Cognitive Principles of Graphic Displays

Barbara Tversky

Department of Psychology, Bldg. 420
Stanford University
Stanford, California 94305-2130
bt@psych.stanford.edu

Abstract

Graphic displays, such as maps, that portray visible things are ancient whereas graphic displays, such as graphs and diagrams, that portray things that are inherently not visible, are relatively modern inventions. They serve a variety of functions, such as providing models, attracting attention, supporting memory, facilitating inference and discovery. Graphic displays use space to convey meaning in ways that are cognitively natural, as suggested by historical and developmental examples. Typically, icons are used to convey elements, based on likenesses and "figures of depiction" and spatial relations are used to convey other relations, based on proximity.

Cognitive Principles of Graphic Displays

Graphics are one of the oldest and newest form of communication. Long before there was written language, there were pictures, of myriad varieties. A few of the multitude of cave paintings, petroglyphs, bone incisions, clay impressions, stone carvings, and wood markings that people fabricated and used remain from ancient cultures. Some of these prealphabetic depictions probably had religious significance, but many were undoubtedly used to communicate, to keep track of events in time, to note ownership and transactions of ownership, to map places, to record songs and sayings, and to transmit messages (e. g., Coulmas 1989; De Frances 1989; Gelb 1963; Mallery 1893/1972; Schmandt-Besserat 1992). As such, they served as permanent records of history, commemorations of cultural past. Because pictures represent meaning more directly than alphabetic written languages, we can guess at their meanings today. In rare cases, we have the benefit of contemporaneous translations, Mallery, for example, was able to speak with many still using pictographic communication as he collected vast numbers of petroglyphs, birch bark markings, and the like from native Americans (1893/1972).

In many places in the world, the use of pictures to communicate developed into complete written languages. All such languages invented ways to represent concepts that are difficult to depict, such as abstract meanings and proper names. Some originally pictoric written languages transformed to using written marks to represent the sound of spoken language rather than using marks to represent meaning directly. As pictures evolved into written languages, their transparency necessarily disappeared. Characters representing abstract concepts were devised and characters representing concrete concepts became schematized and conventionalized. Later, the invention and spread of the alphabet, and then the invention of the movable type printing press decreased reliance on pictures for communication. With the increasing ease of reproducing written language and the spread of literacy, pictures became decorative rather than communicative.

Now, pictures, depictions, and visualizations are on the rise again. As with the proliferation of written language, this is partly due to technologies for reproducing and transmitting pictures. And as with the proliferation of written language, some of the expansion of pictures is due to intellectual insights. For this, the basic insight is using depictions to represent abstract meaning by means of of visual and spatial metaphors and figures of depiction. Although depictions have long been used to convey concrete ideas, their use in conveying abstract ideas is more recent. Early depictions for the most part portrayed things that were inherently visualizable, such as objects or environments, in pictographs, maps, or architectural plans. Many contemporary depictions are visualizations of things that are not inherently visualizable, such as temporal, monetary, causal, or social relations.

Graphs are perhaps the most prevalent example of depictions of abstract concepts, and were invented as recently as the late eighteenth century (e. g., Beniger and Robyn 1978; Carswell and Wickens 1988; Tufte1983), although they probably had their roots in mathematical notation, especially Cartesian coordinate systems. Two Europeans, Playfair in England and Lambert in Switzerland, are credited with being the first to promulgate their use, for the most part to portray economic and political data.

Although those early graphs, X-Y plots with time as one of the variables, are still the most common type of graph in scientific journals (Cleveland 1984), varieties of graphs, graphics, and visualizations abound, with new ones appearing all the time. Bar graphs and pie charts are common for representing quantitative data, with flow charts, trees, and networks widely used for qualitative data. Icons appear in airports, train stations, and highways all over the world, and menus of icons on information highways over the world. Many are used to portray concepts that are difficult to visualize.

The choices of icons and graphic displays are usually not accidental or abitrary. Many have been invented and reinvented by adults and children across cultures and time. Many have analogs in language and in gesture. Many are rooted in natural cognitive correspondences, "figures of depictions," and spatial metaphors, and have parallels in Gestalt principles of perceptual organization.

In this paper, I present an analysis of graphic displays based on their functions and on their structure. The evidence I will bring to bear is eclectic and unconventional, drawing from examinations of historical graphic inventions, children's graphic inventions, and language.

Others have taken a broad view of graphics from other perspectives. Bertin (1983) put forth a comprehensive semiotic analysis of the functions of graphics and the processes used to interpret them that established the field and defined the issues. According to Bertin, the functions of graphs are to record, communicate, and process information, and the goal of a good graphic is simplification to those ends. Ittelson (1996) has pointed to differences in processing of "markings," deliberate, two-dimensional inscriptions on surfaces of objects and other visual stimuli. Winn (1987) has discussed how information is conveyed in charts, diagrams, and graphs. Larkin and Simon (1987) have examined the differences between sentential and diagrammatic external representations, pointing to the advantages of diagrammtic ones for tasks where spatial proximity conveys useful information. Stenning and Oberlander (1995) have analyzed the advantages and disadvantages of diagrammtic and sentential representations in drawing inferences. They argue that diagrams allow expression of some abstractions, much like natural language, but are not as expressive as sentential logics. Cleveland (1984, 1985) has examined the psychophysical advantages and disadvantages of using different graphic elements, position, angle, length, slope, and more, for efficiency in extracting different kinds of information from displays of quantitative data. He and his collaborators have produced convincing cases where conventional data displays can be easily misconstrued by human users. Tufte (1983, 1990, 1997) has exhorted graphic designers to refrain from "chart junk," extraneous marks that convey no additional information, adopting by contrast a minimalist view. Wainer (1984, 1992) has gathered a set of useful prescriptions and insightful examples for graph construction, drawing on work in semiotics, design, and information processing. Kosslyn (1985, 1994), using principles adopted from visual information processing and Goodman's (1978) analysis of symbol systems, has developed a set of prescriptives for graphic design, based on an analysis of the syntax, semantics, and pragmatics underlying graphs. Pinker (1990) provides an analysis of information extraction from graphics that separates processes involved in constructing a visual description of the physical aspects of the graph from those involved in constructing a graph schema of the mapping of the physical aspects to mathematical scales. Carswell and Wickens (Carswell 1992; Carswell & Wickens 1988; 1990) have demonstrated effects of perceptual analysis of integrality on graph comprehension, and others have shown biases in interpretation or memory dependent on graphic displays (Gattis & Holyoak 1996; Levy, et al. 1996; Schiano & Tversky 1992; Shah & Carpenter 1995; Spence & Lewandowsky 1991; Tversky & Schiano 1989).

Some Functions of Graphic Displays

Despite their variability of form and context, a number of cognitive principles underliegraphic displays. These are evident in the many functions they serve as well as in the way information is conveyed in them. Some of their many overlapping functions are reviewed below. As with functions, goals, and constraints on other aspects of human behavior, so the functions of graphic displays are sometimes at odds with each other.

Attract attention and interest. One prevelant function of graphic displays is to attract attention and interest. A related function is aesthetic; graphics may be pleasing or shocking or repulsive or calming or funny.

Models of actual and theoretical worlds. Maps, architectural drawings, molecules, circuit diagrams, organizational charts, flow diagrams are just some of the myriad examples of diagrams serving as models of worlds and the things in them. This function includes both the ancient examples of maps and the contemporary examples of organizational charts and flow diagrams. Note that these are models, and not strictly shrunken or expanded worlds. Effective diagrams omit many features of the modeled world and distort others, and even add features that are not in the modeled world. Maps, for example, are not drawn strictly to scale. Roadmaps exaggerate the sizes of highways and streets so that they can be seen and used. Maps introduce symbolic elements, for railroads, ocean depth, towns, and more, that require a key and/or convention to interpret. The essence of creating an effective external representation is to abstract those features that are essential and to eliminate those that are not, that only serve as clutter. Of course, this is not as simple as it sounds, partly because it is difficult to anticipate all the uses an external representation will have, partly because successful communication rests on redundancy. Current trends in computer graphics go against the maxim of abstracting the essentials. The aim of at least some areas of computer graphics seem to be creating as much detail and realism as possible.

Record information. An ancient function of graphics is to provide records. For example, tallies developed to keep track of property, beginning with a simple one-mark onepiece of property relation, developing into numerals as tallies became cumbersome for large sums and calculations (Schmandt-Besserat 1992). Various native American tribes kept track of their own history year by year with depictions of a major event of the year (Mallery 1972).

Memory. A related function of graphic displays is to facilitate memory. This surely was and is one of the functions of writing, whether pictographic or alphabetic. A modern example is the use of menus, especially icon menus, in computer user interfaces. Providing a menu turns what would otherwise be a recall task into a recognition task. Instead of having to call to mind all the possible commands in a program or files on a drive, a user has only to select the command or file that is needed from a list. There is yet another way that graphs promote memory. Menus and icons are typically displayed in standard places in an array. As anyone who has returned to a previous home after a long lapse of time knows, places are excellent cues to memory. Ancient lore, the Method of Loci, and modern research support the intuition that space is not only an excellent cue but also an excellent organizer of memory (e. g., Bower 1970; Franklin, Tversky, and Coon 1992; Small in press; Taylor and Tversky in press; Yates 1969).

Communication

In addition to facilitating memory, graphic displays also facilitate communication. As for memory, this has also been an important function of writing, to allow communication out of earshot (or eyeshot). Graphic displays allow private, mental conceptualizations to be made public, where they can be shared, examined, and revised.

Convey meaning, facilitate discovery and inference. Effective graphics make it easy for users to extract information and draw inferences from them. Maps, for example, facilitate determining routes and estimating distances. A map of cholera cases in London during an epidemic made it easier to find the contaminated water pump (Wainer 1992). Plotting change rather than absolute levels of a measure can lead to very different inferences (Cleveland 1985). Indeed, the advice in How to Lie with Statistics (Huff 1954) has been used for good or bad over and over. Physics diagrams (Narayanan, Suwa & Motoda 1994) and architectural sketches (Suwa & Tversky 1996) bias users towards some kinds of inferences more readily than others.

Graphic displays accomplish all these functions and more in two separable ways, through the use of graphic elements or icons, and through the spatial array of elements. Different cognitive principles underlie each. In general, graphic elements are used to represent elements in the world and graphic space is used to represent the relations between elements, though there are exceptions to this generalization. This dichotomy into elements and relations maps loosely onto the "what" vs. "where" distinction in vision and in spatial cognition.

The fact that graphic displays are external representation devices augments many of their functions. Spatially organized information can be accessed and integrated quickly and easily, especially when the spatial organization reflects conceptual organized. Several people can simultaneously inspect the same graphic display, and refer to it by pointing and other devices in ways apparent to all, facilitating group communication.

Icons: Figures of Depiction

Sometimes icons can be used to represent meaning directly, for example, highway signs of a picnic table or a water tap on the route to the location of actual ones. Unfortunately, it is often difficult to represent a concept of object directly because the concept is not easily depicted. However, icons can represent concepts indirectly, using a number of "figures of depiction," analogous to figures of speech (Tversky 1995). One common type of figure of depiction is metonymy, where an associated object represents the concept. Returning to computer interfaces, a picture of a folder can represent a file of words and a picture of a trash can represent a place for unwanted folders. Analogous examples in language include using "the crown" to represent the king and "the White House" to represent the president. Synecdoche, where a part is used to represent a whole, or a whole for a part, is another common figure of depiction. Returning to highway signs, an icon of a place setting near a freeway exit indicates a nearby restaurant and an icon of a gas pump a nearby gas station. Analogous examples in language include "give a hand" for help and "head count" for number of people. These same figures of depiction are frequent in icons in early ictographic writing (Coulmas 1989; Gelb 1963; Tversky 1995). For example, early Sumerian writing used a foot to indicate "to go" and an ox's head to indicate an ox. With time, pictographic writing became schematic and less transparent. Children's spontaneous writing and depictions also illustrate these principles (e. g., Hughes 1986; Levin and Tolchinsky-Landsman 1989). Like the inventors of pictographic languages, children find it easier to depict objects, especially concrete ones, than operations. For abstract objects and operations, children use metonymy and synecdoche. For example, children draw hands or legs to indicate addition or subtraction. Interestingly, the latter was also used in hieroglyphics.

The meanings of these depictions are somewhat transparent. Often, they can be guessed, sometimes with help of context, and even when guessing is not likely, they are easily associated to their meanings, and thus easily remembered. (for similar arguments in the context of ASL and gesture, see Macken, Perry and Haas 1993). The meanings of computer icons cannot always be conveyed by a single word. The alternatives, verbal commands, are not always transparent and frequently need to be learned. Does "delete" or "remove" eliminate of a file? Do we "exit" or "quit" a program? Depictions have other advantages over words. Meaning is extracted from pictures faster than from words (Smith and McGee 1980). Icons can be "read" by people who do not read the local language.

A new use of depictions has appeared in email. Seemingly inspired by smiley faces, and probably because it is inherently more casual than other written communication, computer vernacular has added signs for the emotional expression normally conveyed in face-to-face communication by intonation and gesture. These signs combine symbols found on keyboards to denote facial expressions, usually turned 90 degrees, such as :) or ;).

Graphic Arrays: Spatial Metaphors

Graphs, charts, and diagrams convey qualitative and quantitative information using natural correspondences and spatial metaphors, some applied to the simple spatial array of elements, and others applied to spatial (special) signs. The most basic of the metaphors is proximity: proximity in space is used to indicate proximity on some other property, such as time or value. Spatial arrays convey conceptual information metaphorically at different levels of precision, corresponding to the four traditional scale types, nominal, ordinal, interval, and ratio (Stevens 1948). These are ordered inclusively by the degree of information preserved in the mapping. Spontaneously produced graphic displays reflect these scale types. Children, for example, represent nominal relations in graphic displays at an earlier age than ordinal relations, and ordinal relations at an earlier age than interval relations (Tversky, Kugelmass, and Winter 1991).

Nominal scales are essentially clustering by category. Here, elements are divided into classes, sharing a single property or set of properties. Graphic devices indicating nominal relations often use a the simplest form of proximity, grouping (cf. Gestalt Principle of Grouping). Things that are related are placed contiguously or in close proximity; things that are not related are separated in space. Spacing, of course, underlies the Gestalt principle of grouping by proximity. One use of this device that we take for granted is the space left between words in writing. Although it is easy to overlook spacing as a graphic device, early writing did not put spaces between words. The Roman alphabet for the most part preserves a correspondence between written character and sound, but beyond the alphabet, many conventions of writing are based on spatial correspondences, not sound correspondences. Indentation and/or spacing before a new paragraph is another example of using separation in space to indicate separation of ideas.

Another spatial device for delineating a category is a list, where all the items that need to be purchased or tasks that need to be done are written in a single column. Items are separated by empty space, and the items begin at the same point in each row, indicating equivalence. For lists, there is often only a single category; organization into a column indicates that the items are not randomly selected, but rather, share a property. Multiple lists are also common, for example, the list of chores of each housemate. A table is an elaboration of a list, using the same spatial device to organize both rows and columns (Stenning and Oberlander 1995). Examples include a list of countries with their GNP's for each of the last ten years, or a list of schools, with their average achievement scores on a variety of tests. Tables cross-classify. Items within each column and within each row are related, but on different features. For example, columns may correspond to countries and GNP's by year, or to schools and scores by test, and rows may provide the values for each country or school. Train schedules are yet another example, where the first column is typically the stations, the places where the train stops, and subsequent columns are the times for each train. For train schedules, a blank space where there would ordinarily be a time indicates a non-event, that is, this train doesn't stop at that station. Using spatially-arrayed rows and columns, tables group and juxtapose simultaneously.

Empty space is not the only spatial device used to indicate grouping. Often special signs, usually visual ones rather than strictly spatial ones, are added. These seem to fall into two classes, those based on linking or enclosure (cf. Gestalt Principle of grouping) and those based on similarity (cf. Gestalt Principle of Similarity). Many signs used for enclosure do not seem to be arbitrary. Rather, they resemble physical structures that enclose actual things, such as bowls and fences, or physical structures that link things, such as paths. Some analogous structures on paper are lines, parentheses, circles, boxes, and frames. Like paths or outstretched arms, lines link one concept to another, bringing noncontiguous things into contiguity, making distal items proximal. In tables, lines, sometimes whole (_____), sometimes partial (.......)(one might interpret broken lines as more tentative than solid ones), are used to link related items. Tables often add boxes to emphasize the structures of rows and columns or to enclose related items and separate different ones. Newspapers use boxes to distinguish one classified ad from another. Parentheses and brackets in writing are in essence degenerate circles. The curved or bent lines, segments of circles or rectangles, face each other to enclose the related words and to separate them from the rest of the sentence.

Complete circles have been useful in visualizing syllogisms and in promoting inference as in Euler or Venn diagrams or in contemporary adaptations of them (e. g., Shin 1991; Stenning and Oberlander 1995). Circles enclose items belonging to the same set. Circles with no physical contact indicate sets with no common items, and physically overlapping circles indicate sets with at least some common items. To increase the inferential power of Euler diagrams, spatial signs based on similarity have been added, such as filling in similar regions with similar and dissimilar regions with different marks, color, shading, cross-hatching, and other patterns (e. g., Shin 1991). Maps use colors as well as lines to indicate political boundaries and geographic features. For geographic features, many of the correspondences are natural ones. For example, deserts are colored beige whereas forests are colored green, and lakes and seas are colored blue, with deeper (darker) blues indicating deeper water.

Ordinal relations can vary from a partial order, where one or more elements have precedence over others, to a complete order, where all elements are ordered with respect to some property or properties. There are two separable issues in mapping order onto space. One is the devices used to indicate order, and the other is the direction of order. The direction of indicating order will be discussed after interval relations, as the same principles apply. Now to ways of indicating order. Writing is ordered, so one of the simplest spatial devices to indicate rank on some property is to write items according to the order on the property, for example, writing countries in order of GNP, or people in order of age. Empty space is used to convey order, as in indentation in outlines, where successively subordinate items are successively indented relative to superordinate items.

Lines can be used to indicate order as well as equivalence. Lines form the skeletons of trees and graphs, both of which are commonly used to display ordered concepts, to indicate asymmetry on a variety of relations, including kind of, part of, subservient to, and derived from. Examples include hierarchical displays, as in linguistic trees, evolutionary trees, and organizational charts. Other visual and spatial devices used to display order rest on the metaphor of salience. More salient features have more of the relevant property. Such features include size, color, highlighting, and superposition. Some visuo/spatial devices rely on what can be called natural cognitive correspondences. For example, high temperatures are associated with "warm" colors and low temperatures with "cold" colors, as used in weather maps and scientific charts. This association most likely derives from the colors of things varying in temperature, such as fire and ice.

Arrows are a special kind of line, with one end marked, inducing an asymmetry. Although they have many uses, a primary one is to indicate direction, an asymmetric relation. Arrows seem to be based on either or both of two spatial analogs. One obvious analog is the physical object arrow, invented by many different cultures for hunting. It is not the hunting or piercing aspects of physical arrows that have been adopted in diagrams, but rather the directionality. Hunting arrows are asymmetric as a consequence of which they fly more easily in one direction than the other. Another analog is the idea of convergence captured by the > ("V") of a diagram arrow. Like a funnel or river straits, it directs anything captured by the wide part to the point, and straight outwards from there. Arrows are frequently used to signal direction in space. In diagrams, arrows are also commonly used to indicate direction in time. In production charts and computer flow diagrams, for examples, arrows are used to denote the sequence of processes. Terms for time, such as "before" and "after," and indeed thinking about time, frequently derive from terms for and thinking about space (e. g., Clark 1973).

Interval and ratio relations apply more constraints of the spatial proximity metaphor than ordinal relations. In graphic displays of interval information, the spaces between elements are meaningful; that is, greater space corresponds to more on the relevant dimension. This is not the case for ordinal mappings. In displays of ratio information, the ratios of the spaces are meaningful.

The most common graphic displays of interval and ratio information are X-Y plots, where distance in the display corresponds to distance on the relevant property or properties. Bar charts are useful for displaying quantities for several variables at once; here, the height or length of the bar corresponds to the quantity on the relevant variable. Isotypes combine icons and bar charts to render quantities on different variables more readily interpretable (Neurath, 1936). For example, in order to display the yearly productivity by sector for a number of countries, a unit of output for each sector is represented by an isotype, or icon that is readily interpretable, a shaft of wheat for grain, an ingot for steel, an oil well for petroleum. The number of icons per sector is proportional to output in that sector. Icons facilitate comparison across countries or years for the same sector. Isotypes were invented by Otto and Marie Neurath in the 30's as part of a larger movement to increase communication across languages and cultures. That movement included efforts to develop picture languages and Esperanto. Musical notation is a specialized interval scale that makes use of a limited visual alphabet corresponding to modes of execution of notes as well as a spatial scale corresponding to pitch. Finally, for displaying ratio information, pie charts can be useful, where the area of the pie corresponds to the proportion on the relevant variable.

Directionality

In spite of the uncountable number of possibilities for indicating order in graphic displays, the actual choices are remarkably limited. In principle, elements could be ordered in any number of orientations in a display. Nevertheless, graphic displays tend to order elements either vertically or horizontally or both. Similarly, languages are written either horizontally or vertically, in rows or in columns. There are reasons grounded in perception for the preference for vertical and horizontal orientations. The perceptual world has a vertical axis defined by gravity and by all the things on earth correlated with gravity and a horizontal axis defined by the horizon and by all the things on earth parallel to it. Vision is especially acute along the vertical and horizontal axes (Howard 1982). Memory is poorer for the orientation of oblique lines, and slightly oblique lines are perceived and remembered as more vertical or horizontal than they were (Howard 1982; Schiano and Tversky 1992).

Of all the possible orientations, then, graphic displays ordinarily only use the vertical and horizontal. What's more, they use these orientations differently. Vertical arrays take precedence over horizontal ones. Just as for the choice of dimensions, the precedence of the vertical is also rooted in perception (Clark 1973; Cooper and Ross 1975; Lakoff and Johnson 1980; Franklin and Tversky 1990). Gravity is correlated with vertical, and people are oriented vertically. The vertical axis of the world has a natural asymmetry, the ground and the sky, whereas the horizontal axis of the world does not. The dominance of the vertical over the horizontal is reflected in the dominance of columns over rows. It is more usual and more natural to make a vertical list than a horizontal one. Similarly, bar charts typically contain vertical columns.

There is another plausible reason for the dominance of the vertical over the horizontal. Not only does the vertical take precedence over the horizontal, but there is a natural direction of correspondence for the vertical, though not for the horizontal. In language, concepts like more and better and stronger are associated with upward direction, and concepts like less and worse and weaker with downward direction (Clark 1973; Cooper and Ross 1975; Lakoff and Johnson 1980). People and plants, indeed most life forms, grow upwards as they mature, becoming bigger, stronger, and (arguably) better. Healthy and happy people stand tall; sick or sad ones droop or lie down. More of any quantity makes a higher pile. The associations of up with quantity, mood, health, power, status, and more derive from physical correspondences in the world. It is no accident that in most bar charts and X-Y plots, increases go from down to up. The association of all good things with up is widely reflected in language as well (inflation and unemployment are exceptions, but principled ones, as the numbers used to convey inflation and unemployment go up). We speak of someone "at the top of the heap," of doing the "highest good," of "feeling up," of being "on top of things," of having "high status" or "high ideals," of doing a "top-notch job," of reaching "peak performance," of going "above and beyond the line of duty." In gesture, we show success or approval with thumbs up, or give someone a congratulatory high five. The correspondence of pitch with the vertical seems to rest on another natural cognitive correspondence. We produce higher notes at higher places in the throat, and lower notes at lower places. It just so happens that higher notes correspond to higher frequency waves, but that may simply be a happy coincidence.

In contrast, the horizontal axis is standardly used for neutral dimensions, for example, time. Similarly, with the major exception of economics, neutral or independent variables are plotted along the horizontal axis, and the variables of interest, the dependent variables, along the vertical axis. Although graphic conventions stipulate that increases plotted horizontally proceed from left to right, directionality along the horizontal axis does not seem to rest in natural correspondences. The world is asymmetric along the vertical axis, but not along the horizontal axis. Right-left reflections of pictures are hardly noticed but top-bottom reflections are (e. g., Yin 1969). Languages are just as likely to be written left to write as right to left (and in some cases, both), but they always begin at the top. Children and adults from cultures where language is written left to right as well as from cultures where language is written right to left mapped increases on a variety of quantitative variables from down to up, but almost never mapped increases from up to down. However, people from both writing cultures mapped increases in quantity and preference from both left to right and right to left equally often. The relative frequency of using each direction to represent quantitative variables did not depend on the direction of written language (Tversky, et al. 1991). Despite the fact that most people are right-handed and that terms like dexterity derived from "right" in many languages have positive connotations and terms like sinister derived from "left" have negative connotations, the horizontal axis in graphic displays seems to be neutral. Consistent with that, we refer to one side of an issue as "on the one hand," and the other side as "on the other hand," which has prompted some politicians to ask for one-handed advisors. And in politics, both the right and the left claim the moral high ground.

Children's and adults' mappings of temporal concepts showed a different pattern from their mappings of quantitative and preference concepts (Tversky, et al. 1991). For time, they not only preferred to use the horizontal axis, they also used the direction of writing to determine the direction of temporal increases, so that people who wrote from left to right tended to map temporal concepts from left to right and people who wrote from right to left tended to map temporal concepts from right to left. This pattern of findings fits with the claim that neutral concepts such as time tend to be mapped onto the horizontal axis. The fact that the direction of mapping time corresponded to the direction of writing but the direction of mapping quantitative variables did not may be because temporal sequences seem to be incorporated into writing more than quantitative concepts, for example, in schedules, calendars, invitations, and announcements of meetings. Consistent with the previous arguments and evidence, ordinal charts and networks tend to be vertically organized. A survey of the standard scientific charts in all the textbooks in biology, geology, and linguistics at the Stanford Undergraduate Library revealed vertical organization in all but two of 48 charts (Tversky 1995). Furthermore, within each type of chart, there was agreement as to what appeared at the top. In 17 out of the 18 evolutionary charts, Homo sapiens sapiens, that is, the present age, was at the top. In 15 out of the 16 geological charts, the present era was at the top, and in 13 out of the 14 linguistic trees, the proto-language was at the top. In these charts, in contrast to X-Y graphs, time runs vertically, but time does not seem to account for the direction, partly because time is not ordered consistently across the charts. Rather, at the top of each chart is an ideal. In the case of evolution, it is humankind, regarded by some as the pinnacle of evolution, a view some biologists discourage. In the case of geology, the top is the richness and accessibility of the present era. In the case of language trees, the top is the proto-language, the most ancient theoretical case, the origin from which others diverged. In organizational charts, say of the government or large corporations, power and control are at the top. For diagraming sentences or the human body, the whole is at the top, and parts and sub-parts occupy lower levels. In charts such as these, the vertical relations are meaningful, denoting an asymmetry on the mapped relation, but the horizontal relations are often arbitrary.

Basis for Metaphors and Cognitive Correspondences

A major purpose of graphic displays is to represent visually concepts and relations that are not inherently visual. Graphic displays use representations of elements, primarily icons, and the spatial relations among them to do so. To enhance communication, both elements and relations are based on people's perception of and interaction with the familiar physical world, especially the spatial world. People have extensive experience observing and interacting with the physical world, and consequently extensive knowledge about the appearance and behavior of things in it. It is natural for this concrete experience and knowledge to serve as a basis for pictorial, verbal, and gestural expression.

Prescriptions

Not all visualizations are as cognitively compelling as the ones discussed here. With the proliferation of software that generates graphic displays and publishers that promulgate them, there has been an inevitable increase in graphics that are uninformative, or worse yet, misinformative. Let's analyze one, often decried example, the use of three-dimensional icons to convey one-dimensional information (Tufte 1983; Wainer 1980). Some uses are problemmatic. The rising cost of oil, for instance, has been portrayed by proportionately larger oil barrels. Only the relative heights of the barrels are meaningful, but viewers cannot help but respond to the areas or volumes. In response, some propose graphic minimalism, denouncing so called "chart junk" (Tufte 1983), advocating replacing bars with lines or rows of points to emphasize their one-dimensionality. All natural communication, however, is rife with redundancy, for good reason; redundancy reduces error. Graphic minimalism may have aesthetic appeal in the eyes of some, but it may also interfere with conveying a message efficiently and accurately. Thus the three-dimensional bar graphs popular in graphing programs and popular with students but unpopular with certain statisticians are slightly worse than their two-dimensional siblings in perceptual estimation, but neither better nor worse in memory estimation (Levy et al. 1995). Other examples abound, and can be debated.

This review suggests two simple maxims:

- Use space naturally
- Don't use space unnaturally

Naturalness is found in natural correspondences, "figures of depiction," and spatial metaphors, derived from extensive human experience with the concrete world. It is revealed in language and in gesture as well as in a long history of graphic productions.

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