythical case (1998), maps are smaller than the spaces they represent. But understanding reduction of scale seems almost effortless. Children and adults spontaneously gesture when describing space, even large spaces not currently viewed (Iverson and Goldin-Meadow, 1997). They also spontaneously build models of space using props or on paper. For both gestures and models, the representing space is typically smaller than the represented space. Spatial language, terms like "near," "above," and "along," is claimed to be scale-independent (Talmy, 1983). Using space to represent metaphorically spatial concepts is apparently not as immediate as using space to represent space. Graphics using space metaphorically are a recent, Western invention, undoubtedly reflecting their relative lack of transparency. This is in spite of the fact that languages all over the world use space metaphorically. Talented students are said to be at the top of heap or the head of the class, people are said to fall ill or into depressions, fields are described as wide open for those who wish to take the road less trodden. Gestures, too, reflect these spatial metaphors, high five, thumbs up or down. Up, on the whole (unemployment and inflation excepted), is good, more, powerful, strong, healthy.

Children use diagrammatic space to represent metaphorically spatial concepts.

Despite their late appearance, there is evidence that graphics that use space metaphorically do so in cognitively natural ways (Tversky, 1995, 2001). We asked children and adults in three language cultures to put stickers on paper to represent three entities that varied in space, time, quantity, or preference (Tversky, Kugelmas, and Winter, 1991). Children were asked, for example, to place stickers on paper to reflect the time they ate breakfast, the time they ate morning snack, and the time they ate dinner, or to reflect a TV show they disliked, one they liked a little, and one they liked a lot. Only a few of the preschool children failed to put the stickers on a line, as if they were representing three different and unrelated entities, categorical relations. Most of the children put the stickers on a line, that is, they represented these concepts at the level of ordinal information. Only the older children and the adults used space to represent nonspatial concepts at the interval level of information. Their placement of stickers reflected the order among the elements, but also the interval between the elements, so that the stickers for breakfast and morning snack were closer than the stickers between morning snack and dinner. The directions of increase conformed to the linguistic and gestural metaphors, that is, increases were portrayed as upwards or leftwards or rightwards, but downwards increases were avoided. Interestingly, the direction of the written language did not affect the direction of increases, except in the case of temporal relations. For temporal relations, increases tended to go rightwards for writers of English and leftwards for writers of Arabic, with Hebrew writers in between. In Arabic, both letters and numbers go leftwards, at least in early years of education, but in Hebrew, letters go leftwards but numbers go rightwards. In addition, Hebrew-speakers are more likely to be exposed to European languages.

Proximity in diagrammatic space signifies proximity in metaphoric space.

The basic spatial metaphor underlying graphics is one of proximity. The closer things are in real or conceptual space, the closer they are represented in diagrammatic space. Proximity may preserve relational information at several levels of information. Categorical uses include putting things into piles or groups by type, as in sorting nails and screws or knives and forks, or people by country or occupation. Ordinal uses include putting things in orders that correspond to other orders, for example, listing children by age or groceries by the order of encounter in the supermarket. Networks reflecting various hierarchies, such as taxonomies or organizational charts, are common uses of partial orders, a combination of categorical and ordinal uses of space. Interval uses include graphs of statistical data. For these, both the order of elements and the distance between elements are meaningful. Where there is a natural zero, space is used on a ratio scale in which case, ratios between elements are meaningful.

Graphical space may mix metaphors. A poignant graphic by Minard depicts Napoleon's failed campaign on Russia. The graphic is on a schematic map that highlights the major battles and geographic features from the French border to Moscow. Space is also used to indicate the changing size of Napoleon's army, a thick band leaving France, a trickle returning. Below, space is used to convey the diminishing temperatures of the winter. Distance, quantity, time, and temperature graphically tell a sad story.

Elements of graphics

Icons and figures of depiction.

Graphics use elements as well as space to convey meaning. The simplest and most direct kind of element is an icon, where the element bears resemblance to the thing it represents. These are as old as ideographic languages, where schematic animals and edibles represented their real-world counterparts, and as new as the latest computer or Olympics icons. But many useful concepts cannot be readily depicted. Figures of depiction have been spontaneously adopted, again since ancient times. Synechdoche, where a part represents a whole, is common, as in the horns or head of a sheep to stand for sheep. Similarly, metonomy, where an entity associated with a concept stands for the concept, as in a crown for a king or scales for justice or scissors for delete. The same devices, of course, appear in figures of speech. Icons that are related to the things they represent by figures of depiction also appeared in ancient scripts and appear in contemporary machinery. The advantage of icons and figures of depiction is that their meanings are readily understood and remembered.

Geoglyphs.

There is another kind of element that is prevalent across a wide range of graphics and that is readily understood in context. Lines, crosses, arrows, and blobs are simple, schematic geometric figures that are an integral component of many kinds of graphics, maps, graphs, and mechanical diagrams for examples. Their meanings are related to the their geometric or Gestalt properties. Lines, for example, connect, they serve as paths from one point to another, suggesting a relationship between the points. Crosses are intersections of lines. And arrows are asymmetric lines, suggesting an asymmetric relationship. Blobs are two-dimensional, suggesting an area. Their amorphous shape suggests that shape is irrelevant. Like words in language, geoglyphs can be combined in various ways to create varying meanings. Like words in language, there are constraints on how they can be combined. It is time to illustrate these claims with research.

Bars and lines in graphs.

Line and bar graphs appear widely, not only in scientific journals, but also in daily newspapers, often interchangeably, seemingly dependent on the creativity of the graphic artist. An examination of their geometric and Gestalt properties, however, suggests that they may be interpreted quite differently. As noted, lines connect, indicating a relationship. Bars, by contrast, contain and separate. Bars are boxes or frames. A line between X and Y suggests that there is a relationship between X and Y, that X and Y vary on the same dimension. A bar for X and a bar for Y suggests that all the X's share some property and all the Y's share a different property.

To ascertain whether people interpret lines and bars differently, Zacks and I (Zacks and Tversky, 1999) asked people to interpret an unlabeled line graph or an unlabeled bar graph. In accordance with the current analysis, people overwhelmingly interpreted lines as trends and bars as discrete relations. So for line graphs, people said, there's an increase from A to B or a trend from A to B. For bar graphs, people said, the B's are higher than the A's or there are more B's than A's. The next step was to provide content to the graphs, either continuous content, so compatible with lines or trends, or discrete content, so compatible with bars. In both cases the graphs depicted height; for the continuous case, of 10 and 12 year olds, and for the discrete case, of women and men. As before, participants were asked to interpret the graphs. And, as before, the form of the graphic affected the interpretations. There were more trend interpretations of line graphs and more discrete interpretations of bar graphs, in many cases, conflicting with the nature of the underlying variable. There was an effect of the underlying variable, continuous or discrete, but the effect of the graphic format was greater. Some participants even said, as people get more male, they get taller.

The third step was to provide continuous or discrete interpretations, and ask participants to construct graphs depicting them. The same variables were used, height of 10 and 12 year olds or height of men and women, described either as a trend, height is great for 12 year olds (men) than for 10 year olds (women), or as a discrete comparison, 12 year olds (men) are taller than 10 year olds (women). The type of description affected the type of depiction:

more participants drew lines for trend descriptions and bars for discrete comparisons, again overriding the underlying nature of the variables in many cases. The correspondance between the language of the interpretations and the “language” of the graphics is striking

Lines, Curves, Crosses, and Blobs in Route Maps.

The correspondence between the language of description and the language of graphics is no less striking in route directions. Lee and I (Tversky and Lee, 1998, 1999) caught hungry students outside a dormitory and asked them if they knew the way to a local fast food restaurant. If they did, we handed them a piece of paper, and asked them to either sketch a map or write instructions to location. Both map sketches and verbal directions varied widely, in length, detail, and elegance. Despite this variability, they both had the same underlying structure.

The structure of the route directions and maps was analyzed using a scheme developed by Denis (1997). He found that route directions could be decomposed into a series of segments. Each segment in turn had four elements: a start point, an orientation, a progression, and an end point, as in “exit the Central Square station, turn left, go down Mass Avenue until you come to Café Centro.” Not only could the route directions be decomposed into a series of those four segments, but also the route maps. Interestingly, there was more missing information in the directions than in the maps. The directions frequently omitted the progression and either the start or end point, as in, “left on Mass Ave., left on Magazine, right on William.” Both missing start or end points and progression can be easily inferred from context. Sketch maps rarely omitted information as the graphic medium forces completion.

Not only could the sketches and descriptions be decomposed into the same four types of elements, but also there was remarkable correspondence between the linguistic and graphic components. Start and end points were represented by landmarks. In the case of descriptions, these were names, usually of streets or buildings. In the case of sketches, landmarks were blobs and streets were lines, often labeled. Orientations in descriptions were accomplished primarily by "turn," "make a," and "take a." In depictions, turns were indicated by +'s or T's or L's depending on the nature of the intersection. In both descriptions and depictions, the exact angle of orientation was not indicated. This is more surprising for sketch maps, as they could be analog, could represent the exact angle of the intersection. The same phenomenon occurs in representing progression. Descriptions tended to use "go down" or "follow around," where "go down" corresponded to a straight path and "follow around" corresponded to a curved path. Maps also made primarily a dichotomous distinction between straight and curved paths, again, in spite of their potential to reflect the actual spatial relations. Distance was not represented analogically in sketch maps either. Long straight distances were shortened, and short distances that had tricky turns were enlarged. This corresponded to differences in relative length in descriptions. The correspondence between descriptive and depictive elements suggests that they both derive from a common underlying conceptual structure.

In all, both route directions and route maps consisted of a small number of elements, used in combinations. This led us to think that we could provide people with verbal or graphic tool kits that would suffice to create routes. We gave verbal or visual versions of tool kits representing the four types of segments to new groups of participants. We asked them to use the tool kits to create a large number of route directions or maps. We told the participants that the took kits would probably not be sufficient for their purposes, and they should feel free to add to the tool kit when needed. Despite this suggestions, few participants added few elements to either tool kit. A few participants added freeway ramps, for example. These graphic devices commonly produced by people have been incorporated into an algorithm for generating route maps which have met with great enthusiasm on the part of users (Agrawala and Stolte, 2001; see mapblast.com).

The sketch maps, then, not only schematize, but also distort the actual information. Does it matter? Probably not. Sketch maps are ancient. They have undergone countless spontaneous user tests. Sketch maps are typically used in an environment. The environment disambiguates and corrects the schematized information. If a turn on a map is 90 degrees, but the intersection is 60, the navigator has little choice but to turn 60 degrees. After all, route directions also suffice to bring travelers to their destinations, and they, too, underspecify and schematize the information. Both have pragmatics associated with them as well as syntax and semantics. The pragmatics include the implicit knowledge that turns and distances are approximate. These pragmatics of route directions and depictions are understood by their creators and users alike.

Arrows in Mechanical Diagrams.

Another graphic device used by about half the participants was arrows, indicated the route. As noted, arrows are like lines; they indicate a relationship. But arrows are asymmetric, so they indicate an asymmetric relation. The very form of arrows has natural equivalents, not just in the arrows used in hunting, but also the arrows created by fluids descending pliable matter. Arrows serve a multitude of functions in diagrams, expressing asymmetric relations. Arrows were redundant in route maps as the maps only showed the roads relevant to the route, and the start and end points were known. In route maps, they indicate spatial order and direction. In maps and in mechanical diagrams, arrows can be used to label parts; they link a name with a part, or point to a part. In mechanical diagrams, arrows can indicate temporal order and direction; they can also indicate directions of motion, and manner of motion. Just as spatial proximity can represent proximity on abstract dimensions, so arrows can indicate order and direction of abstract dimensions, notably, causality.

To understand the role of arrows in mechanical diagrams, Heiser and I (2002) asked participants to write descriptions of diagrams. Each participant described a single diagram, either of a bicycle pump or a car brake or a pulley system, either with arrows indicating the operation of the device or without. When participants saw diagrams without arrows, they wrote primarily structural descriptions, providing details of the spatial relations among the parts of the system. When participants saw diagrams with arrows, they wrote causal, functional descriptions. The arrows provided the temporal order of the operation of the device. The inference from temporal to causal was apparently immediate. As in the previous examples, routes and graphs, we ran the mirror-image experiment, asking participants to produce diagrams from descriptions of the devices. As expected, more participants produced diagrams without arrows for structural descriptions and more participants produced diagrams with arrows for functional descriptions. Arrows, then, allow mental animation of systems; they promote understanding of a system's dynamics and function. Actual animations are computationally expensive and not easily transported. What's more, animated and static graphics have been compared in a multitude of contexts, concrete and abstract. When the content of animated and static graphics is equated, and when interactivity is equated, there is no evidence to support the superiority of animations (Tversky, Morrison, and Betrancourt, in press).

Geoglyphs, such as lines, arrows, crosses, and blobs, appear in a wide range of diagrams. They have interpretations that are readily understood in context from their geometric or Gestalt properties. They can be combined in a multitude of rule-bound ways to create different graphical ideas. Thus, they have many properties in common with semantic elements, words, in spoken or written language. Geoglyphs parallel language also in meaning; the meanings of words like relation, intersection, and field, spatial concepts all, not only correspond to lines, crosses, and blobs, but are rich in possible meanings, which contexts specify.

The "Language" and Funcctions of Graphic Communication

Graphics use space and elements in space to represent concepts that are inherently spatial and concepts that are metaphorically spatial. The elements, whether icons or figures of depiction or geoglyphs, bear many relations to semantic elements of spoken and written language, morphemes. They can be combined to create many complex meanings. How they are combined and spatially arrayed is systematic, not random. The conventions of combination and array bear resemblance to syntax. There is a pragmatics to graphics as well. For example, in sketch maps, graphic space is not meant to be interpreted metrically, in contrast to completed architectural drawings, where graphic space is meant to be interpreted metrically.

Graphics serve a multitude of functions. They record information, preserving it over time. They are a cognitive tool, taking over from working memory some of its' functions, notably, storage and computation. They can be inspected and reinspected, leading to new inferences and insights. They are public, allowing a community to think about a set of issues collectively and revise conceptions collectively. The use of space in graphics facilitates comprehension and capitalizes on human efficacy to make spatial inferences.

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