Functional Significance of Visuospatial Representations

Barbara Tversky
Stanford University

Footnote: Preparation of this chapter and some of the research reported were supported by Office of Naval Research, Grants Number NOOO14-PP-1-O649 and N000140110717 to Stanford University. Amy Shelton provided excellent information on the brain, for which I am grateful. I am also grateful to Priti Shah and several anonymous reviewers who graciously pointed to inclarities and infelicities. I hope I have succeeded in correcting them..

Table of Contents

Further Reading.

On bodies, events, and brain:

Meltzoff, A. and Prinz, W. (Editors). *The imitative mind.* Cambridge: Cambridge University Press.

On cognitive maps:

Kitchin, R. and Freundschuh, S. M. Editors. (2000). Levels and structure of cognitive mapping *Cognitive mapping: Past, present and future*. London: Routledge.
On navigation:
R. Golledge (Editor). *Cognitive mapping and spatial behavior*. Baltimore, MD: The Johns Hopkins Press.
On language and space:
Bloom, P., Peterson,M. P., Nadel, L., and Garrett, M. (Editors),
Language and space. Cambridge: MIT Press.
On metaphoric space:
Gattis, M. (Editor). (2001). Spatial schemas in abstract thought. Cambridge: MIT Press.

Abstract

150-200
Mental spaces are not unitary. Rather, people conceive of different spaces differently, depending on the functions they serve. Four such spaces are considered here. The space of the body subserves proprioception and action; it is divided by body parts, with perceptually salient and functionally significant parts more accessible than others. The space around the body subserves immediate perception and action; it is conceived of in three dimensions in terms of relations of objects to the six sides of the body, front/back, head/feet, left/right. The space of navigation subserves that; it is constructed in memory from multi-modal pieces, typically as a plane. The reconstruction generates systematic errors. The space of external representations, of pictures, maps, charts, and diagrams, serves as cognitive aids to memory and information processing To serve those ends, graphics schematize and may distort information.

Introduction: Four Functional Spaces

When physicists or surveyors exercise their trades, aspects of space are foreground, and the things in space background. Things are located in space by means of an extrinsic reference system, in terms of metric measurement. Within the reference system, aspects of the space, whether large or small, distal or proximal, for entities small or large, are uniform. Surveyors laying out a road, for example, need to know the exact distance from point A to point B, the exact curvature of the terrain, the exact locations of other objects, natural and built. In other words, they need first to measure aspects of the space as accurately as possible. For human cognition, the void of space is treated as background, and the things in space as foreground. They are located in space with respect to a reference frame or reference objects that vary with the role of the space in thought or behavior. Which things, which references, which perspective depend on the function of those entities in context, on the task at hand. In human cognition, the spatial relations are typically qualitative, approximate, categorical, or topological rather than metric or analog. They may even be incoherent, that is, people may hold beliefs that cannot be reconciled in canonical three-dimensional space. Human directions to get from A to B, for example, are typically a string of actions at turning points, denoted by landmarks, as in "go down Main to the Post Office, take a right on Oak." The directions are given in terms of entities in the space, paths and landmarks, and in approximate terms, right, left, straight (Denis, 1997; Tversky and Lee, 1998). What's more, for human cognition, there are many spaces, differing in the roles they play in our lives. Those considered here are the space of the body, the space surrounding the body, the space of navigation, and the space of external representations, such as diagrams and graphs. These mental spaces do not seem to be simple internalizations of external spaces like images (e. g., Kosslyn, 1980; 1994b; Shepard, 1994; Shepard and Podgorny, 1978); rather, they are selective reconstructions, designed for certain ends.

What are the different functions that space serves us? The space of the body, the space around the body, the space of exploration, and a uniquely human space, the space of depictions, serve different functions in human activity and hence in human cognition. Things in space impinge on our bodies, and ur bodies act and move in space. In order to interpret those impingements, we need knowledge of the receptive surfaces on the body. In order to coordinate those actions, we need knowledge of what the body can do and feedback on what the body has done. The space of the body has a perceptual side, the sensations from outside and inside the body, and a behavioral side, the actions the body performs. Proprioception tells one about the other. Representations of the space of the body allow us to know what the parts of our bodies can do, where they are, what is impinging on them, and, importantly, how to interpret the bodies of others. Actions of others may have consequences for ourselves, so we need to anticipate those by interpreting others' intentions. The space around the body is the space in which it is possible to act or see without changing places, by rotating in place. It includes the surrounding objects that might get acted on or need to be avoided. The space around the body represents the space that can immediately affect us and that we can immediately affect. Both these spaces are experienced volumetrically, though the space of the body is decomposed into its' natural parts and the space around the body is decomposed into the six regions projecting from the six surfaces of the body. The space of navigation is the space of potential travel. It is too large to be seen at once, so it is pieced together from a variety of kinds of experience, perceptual, from actual navigation, or cognitive, from maps or descriptions. In contrast to the space of the body and the space around the body, it is known primarily from memory, not from concurrent perception. It is typically conceived of as primarily flat. Finally, the space of external representations considered here is typically space on paper meant to represent an actual space, as in a map or architectural drawing, or to represent a metaphoric space, as in a diagram or graph. External representations are creations of people to aid cognition. They can be directly perceived, but they themselves are representations of something else. This is a capsule of what is yet to come.

The Space of the Body

Through our bodies, we perceive and act on the world around us, and learn about the consequences of our actions. One way that we view and think about bodies is as objects. Common objects can be referred to at several levels of abstraction. What I am wearing on my feet can be called clothing or shoes or running shoes. What I am sitting on can be referred to as furniture or a chair or a desk chair. Despite those possibilities, there is a preferred level of reference, a most common way of talking in everyday speech, the level of shoe or chair, over a broad range of contexts. This level has been termed the *basic* level (Rosch, 1978). The basic level has a special status in many aspects of human cognition. Central to recognition and to categorization of objects at the basic level is contour or shape. Underlying shape for most objects, are parts in the proper configuration (cf. Biederman, 1987; Hoffman and Richards, 1984; Tversky and Hemenway, 1984). Although objects have many features, parts constitute the features most diagnostic of the basic level of categorization. Many other cognitive tasks converge on the basic level. For example, it is the highest level for which people can form a general image; people report that forming images of shoes or chairs is not difficult, but forming single images of clothing or furniture is not possible. It is the highest level for which action patterns are similar. The same behaviors are appropriate to different kinds of shoes and different kinds of chairs, but not toward different pieces of clothing or furniture. The basic level is also the highest level for which a general image, one that encompasses the category, can be formed, the highest level for which action patterns are similar, the fastest level to identify, the earliest level acquired by children and introduced to language, and more (Rosch, 1978).

Thus, the basic level has a special status in perception, action, and language. Parts may be critical to the basic level because they form a link from perception or appearance of an object, to its' function. Parts that are perceptually salient tend to be functionally significant as well; moreover, the shapes of parts give clues to their functions (Tversky and Hemenway, 1984). Think of arms, legs, and backs of chairs, and of course, of people. What is especially intriguing for the parts of the human body is that the size of the brain representations are not proportional to the physical size of the parts themselves. The brain has twin representations of the body, on either sides of sensory-motor cortex, one for the sensory part, one for the motor part. In both cases, certain parts, like lips and hands, have larger than expected amounts of cortex devoted to them, and other parts, like backs, have smaller than expected amounts of cortex devoted to them.

Bodies are a privileged object for humans. Unlike other objects, they are experienced from inside as well as from outside. People determine the actions of their own bodies and those actions provide sensory feedback. Insider knowledge of the body seems to affect how bodies are perceived. Consider an interesting phenomenon in apparent motion. Apparent motion occurs when two similar integratable stimuli occur in rapid succession. Instead of perceiving two static images, people perceive a single image that is moving. Apparent motion is the basis for movies, and for the lights on movie marquees. The motion is normally seen at the shortest path. However, when the shortest path for apparent motion violates the ways that bodies can move, a longer motion path is seen for intermediate interstimulus intervals (Heptulla-Chatterjee, Shiffrar, and Freyd, 1996). Thus, when a photo of an arm in front of the body and an arm behind the body are played in rapid succession (but not too rapid), viewers see the elbow jutting out rather than passing through the body. The shortest path is preferred for objects, even when it violates a physical property of the world, that one solid object cannot pass through another solid object, suggesting that knowledge of the body is privileged for perception. In other experiments, people were asked to judge whether two photos of humans in contorted positions of the body were same or different. Observers were more accurate when they actually moved the limbs, arms or legs, whose positions were changed in the photos, provided the movements were random (Reed and Farah, 1995). Neuroscience literature also indicates privileged areas of the brain for representing the body; when those areas, primarily in parietal cortex, are damaged, there can be disruption of identification or location of body parts (e. g., Berlucchi and Aglioti, 1997; Gross and Graziano, 1995). Moreover, sections of the lateral occipital temporal cortex are selectively responsive to the sight of human bodies (Downing, Jiang, Shuman, and Kanwisher, in press).

Insider knowledge of the body seems to affect mental representations of the space of the body as well, as revealed in the speed with which different body parts are identified. Despite diversity in languages, certain body parts are named across most of them: head, arm, hand, leg, foot, chest, and back (e. g., Andersen, 1978). These parts differ in many ways, including size, contour distinctiveness, and function. In detecting parts in imagery, size is critical; larger parts are verified faster than smaller ones (Kosslyn, 1980). In object recognition, parts that are distinct from their contours, parts that stick out, are critical

(Biederman, 1987; Hoffman and Richards, 1984; Tversky and Hemenway, 1984). Finally, although functional significance of parts is correlated with contour distinctiveness, the correlation is not perfect. Is one of these factors, size, perceptual salience, or functional significance, more critical to mental conceptions of the body than others? In a series of experiments, participants saw either the name of one of the frequently-named body parts or a depiction of a side view of a body with one of the parts highlighted (Morrison and Tversky, 1997; Tversky, Morrison, and Zacks, in press). They compared this to a depictions of a side view of a body with a part highlighted, responding same or different depending on whether the parts matched or mismatched. Neither of the comparisons, name-body or body-body, revealed an advantage for large parts; on the contrary, large parts were *slower* to verify than small ones. For both comparisons, verification times were faster for parts that were high on contour distinctiveness and functional significance. Functional significance was roughly indicated by relative size in sensorimotor cortex. For body-body comparisons, verification times were more highly correlated with contour distinctiveness; these comparisons can be quickly made just on the basis of visual appearance, without processing the body as a body or the parts as actual parts. That is, the two pictures can be treated as meaningless visual stimuli for the comparison entailed. In contrast, for name-body comparisons, verification times were more highly correlated with functional significance. In order to compare a name with a depiction, at least some aspects of meaning must be activated. Names are powerful. In this case, it appears that names activate aspects of meaning of body parts that are closely tied to function.

People move the separate parts of their bodies in specific ways in order to accomplish the chores and enjoy pleasures of life. They get up and dressed, walk to work (or to their cars), pick up mail, open doors, purchase tickets, operate telephones, eat food, hug friends and family. The space of the body functions to achieve these ends. Different body parts are involved in different sorts of goals and functions, the feet and legs in navigating the world, the hands and arms in manipulating the objects that serve us. Mental representations of the space of the body reflect the functions of the body parts.

The Space Around the Body

The space around the body is the arena for learning about the world and for taking actions and accomplishing goals in it. The proximal space from which the world can be perceived and in which action can readily be taken is a second natural delineation of space by function. One effective way to study the cognition of space, the space around the body and other spaces as well, is through narrative descriptions of space. When descriptions of space are limited and coherent, people are able to construct mental models of them (e. g., Ehrlich and Johnson-Laird, 1982; Franklin and Tversky, 1990; Glenberg, Meyer, and Lindem, 1987; Mani and Johnson-Laird, 1982; Morrow, Greenspan and Bower, 1989; Rinck, Hahnel, Bower, and Glowalla, 1997; Taylor and Tversky, 1992b; Tversky, 1991). The mental spatial models are mental representations that preserve information about objects and the spatial relations among them, and are updated as new information comes in. They allow rapid inferences of spatial elements, locations, distances, and relations from new viewpoints.

Narratives have been used to establish mental models of the space around the body (e. g., Bryant, Tversky, and Franklin, 1992; Franklin and Tversky, 1990; Franklin, Tversky, and Coon, 1992; Tversky, Kim, and Cohen, 1999). Participants studied narratives that addressed them as “you,” and placed them in an environment such as a hotel lobby, a museum, or a barn, surrounded by objects at all six sides of their bodies, front, back, head, feet, left, and right. Thus, the narratives described the world from the point of view of the observer (you), in terms of directions from the observer. After learning the environment from narratives, participants were reoriented to face a new object, and probed with direction terms for the objects currently in those directions. Several theories predicting the relative times to retrieve objects at the various directions around the body were evaluated (Franklin and Tversky, 1990). The data did not fit the Equiavailability Theory, according to which all objects should be equally accessible because none is privileged in any way. The data also did not conform to a pattern predicted from an Imagery Theory, according to which observers would imagine themselves in a scene, and then imagine themselves examining each direction for the relevant object; an imagery account predicts slower times to retrieve objects in back of the observer than to left and right, counter to the data. The pattern of retrieval times fit the *Spatial Framework Theory* best. According to that theory, people remember locations of objects around the body by constructing a mental spatial framework consisting of extensions of the axes of the body, head/feet, front/back, and left/right, and attaching the objects to them. Accessibility of directions depends on asymmetries of the body and asymmetries of the world. The only asymmetric axis of the world is the up/down axis created by gravity. Gravity of course has broad effects on the way the world appears and the way we can act in it. For the upright observer, this axis coincides with the asymmetric head/feet axis of the body. Times to retrieve objects at head and feet are in fact, fastest. The front/back axis is also asymmetric, but does not coincide with any asymmetric axis of the world. The front/back axis separates the world that can be readily perceived and acted on from the world behind the back, difficult both for perception and action. Finally, the left/right axis lacks any salient asymmetries, and is, in fact, slowest.

The spatial situation can be varied in many ways, by altering the orientation of the observer (Franklin and Tversky, 1990), by adding more observers (Franklin, et al., 1992), by putting the array in front of the observer instead of surrounding the observer. (Bryant, et al., 1992), by having the environment rotate around the observer instead of having the observer turn to reorient in the environment (Tversky, et al., 1999). These variants in the situation lead to consequent variants in the retrieval times that can be accounted for by extensions of the Spatial Framework theory. When the observer is described as reclining, and turning from side to front to back to side, no body axis correlates with gravity. Retrieval times in this case depend only on body asymmetries. The front/back axis of the body seems to be the most salient as it separates the world that can be readily perceived and manipulated from the world behind the back. Along this axis, front has a special status, as it is the direction of orientation, of better perception, of potential movement. In fact, for the reclining case, times to retrieve objects in front and back are faster than times to retrieve objects at head and feet, and times to front faster than those to back (Bryant, et al., 1992; Franklin and Tversky, 1990). What about narratives describing two characters, for example, in different scenes. In that case, the viewpoints of each character in each scene are taken in turn; in other words, participants construct and use separate mental models for each situation, yielding the spatial framework pattern of data. However, when two characters are integrated into a single scene, participants seem to construct a single mental model that incorporates both characters, and take a single, oblique point of view on them and the objects surrounding them (Franklin, et al., 1992). In this case, they do not take the point of view of either of the characters so their bodies are not aligned with any of them. Thus no area of space is privileged for the participant, and in fact, reaction times are the same for all directions for both characters. How about when narratives describe the environment as rotating rather than the observer as turning? In the case of the rotating environment, participants take twice as much time to reorient as when narratives describe the observer as reorienting. In the world we inhabit, people move, not environments, so although people can perform mental feats that the world does not, it takes longer to imagine impossible than possible, normal, mundane interactions with the world (Tversky, et. al., 1999).

Not only can the spatial situation be varied, the mode of acquisition can be varied; the space around the body can be acquired from narrative, from diagrams, from models, and from experience (Bryant and Tversky, 1999; Bryant, Tversky and Lanca, 2001; Franklin and Tversky, 1990). As long as retrieval is from memory rather than perception, the Spatial Framework pattern of retrieval times obtains (Byant, et al., 2001). When responding is from perception, then patterns closer to the imagery model obtain. This is because it in fact takes longer to look behind than to look left or right. Surprisingly, as participants learn the environments, they cease looking, so that even though the information is available from perception, they respond from memory. As a consequence, the retrieval times come to correspond to the Spatial Framework model. Although diagrams and models are both external spatial representations of the scenes, they instill slightly different mental models (Bryant and Tversky, 1999). The models were foot high dolls with depictions of objects hung in the appropriate directions around the doll. When learning from models, participants adopt the embedded point of view of the doll, and, just as from the original narratives, they imagine themselves reorienting in the scene. The diagrams depicted stick figures with circles at the appropriate directions from the body; the circles contained the names of the objects. When learning from diagrams, participants adopt an outside point of view and imagine the scene rotating in front of them, as in classic studies of mental rotation (e. g., Shepard and Cooper, 1982). We speculated that the 3-D models encouraged participants to take the internal viewpoint of the doll, whereas the flat and flattened space of the diagram encouraged participants to treat the diagram as an object, in other words, to mentally manipulate the external representation instead of using it to induce an internal perspective. These perspectives, however, are flexible; when directed to do so, participants used the diagram to take an internal viewpoint or used the model to adopt an external one. The two perspectives and the mental transformations of them, viewing an object from outside vs. viewing a surrounding environment from inside, appear in other analogous tasks, and are subserved by different neural substrates (e. g., Zacks, Rypma, Gabrieli, Tversky, and Glover, 1999). They reflect the two dominant perspectives people take on space, an external view, prototypically the view people have on objects that they observe and manipulate, and an internal view, prototypically the view people have on environments that they explore. One remarkable feature of human cognition is that it allows both viewpoints on both kinds of external realities.

The space around the body, that is, the space immediately surrounding us, the space that functions for direct perception and potential action, is conceptualized in three dimensions constructed out of the axes of the body or the world. Objects are localized within that framework, and their relative locations are updated as the spatial situation changes. The mental spatial framework created out of the body axes underlies perspective-taking, allows updating across rotation and translation, and may act to establish allocentric or perspective-free representations of the world from egocentric experience.

The Space of Navigation

The space of navigation serves to guide us as we walk, drive, fly about in the world. Constituents of the space of navigation include places, which may be buildings or parks or piazzas or rivers or mountains, as well as countries or planets or stars, on yet larger scales. Places are interrelated in terms of paths or directions in a reference frame. The space of navigation is too large to perceive from one place so it must be integrated from different pieces of information that are not immediately comparable. Like the space around the body, it can be acquired from descriptions and from diagrams, notably maps, as well as from direct experience. One remarkable feature of the human mind is the ability to conceive of spaces that are too large to be perceived from one place as integral wholes. In order to conceive of spaces of navigation as wholes, we need to paste, link, join, superimpose, or otherwise integrate separate pieces of information. In addition to being separate, that information may be in different formats or different scales or different perspectives; it may contain different objects, landmarks, paths, or other details. Linking disparate pieces of information can be accomplished through spatial inferences anchored in common reference objects, reference frames, and perspectives. The linkage is necessarily approximate, leading to consistent errors, as shall be seen in the section on cognitive maps.

Places. Many navigable environments can be loosely schematized as landmarks and links, places and paths. Places, that is, configurations of objects such as walls and furniture, buildings, streets, and trees, selectively activate regions of the parahippocampus, part of the network of brain structures activated in imagining travel. Not only is this area selectively active under viewing of scenes, but also patients with damage to this area experience severe difficulties acquiring spatial knowledge of new places (e. g., Aguire and D'Esposito, 1999; Cave and Squire, 1991; De Renzi, 1982; Epstein and Kanwisher, 1998; Rosenbaum, Priselac, Kohler, Black, Gao, Nadel, and Moscovitch, 2000). The brain has areas selectively sensitive to only a small number of kinds of things, places, faces, objects, and bodies, suggesting both that these entities have special significance to human existence and that they are at least somewhat computationally distinct.

Perspective of Acquisition. Descriptions of the space of navigation locate places with respect to one another and a reference frame, from a perspective. They typically use one of two perspectives, or a mixture of both (Taylor and Tversky, 1992a, 1996). In a *route* perspective, the narrative takes a changing point of view within an environment, addressing the reader or listener as "you," describing you navigating through an environment, locating landmarks relative to your changing position in terms of your left, right, front, and back. For example, "As you drive down Main Street, you will pass the bank on your right and the post office on your left. Turn right on Cedar, and the restaurant will be on your left." In a *survey* perspective, the narrative takes a stationary viewpoint above the environment, locating landmarks relative to each other in terms of an extrinsic frame of reference, typically, north-south-east-west. For example, "The bank is east of the post office and the restaurant is north of the post office." The components of a perspective, then, are a landmark to be located, a referent, a frame of reference, a viewpoint, and terms of reference. In both speech and writing, perspectives are often mixed, typically without signaling (e. g., Emmorey, Tversky, and Taylor, in press; Taylor and Tversky, 1992a, 1996). When descriptions are read for the first time, switching perspective slows reading time as well as statement verification time (Lee and Tversky, submitted). However, when descriptions from either perspective are well-learned, participants respond as fast and as accurately to inference statements from the read perspective as from the other perspective (Taylor and Tversky, 1992b). Moreover, maps constructed from reading either perspective are highly accurate. This suggests that both route and survey perspectives can instill mental representations of environments that are perspective-free, more abstract than either perspective, perhaps representations like architects' models, that allow the taking of different perspectives with ease.

There is a third linguistic perspective used to describe smaller environments, those that can be seen from a single viewpoint, such as a room from an entrance. This perspective has been termed a *gaze description* (Ehrich and Koster, 1983; Ullmer-Ehrich, 1982) . In a gaze description, landmarks are described from the stationary viewpoint of an observer relative to each other in terms of the observer's left and right. For example, "The desk is left of the bed, and the bookcase is left of the desk." These three perspectives correspond to the three perspective analyzed by Levinson (Levinson, 1996), gaze to relative, route to intrinsic, and survey to extrinsic. They also correspond to natural ways of acquiring environments, from a single external viewpoint, from traveling through the environment, and from viewing an environment from a height (Taylor and Tversky, 1996; Tversky, 1996). These distinct ways of perceiving and acquiring environments may account for the confluence of type of reference object, reference frame, and viewpoint in the three types of description.

When environments are more complex and acquired from experience, type of experience, notably, learning from experience versus learning from maps, can affect the mental representations established. In particular, some kinds of information are more accurate or accessible from some experiences than others. Those who learned an industrial campus from experience estimated route distances better than those who learned from a map (Thorndyke and Hayes-Roth, 1982). In learning a building, those who studied a map were better at imagining adjacent rooms that were not directly accessible by navigation than those who navigated the building (Taylor, Naylor, and Checile, 1999). The goals of participants, to learn the layout or to learn routes, had parallel effects on mental representations. This suggests that some of the effects of learning from navigation versus maps may have to do with goals or expectations regarding the environment. Learning a route and studying a map appear to activate different areas of the brain as well (e. g., Aquirre and D'Esposito, 1997; Ghaem, Mellet, Crivello, Tzourio, Mazoyer, Berthoz, and Denis, 1997; Maguire, Frackowiak, and Frith, 1997). Similarly, acquiring a virtual environment from a route perspective yields relatively more activation in the navigation network pathways, that is, parietal, posterior cingulate, parahippocampal, hippocampal, and medial occipital gyrus, whereas acquiring a virtual environment from an overview perspective yields relatively more activation in ventral structures, such as ventral occipital and fusiform gyrus. The perspective-dependent pathways active at encoding were also active in recognition of the environments, and there were additional parallel effects of perspective of test stimuli (Shelton, Burrows, Tversky, and Gabrieli, 2000; Shelton, Tversky, and Gabrieli, 2001).

Cognitive Maps. The mental representations that we draw on to answer questions about directions and distances, to tell someone how to get from A to B, to make educated guesses about weather patterns, population migrations, and political spheres of influence, and to find our ways in the world differ from the prototypical map on paper. In contrast to maps on paper, mental maps appear to be fragmented, schematized, inconsistent, incomplete, and multimodal. This is an inevitable consequence of spatial knowledge acquired from different modalities, perspectives, and scales. *Cognitive collage* , then, is a more apt metaphor than *cognitive map* (Tversky, 1993). In contrast to libraries and map stores, our minds do not appear to contain a catalog of maps in varying scales and sizes that we can retrieve on demand. Evidence for this view comes from studies of systematic errors in memory and judgement (for reviews, see Tversky, 1993, 2000b, 2000c).

These systematic errors, some of which will be reviewed below, suggest that people remember the location of one spatial object relative to reference spatial entities in terms of an overall frame of reference from a particular perspective. Some evidence for each of these phenomena will be reviewed. Locations are indexed approximately, schematically, not metrically. Thus, the choice of reference objects, frames of reference, and perspective lead to systematic errors in their direction. As Talmy has observed, the ways language schematize space reflect and reveal the ways the mind schematizes space (Talmy, 1983; Tversky and Lee, 1998). Spatial perception and memory are relative,not absolute. The location of one object is coded relative to the location of a reference object, ideally a prominent object in the environment, and also relative to a reference frame, such as the walls and ceiling of a building, large features of the surroundings such as rivers, lakes, and mountains, or the cardinal directions, north, south, east, or west.

Reference Objects. When asked the direction from Philadelphia to Rome, most people indicate that Philadelphia is north of Rome. Similarly, when asked the direction from

Boston to Rio, most people indicate that Boston is east of Rio. Despite being in the majority, these informants are mistaken. But they are mistaken for good reason. People remember the locations and directions of spatial entities, continents in this case, but also cities, roads, and buildings, relative to each other, a heuristic related to perceptual grouping by proximity. In the case of Philadelphia and Rome, the United States and Europe serve as reference objects for each other; hence, they are grouped, and remembered as more aligned that they actually are. In actuality, Europe is for the most part north of the United States. In the case of Boston and Rio, North and South America are grouped and remembered as more aligned than they actually are; in actuality, South America lies mostly east of North America. Such errors of alignment have been found for artificial as well as real maps, for visual blobs as well as geographic entities (Tversky, 1981).

Landmarks are used to structure routes and organize neighborhoods. When asked where they live, people often saying near the closest landmark they think their inerlocuter will know (Shanon, 1983). Dramatic violations of metric assumptions are one consequence of encoding locations relative to landmarks. Distance estimates to a landmark from an ordinary building are reliably smaller than distance estimates from a landmark to an ordinary building (McNamara and Diwadkar, 1997; Sadalla, Boroughs, and Staplin, 1980).

Perspective of Judgement. Saul Steinberg delighted the readers of *The New Yorker* for many years with his maps that poked fun at egocentric views of the world. The New Yorker's view, for example, exaggerated the size and distances of the streets of Manhattan and reduced the sizes and distances of remote areas. These whimsical maps turned out to presage an empirically documented phenomenon, that spaces near one's perspective loom larger and are estimated to be larger than spaces far from one's perspective. Unlike the cartoon maps, the research also showed that perspective is flexible; students located in Ann Arbor adopted a west coast perspective as easily as an east coast perspective, and from either perspective, overestimated the near distances relative to the far ones (Holyoak and Mah, 1982).

Reference Frames. External reference frames, such as the walls of a room or the cardinal directions or large environmental features such as bodies of water or mountains, also serve to index locations and directions of spatial objects. Objects may also induce their own reference frame, usually constructed out of its' axis of elongation or symmetry and the axis perpendicular to that. When asked to place a cutout of South America in a north-south east-west reference frame, most people upright South America so that its' natural axis of elongation is rotated in the mind toward the nearest axis of the world, the north-south axis. Similarly, when asked the direction from Stanford to Berkeley, most people incorrectly indicate that Stanford is west of Berkeley, when in fact, Stanford is slightly east of Berkeley. This is because the natural axis of elongation of the San Francisco Bay area is rotated in memory toward the closest environmental axis, the north-south axis. Rotation effects also appear for other environments, roads, artificial maps, and visual blobs (Tversky, 1981).

Reference frames other than the cardinal directions are used to anchor spatial entities. States are used to index the locations of cities, so that, for example, most people mistakenly think that San Diego is west of Reno because for the most part, California lies west of Nevada (Stevens and Coupe, 1978). Geographic objects can also be indexed functionally. For example, buildings in Ann Arbor are grouped by town versus university although in fact, they are interwoven. People erroneously underestimate distances within a functional grouping relative to distances between functional groupings (Hirtle and Jonides, 1985). Political groupings have a similar affect; Hebrew speakers underestimate distances between Hebrew-speaking settlements relative to Hebrew-speaking to Arabic-speaking settlements; likewise, Arabic speakers underestimate distances between Arabic-speaking settlements relative to Arabic-speaking to Hebrew-speaking settlements (Portugali, 1993).

Why Systematic Errors? The biases and errors in the space of navigation reviewed here are not the only ones that have been investigated; there are a variety of other fascinating errors of direction, location, orientation (see Tversky, 1992, 2000b, 2000c for reviews). The space of navigation serves a richness of functions in our lives, allowing us to find our ways to home and other destinations, to describe environments and routes to others, to make judgements of location, distance, and direction, to make inferences about metereological, geographic, geological, and political events. Our knowledge of spaces too large to be seen from one place requires us to piece together disparate pieces of spatial information. Integrating disparate pieces of information can be accomplished through common objects, reference objects, reference frames, and perspectives. The integration is necessarily schematic, and the schematization inevitably leads to error.

Why would the mind or brain develop and use processes that are guaranteed to produce error? These systematic errors contrast with other spatial behaviors that are finely tuned and highly accurate, such as catching fly balls, playing the piano, wending one’s way through a crowd to some destination. Unlike the judgements and inferences and behaviors reviewed here, these highly accurate behaviors are situated in environments replete with cues and are highly practiced. The errors described here are often one-time or infrequent responses made in the abstract, not situated. They need to be performed in limited capacity working memory and are based on schematized mental representations constructed ad hoc for current purposes. In many cases, the errors induced by schematization are corrected in actual practice. A turn that is actually 60 degrees may be described ambiguously as a right turn or remembered incorrectly as 90 degrees but the schematization won't matter as the actual environment will disambiguate the vagueness of the expression and won't allow the error to be enacted (see Tversky, in press a, for development of these ideas about optimization and error).

In practice, actual navigation depends on far more than cognitive maps or collages, which are error-prone. Actual navigation is situated in environments that evoke memories not otherwise likely to be aroused. Actual navigation is motoric and invokes motor, proprioceptive, and vestibular responses that may not be otherwise accessible. Some of the intriguing findings are that motor responses may dominate visual ones in memory for locations (Shelton and McNamara, 2001), and motor responses are more critical for updating rotational than translational movement (Rieser, 1999). The interconnections between the cognitive and the sensorimotor in navigation are fascinating, but beyond the purview of this chapter (see Golledge, 1999, for a recent collection of papers).

The Space of External Representations.

One distinctly human endeavor is the creation of external tools that serve cognition. Such inventions are ancient, going back to prehistory. Trail markers, tallies, calendars, and cave paintings have been found across the world, as have schematic maps in the sand, on petroglyphs, in portable wood carvings or constructions of bamboo and shells (e. g., Southworth and Southworth, 1982; Tversky, 2000a). Yet another ancient example of an external cognitive tool, invented independently by many cultures, is writing, whether ideographic, reflecting meaning, or phonetic, reflecting sound.

The space of external representations has a different status from the previous spaces, it is invented, created in order to enhance human cognition. It uses space and spatial relations to represent both inherently spatial relations, as in maps and architectural drawings, and metaphorically spatial relations, as in flow diagrams, organizational charts, and economic graphs. Interesting, using space to represent space is ancient and ubiquitous, whereas using space to represent metaphoric space is modern. External cognitive tools function to extend the powers of the mind by offloading memory and computation (e. g., Donald, 1991; Kirsch, 1995). At the same time, they capitalize on human skills at spatial reasoning (e. g., Larkin and Simon, 1987

External representations consist of elements and the spatial relations among them. Typically, elements in a diagram or other external representation are used to represent elements in the world. Thus a tally uses one undistinguished mark on paper or wood or bone to represent one element in the world. Typically, spatial relations in a diagram are used to represent relations among elements in the world. Distance in a map usually corresponds to distance in real space. A notable exception to this is mathematical notation, where elements such as + and - are used to represent relations or operations on elements.

Elements. In many cases, elements bear resemblance to what they represent. This is evident in ideographic languages such as Hittite, Sumerian, Egyptian, and Chinese, where for example, a depiction of the sun or of a cow is used to represent the corresponding objects (e. g., Gelb, 1963). Not only resemblances, but figures of depiction are used to convey more abstract concepts, synecdoche, where a part stands for a whole, as in the horns of a ram for a ram, and metonymy, where a symbol or an association substitutes, as in a staff of office for a king. These figures of depiction appear in modern icons as well, where a trash can is for dumping files and a scissors for cutting them. Obviously, these devices are used in descriptions as well as depictions, for example, when the U. S. government is referred to as the White House. The power of depictions to represent meanings iconically or metaphorically is nevertheless limited, and most languages developed devices for representing the sounds of words to increase the range of writing.

In many useful diagrams, similar elements appear with similar abstract meanings, geometric elements such as lines, crosses, blobs, and arrows. Their interpretations are context-dependent, as for many word meanings, such as *line* or *relation* or *area* or *field*. For these schematic elements, their meanings share senses that appear to be related to the mathematical or Gestalt properties of the elements. Lines in tallies are undistinguished shapes that indicate objects whose specific characteristics are irrelevant. In other diagrams, notably maps and graphs, lines are one-dimensional paths that connect other entities, suggesting that they are related. Crosses are intersections of paths. Blobs or circles are two-dimensional areas whose exact shape is irrelevant or can be inferred from context. Thus, these elements schematize certain physical or semantic properties, omitting others. Like classifiers in spoken language, for example, *roll* or *sheet* of paper, they often abstract characteristics of shape. Three research projects illustrate the use of such schematic elements in graphs, diagrams, and maps respectively.

*Bars and lines in graphs***.** As noted, lines are paths that connect elements, thereby calling attention to an underlying dimension. Bars, by contrast, separate; they contain all the elements that share one feature and separate them from the elements that share other features. In graphs, then, lines should be more readily interpreted as trends and bars as discrete comparisons. Similarly, trend relationships should be more readily portrayed as lines and discrete relations as bars. In studies of graph interpretation and production, exactly this pattern was found (Zacks and Tversky, 1999). One group of participants was asked to interpret bar or line graphs of one of two relations: height of 10 and 12 year olds, where the underlying variable, age, is continuous; or height of women and men, where the underlying variable, gender, is discrete. Participants were more likely to interpret line graphs as trends, even saying that as people get more male, they get taller. They were more likely to interpret bar graphs as discrete comparisons, as in 12 year olds are taller than 10 year olds. Mirror results were obtained for producing graphs from descriptions. Discrete descriptions yielded bar graphs and trend descriptions yielded line graphs, even with discordant with the underlying discrete or continuous variable, age or gender.

*Arrows in diagrams***.** Arrows are asymmetric paths, so they indicate an asymmetric relation, such as time or motion. Their interpretation seems to have a natural basis, both in the arrows sent to hunt game and in the arrows formed by water descending hills. As such, they are readily interpreted and used to indicate direction, in space, time, and causality. About half the participants sketching route maps to a popular fast food place put arrows on their maps to convey direction in space (Tversky and Lee, 1998). Diagrams of complex systems illustrate the power of arrows to affect mental representations of them. Participants were asked to describe diagrams of a bicycle pump, a car brake, or a pulley system (Heiser and Tversky, submitted). Half the diagrams had arrows and half did not. Participants who saw diagrams without arrows wrote structural descriptions of the systems; they described the system’s parts and spatial relations. Participants who saw diagrams with arrows wrote functional descriptions; they described the sequence of operations performed by the systems and the outcomes of each operation or action. The arrows suggest the temporal sequence of operations. Apparently, the human mind jumps from temporal order to causal order in fractions of a second. As for graphs, production mirrored comprehension: given structural descriptions of the pump, brake, or pulleys, participants produced diagrams without arrows, but given functional descriptions, participants’ diagrams included arrows.

*Lines, crosses, and blobs in route maps***.** Route maps include a greater variety of schematic elements. Straight lines are produced and interpreted as more or less straight paths, and curved lines as more or less curvy paths. Crosses are produced and interpreted as intersections where the actual angle of intersection is not represented. Circular or rectangular shapes stand for landmarks of varying shapes and sizes. These uses are all the more surprising as maps offer the potential for analog representation, yet both producers and users of route maps seem satisfied with schematic, approximate, even categorical representation of paths, nodes, and landmarks (Tversky and Lee, 1998, 1999). Interestingly, the elements and distinctions made in route maps are the same as those made in route directions given in language, suggesting that the same conceptual structure underlies both, and encouraging the possibility of automatic translation between them.

Relations. Spatial relations can be depicted at several levels of abstraction, capturing categorical, ordinal, interval, and ratio relations. Proximity in space is used to convey proximity on spatial and nonspatial relations. How close one person stands to another, for example, can reflect social distance, which in turn depends on both the relations between the individuals and the sociocultural context. Categorical uses of space include separating the laundry belonging to different family members by separate piles and separating the letters belonging to different words by the spaces between words, a spatial device adopted by phonetic writing systems. Ordinal uses of space include listing groceries to be purchased in the order of the route taken through the store, listing presidents in historical order or listing countries in order of geography, size, or alphabet. Hierarchical trees, such as those used in evolutionary or organizational charts, are also examples of ordinal spatial relations that convey other ordinal relations, such as time or power. In interval uses of space, the distance between elements as well as the order of elements is significant. Graphs, such as those plotting change in productivity, growth, crime rate, and more over time, are a common example. Note that in each of these cases, proximity in space is used to represent proximity on some nonspatial attribute. Space, then, is used metaphorically, similar to spatial metaphors in speech, as in, the distance between their political positions is vast.

For both interval and ordinal mappings, direction of increases are often meaningful. In particular, the vertical direction, the only asymmetric direction in the world, one induced by gravity, is loaded with asymmetric associations (e. g., Clark, 1973; Lakoff and Johnson, 1980; Tversky, Kugelmass, and Winter, 1991). Both children and adults prefer to map concepts of quantity and preference from down to up rather than up to down. For the horizontal axis, they are indifferent as to whether increases in quantity or preference should go left to right or right to left, irrespective of whether they write right to left or left to right (Tversky, et al., 1991). Almost all the diagrams of evolution and geological ages used in standard textbooks portrayed man or the present day at the top (Tversky, 1995a). The association of up with good, strong, and valuable appears in language as well, in both word and gesture. We say that someone’s on top of the heap or has fallen into a depression. We give a high five or thumbs down.

The progression of levels of information mapped in external representations from categorical to ordinal to interval is mirrored in development. Four and five-year old children, speakers of a language written left-to-right as well as speakers of languages written right-to-left sometimes only represent temporal, quantitative, and preference relations at only a categorical level; for example, breakfast, lunch, and dinner are separate events, not ordered on a time scale. Most young children, however, do represent these relations ordinally on paper, but not until the preteen years do children represent interval relations (Tversky, et al., 1991).

Maps are often given as a quintessential example of ratio use of space, where not only intervals between points are meaningful, but also ratios of intervals; that is, zero is meaningful rather than arbitrary. And indeed, distance and direction between elements representing cities on a map are often meant to represent distance and direction between cities in the world. Yet, not all maps, either ancient or modern, seem to intend to represent distance and direction metrically (Tversky, 2000a). Sketch maps drawn to aid a traveler to get from A to B typically shrink long distances with no turns (Tversky and Lee, 1998). Maps from many cultures portray historical and spiritual places, such as medieval Western maps that show the Garden of Eden and the continent of Asia at the top, with Europe left and Africa right at the bottom. Similar melanges of legend and geography appear in ancient New World and Asian maps (see wonderful collections in Harley and Woodward, 1987, 1992 and Woodward and Lewis, 1994, 1998). Tourist maps, ancient and modern, frequently mix perspectives, showing the system of roads from overview perspective with frontal views of tourist attractions superimposed. Such maps allow users both to navigate to the attractions and to recognize the attractions when they arrive. An exemplary contemporary map that has served as a model for graphic designers is the London Underground Map. It intentionally distorts metric information in the service of efficient representation of the major subway lines and their interconnections. Subway lines are represented as straight lines, oriented horizontally, vertically, or diagonally, not reflecting their actual paths. This map is efficient for navigating a subway system, but not for conveying distances and directions in the ground overhead. Even highway maps, which are meant to convey direction and distance accurately for drivers, distort certain information. If the scale of such maps were faithfully used, highways and railways wouldn't be apparent. Symbols for certain structures like rest stations and tourist attractions are also routinely added.

Maps, then, schematize and present the information important for the task at hand. Underground maps suit different purposes from road maps which serve different purposes from topographic or tourist maps, and successful versions of each of these select and even distort certain information and omit other. Successful diagrams do the same.

Schematic diagrams save information processing, but they also bias certain interpretations.

Distortions in Memory for External Representations. Like internal representations, external representations are organized around elements and spatial relations among them with respect to a reference frame. Just as there are systematic distortions in memory for maps and environments in the direction of other elements and reference frames, memory for external representations is distorted in the same directions (e. g., Pani, Jeffres,, Shippey, and Schwartz,1996; Schiano and Tversky, 1992; Tversky and Schiano, 1989; Shiffrar and Shepard, 1991). Distortions in memory for external representations, in particular graphs, also illustrate semantic factors in organizing external representations. In X-Y plots, the most common graph, the imaginary diagonal has a special status as it is the line where X = Y. The identity line serves as an implicit reference frame for lines in X-Y graphs. Participants viewed lines in axes that were interpreted either as X-Y plots or as shortcuts in maps. In memory, graph lines were distorted toward the 45 degree line but lines in maps were not (Schiano and Tversky, 1992; Tversky and Schiano, 1989). Lines that were given no meaningful interpretation showed yet a different pattern of distortion (Schiano and Tversky, 1992). These studies demonstrate the effects of meaning on selection of reference frame and consequent memory. Other distortions are general effects of perceptual organization, not dependent on the meaning assigned the stimuli. Symmetry exerts one such effect. Rivers on maps, curves on graphs, and nearly symmetric forms assigned no meaning are all remembered as more symmetric than they actually were (Freyd and Tversky, 1984; Tversky and Schiano, 1989). As usual, systematic distortions give insight into the way stimuli are organized, with both perceptual and conceptual factors operative.

Creating Graphic Representations. External representations constructed by people all over the world and throughout history as well as from laboratory studies on children and adults from different cultures demonstrate that external representations use elements and the spatial relations among them in meaningful, readily interpretable, cognitively natural ways. Maps, charts, and diagrams have been developed in communities of users, similar to spoken language. Also similar to spoken language, depictions are produced and used, produced and used, leading to refinements and improvements in accuracy and efficiency (e. g., Clark, 1996; Engle, 1998; Schwartz, 1995). Elements in external representations use likenesses, figures of depictions, and schematic forms to stand for elements in the world. Proximity in the space of external representations is used to convey proximity in spatial as well as other relations at several levels of abstraction. These direct and figurative uses of elements and space render external representations easy to produce and easy to comprehend. This is not to say that diagrams are immediately comprehended;

they may be incomplete, ambiguous, or difficult to interpret, yet, on the whole, they are more directly related to meaning than, say, language. Diagrams schematize, but language schematizes even more so; diagrams retain some visual and spatial correspondences or metaphoric correspondences to the things they represent.

Many have proposed that graphics form a “visual language” (e. g., Horn, 1998). The “visual language” of graphics lacks the essential structural and combinatoric features of spoken languages, but it can be used to communicate. The components and principles of natural language form an insightful framework for analyzing properties of depictions. Following this analysis, elements of graphics compare to words of a language, the semantic level of structure, and the spatial relations between elements as a rudimentary syntax, expressing the relations among elements. Spatial relations readily convey proximity and grouping relations on spatial and other dimension, but obviously, natural language can convey a far richer set of relations, including nesting, overlap, conditionals, and negation. The addition of other elements to simple spatial relations allows expression of many of these relations. Hierarchical trees express part-of and kind-of and other hierarchical relations. Venn diagrams show them as well, along with intersection and negation. Developing complete graphic systems for expressing complex logical relations that would allow logical inference has proved to be a challenge (e. g., Allwein and Barwise, 1996; Barwise and Etchemendy, 1995; Shin, 1995; Stenning and Oberlander, 1995). Some, like the present paper, have analyzed how graphics communicate (e. g., Pinker, 1990; Winn, 1987). Others have proposed guidelines for creating graphic representations (e. g., Cleveland, 1985;,Kosslyn, 1994a; Tufte, 1983; 1990; 1997).

Comprehending Graphic Representations. Still others have presented analyses of how graphics are comprehended (e. g, Carpenter and Shah, 1998; Larkin and Simon, 1987; Pinker, 1990; see also, Glasgow, Naryanan, and Chandrasekeran, 1995). For example, according to Carpenter and Shah (1998), graph comprehension entails three processes: pattern recognition; translation of visual features into conceptual relations; determining referents of quantified concepts and associating them to functions. These processes occur in iterative cycles. Graph comprehension is easier when "simple pattern identification processes are substituted for complex cognitive processes" (p. 98). In the wild, comprehension and production of graphics work hand in hand in cycles so that created graphics get refined by a community of users at the same time creating conventions within that community (e. g., Clark, 1996; Zacks and Tversky, 1999).

Three-dimensionality and animation present special challenges to graph comprehension. The availability and attractiveness of these techniques has enticed many, yet there is little support that they are beneficial to comprehension. Moreover, there is evidence that each presents difficulties for perception and comprehension, suggesting that they should not be adopted as a default but rather only under considered circumstances.

Three-dimensional graphics are often used gratuitously, to represent information that is only one- or two-dimensional. Bar graphs are common example. Yet reading values from three-dimensional bar graphs is less accurate than reading values from traditional two-dimensional bar graphs (Zacks, Levy, Tversky, and Schiano, 1998). Moreover, three-dimensional displays are often perceptually unstable, reversing like Necker cubes, and parts of three-dimensional displays often occlude relevant information (Tversky, 1995b). Even when data are inherently three-dimensional, comprehending the conceptual interrelations of the variables is difficult (Shah and Carpenter, 1995).

Animation is increasingly used to convey conceptual information, such as weather patterns (Lowe, 1999), the sequence of operations of mechanical or biological systems (e. g., Palmiter and Elkerton, 1993) or the sequence of steps in an algorithm (e. g., Byrne, Cantrambone, and Stasko, 2000). Many of these are exactly the situations where animations should be effective, namely, for conveying changes in spatial (or metaphorically spatial) relations over time. Nevertheless, there is no convincing evidence that animations improve learning or retention over static graphics that convey the same information (for a review and analysis, see Tversky, Morrison, and Betrancourt, in press). The cases where animations were reported as superior have been cases where the proper controls have not been included or where interaction is involved for animations. Even more than three-dimensionality, animations can be difficult to perceive, especially when they portray parts moving in relation to one another. Generations of great painters depicted galloping legs of horses incorrectly, presumably because the correct positions could not be ascertained from watching natural animations. Stop-gap photography allowed correction of those errors. Even when a single path of motion is portrayed, it can be misinterpreted, as the research on naïve physics showing incorrect perceptions of trajectories has demonstrated (e. g., Kaiser, Proffitt, Whelan, and Hecht, 1992; Pani, Jeffres, Shippey, and Schwartz,1996; Shiffrar and Shepard, 1991). Despite the lack of support for animations to convey information about changes in parts or states over time, there may be other cases where animations may be effective, for example, when used in real time for maintaining attention, as in fill bars that indicate the percent of a file that has been downloaded or in zooming in on details.

One lesson to be learned from the work on 3-D and animation is that realism per se is not necessarily an advantage in graphic communication. Effective graphics schematize the information meant to be conveyed so that it can be readily perceived and comprehended. Realism can add detail that is irrelevant, and makes the relevant harder to discern.

External and Internal Representations

External visuospatial representations bear many similarities to those that reside in the mind This is not surprising as external representations are created by human minds to serve human purposes, many of the same purposes that internal representations serve. Of course, there are differences as well. The constraints on internal representations, for example, working memory capacity and long term memory fallibility, are different from the constraints on external representations, for example, construction ability and the flatness of paper. Their functions differ somewhat as well. Yet both internal and external representations are schematic, that is, they omit information, they add information, and they distort information. In so doing, they facilitate their use, by preprocessing the essential information and directing attention to it. The cost of schematization is the possibility of bias and error, when the representations are used for other purposes. And it is these biases and errors that reveal the nature of the schematization.

Multiple Functional Systems in the Brain.

Prima facie evidence for the multiplicity of spaces in the mind comes from the multiplicity of spaces in the brain. Many have been suggested, varying in ways that are not comparable, among them, content, modality, reference frame, and role in behavior. As the features distinguishing each space are not comparable, they do not form a natural taxonomy. However, they do suggest the features of space that are important enough in human existence to be specially represented in the brain.

Space is multi-modal, but for many researchers, vision is primary. The visual world captured by the retina is topographically mapped in occipital cortex, the primary cortical projection area for the visual system. Yet even in occipital cortex, there are many topographic maps, differing in degree of processing of the visual information. As visual information undergoes increasing processing, spatial topography becomes secondary and content becomes primary. There are regions in occipital cortex and nearby that are differentially sensitive to different kinds of things, objects, faces, places, and bodies (e. g., Epstein and Kanwisher, 1998; ; Downing, Jiang, Shuman, and Kanwisher, submitted; Haxby, Gobbini, Furey, Ishai, Schouten, and Pietrini, 2001). Some of the regions partial to kind of object retain an underlying topography. Significantly, areas representing the fovea overlap with areas sensitive to faces whereas areas representing the periphery have greater overlap with areas sensitive to places (Levy, Hasson, Avidan, Henler, and Malach, 2001).

After occipital cortex, the visual pathways split into two major streams, one ventral, to the temporal lobe and one dorsal to the parietal lobe. These have been termed the "what" and "where" systems by some researchers (Ungerleider and Mishkin, 1982), the "what" and "how" systems by others (Milner and Goodman, 1992) and object-centered vs. viewer-centered by yet others (Turnbull, Denis, Mellet, Ghaem, and Carey, 2001). Damage to the ventral pathway results in difficulties in identifying objects whereas damage to the dorsal pathway leads to difficulties in locating objects in space, demonstrated in tasks that entail interactions with the objects. However conceived, the dorsal system seems to be responsible for aspects of objects and the ventral for relations of objects to surrounding space.

Farther upstream are regions underlying the integration of spatial information from more than one modality, for example, vision and touch. Neurons in the ventral premotor cortex and the putamen of macaque monkeys have receptive fields tied to parts of the body, notably parts of the face and arms. These neurons respond to both visual and tactile stimuli (Graziano and Gross, 1994; Gross and Graziano, 1995). Single cells in ventral premotor cortex of macaques respond when the monkey enacts a particular action, like grasping or tearing, and when the monkey views someone else performing that action (Fogassi, Gallese, Fadiga, Luppin, Matelli, and Rizzolatti, 1996; Rizzolatti, Fadiga, Fogassi, and Gallese, in press). A variety of spatial reference systems are also built into the brain. Neurons in temporal cortex of macaques are selectively responsive to different spatial reference systems, those of viewer, of object, and of goal (Jellema, Baker, Oram, and Perrett, in press). Other evidence suggests that objects and locations are represented in multiple reference systems. Recordings from rat hippocampus show that as they explore new environments, rats establish allocentric as well as egocentric representations of the space around them (O'Keefe and Nadel, 1978). Also illuminating are studies of patients with spatial neglect, who, due to brain damage, do not seem to be aware of half of their visual field, more commonly, the left half. Consistent with the single-cell recordings from macaques, a recent analysis of dozens of cases of neglect shows that the critical site for damage is right (Karnath, Ferber, and Himmelbach, 2001). Careful studies have shown that the neglect is not simply of the visual field; for example, it may be of the left half of an object in the right visual field. Nor is the neglect confined to the visual modality; it extends, for example, to touch. Such studies as well as work on intact people suggest that objects and locations are coded in terms of several reference systems simultaneously, for example, those that depend on the object, on the viewer, and on the environment (Behrmann and Tipper, 1999; Robertson and Rafal, in press.).

All in all, the neuroscientific evidence shows that the brain codes many aspects of space, notably, the things in space, their spatial relations in multiple reference frames, and interactions with space and with things in space. Many of these form the basis for the functional spaces distinguished here. And many subserve functions other than spatial thinking, supporting the naturalness of thinking about other domains spatially. Moreover, some are directly linked to other senses or to action. Significantly, regions that subserve space may serve other functions as well, establishing a basis for thinking about space metaphorically.

In Conclusion

From the moment of birth (and undoubtedly before), we are involved in space, and consequently, in spatial cognition. Sensations arrive on our bodies from various points in space; our actions take place in space and are constrained by it. These interactions occur at discernable levels, that of the space of the body, that of the space in reach or in sight around the body, that of the space of navigation too large to be apprehended at once, and that of the space of external representations, of graphics constructed to augment human cognition. Each mental space extracts and schematizes information useful for function in that space. So useful are these mental spaces that they subserve thinking in many other domains, those of emotion, interpersonal interaction, scientific understanding (e. g., Lakoff and Johnson, 1980). We feel up or down, one nation's culture or language invades or penetrates another, inertia, pressure, and unemployment rise or fall. At its' most lofty, the mind rests on the concrete.

References

Aguirre, G. K. and D'Esposito, M. (1997). Environmental knowledge is subserved by separable dorsal/ventral neural areas. *Journal of Neuroscience*,17, 2512-2518.

Aguirre, G., K. and D'Esposito, M. (1999). Topographical disorientation: A synthesis and taxonomy. *Brain*, 122, 1613-1628.

Allwein, G. and Barwise, J. Editors (1996). *Logical reasoning with diagrams*. Oxford:
O
Oxford University Press.

Andersen, E. S. (1978) Lexical universals in body-party terminology. In J. H. Greenberg (Ed.), *Universals of human language*, Vol. 3. Pp. 335-368. Stanford, CA: Stanford University Press.

Barwise, J. and Etchemendy, J. (1995) In J. Glasgow, N. H. Naryanan, and G.Chandrasekeran, Editors. *Diagrammatic reasoning: Cognitive and computational perspectives*. Cambridge: MIT Press.

Behrmann, M. and Tipper, S. P. (1999). Attention accesses multiple reference frames: Evidence from neglect. *Journal of Experimental Psychology: Human Perception and Performance*, 25, 83-101.

Berlucchi, G. and Aglioti, S. (1997). The body in the brain: Neural bases of corporeal awareness. *Trends in Neuroscience*, 12, 560-564.

Bertin, J. (1981). *Graphics and graphic-information-processing.* N. Y.: Walter de Gruyter.

Biederman, I. (1987). Recognition-by-components: A theory of human image understanding. *Psychological Review*, 94, 115-145.

Byrne, M. D., Catrambone, R. & Stasko, J. T. (2000). Evaluating animations as student aids in learning computer algorithms. Computers & Education, 33, 253-278.

Braine, L. G. (1978). A new slant on orientation perception. *American Psychologist*, 33, 10-22.

Bryant, D. J., Tversky, B., & Franklin, N. (1992). Internal and external spatial frameworks for representing described scenes. *Journal of Memory and Language*, 31, 74-98.

Bryant, D. J. and Tversky, B. (1999). Mental representations of spatial relations from diagrams and models. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 25, 137-156.

Bryant, D. J., Tversky, B., and Lanca, M. (2001). Retrieving spatial relations from observation and memory. In E. van der Zee and U.Nikanne (Editors), *Conceptual structure and its interfaces with other modules of representation*. Pp.116-139. Oxford: Oxford University Press.

Card, S. K., Mackinlay, J. D., and Shneiderman, B. (1999). *Readings in information visualization: Using vision to think*. San Francisco: Morgan Stanley.

Carpenter, P. A. and Shah, P. (1998). A model of the perceptual and conceptual processes in graph comprehension. *Journal of Experimental Psychology: Applied*, 4, 75-100.

Carswell, C. M. (1992). Reading graphs: Interaction of processing requirements and stimulus structure. In B. Burns (Ed.), *Percepts, concepts, and categories*. Pp. 605-645. Amsterdam: Elsevier.

Carswell, C. M. & Wickens, C. D. (1990). The perceptual interaction of graphic attributes: Configurality, stimulus homogeneity, and object integration. *Perception and Psychophysics,* 47, 157-168.

Casati, R. and Varzi, A. (2000). *Parts and places.* Cambridge: MIT Press.

Cave, C. G. and Squire, L. R. (1991). Equivalent impairment of spatial and nonspatial memory following damage to the human hippocampus. *Hippocampus,* 1, 329-340.

Clark, H. H. (1973). Space, time, semantics, and the child. In T. E. Moore (Ed.), *Cognitive development and the acquisition of language*.Pp. 27-63. N. Y.: Academic Press.

Cleveland, W. S. (1985). The elements of graphing data. Monterey, CA: Wadsworth.

De Renzi, E. (1982). *Disorders of space exploration and cognition*. Chichester: John Wiley.

Denis, M. (1997). The description of routes: A cognitive approach to the production of spatial discourse. *Current Psychology of Cognition*, 16, 409-458.

Donald, M. (1991). Origins of the modern mind. Cambridge: Harvard University Press.

Downing, P. A., Jiang, Y., Shuman, M. and Kanwisher, N. (submitted '01) A cortical selection for visual processing of the human body.

Ehrich, V. & Koster, C. (1983). Discourse organization and sentence form: The structure of room descriptions in Dutch. *Discourse Processes,* 6, 169-195.

Ehrlich, K., & Johnson-Laird, P. N. (1982). Spatial descriptions and referential continuity. *Journal of Verbal Learning and Verbal Behavior*,21, 296-306.

Emmorey, K., Tversky, B., and Taylor, H. A. (In press). Using space to describe space: Perspective in speech, sign, and gesture. *Journal of Spatial Cognition and Computation*.

Engle, R.A. (1998). Not channels but composite signals: Speech, gesture, diagrams and object demonstrations are integrated in multimodal explanations. In M.A. Gernsbacher & S.J. Derry (Eds.*) Proceedings of the Twentieth Annual Conference of the Cognitive Science Society*. Mahwah, NJ: Erlbaum.

Epstein, R. & Kanwisher, N. (1998) A cortical representation of the local visual environment. *Nature*, 392, 599-601.

Fogassi, L, Gallese, V., Fadiga, L., Luppino, G., Matelli, M. and Rizzolatti, G. (1996). *Journal of Neuropsychology*, 76, 141-157.

Franklin, N. and Tversky, B. (1990). Searching imagined environments. *Journal of Experimental Psychology: General*, 119, 63-76

Franklin, N., Tversky, B., and Coon, V. (1992). Switching points of view in spatial mental models acquired from text. Memory and Cognition, 20, 507-518.

Freyd, J. and Tversky, B. (1984). The force of symmetry in form perception. *American Journal of Psychology*, 97, 109-126.

Gattis, M. and Holyoak, K. J. (1996). Mapping conceptual to spatial relations in visual reasoning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 22, 1-9.

Gelb, I. (1963). *A study of writing*. Second edition. Chicago: University of Chicago Press.

Ghaem, O., Mellet, E., Crivello, F., Tzourio, N., Mazoyer, B., Berthoz, A., & Denis, M. (1997). Mental navigation along memorized routes activates the hippocamus, precuneus, and insula. *NeuroReport*, 8, 739-744.

Glasgow, J., Narayanan, N. H., and Chandrasekaran, B. (1995). *Diagrammatic Reasoning: Cognitive and Computational Perspectives*. Cambridge: MIT Press.

Glenberg, A. M., Meyer, M. and Lindem, K. (1987). Mental models contribute to foregrounding during text comprehension. *Journal of Memory and Language*, 26, 69-83.

Golledge, R. G. (1999). (Editor). Wayfinding behavior: Cognitive mapping and other spatial processes. Baltimore: Johns Hopkins Press.

Goodale, M. A. and Milner, A. D. (1992). Separate visual pthways for perception and action. *Trends in Neuroscience*, 15, 20-25.

Graziano, M. S. A. and Gross, C. G. (1994). Mapping space with neurons. *Current Directions in Psychological Science*, 3, 164-167.

Gross, C. G. and Graziano, M. S. A. (1995). Multiple representations of space in the brain. *The Neuroscientist*, 1, 43-50.

Harley, J. B. and Woodward, D. (Eds.) (1987). *The history of cartography. Vol. 1: Cartography in prehistoric, ancient and medieval Europe and the Mediterranean*. Chicago: University of Chicago Press.

Harley, J. B. and Woodward, D. (Editors) (1992) *The history of cartography. Vol. 2. Book One: Cartography in the traditional Islamic and South Asian Societies*. Chicago: University of Chicago Press.

Haxby, J. F., Gobbini, M. I, Furey, M. L., Ishai, A., Schouten, J. L., and Pietrini, P. (2001). *Science*, 293, 28, 2425-2427.

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

Heptulla-Chatterjee, S., Freyd, J. and Shiffrar, M. (1996). Configurational processing in the perception of apparent biological motion. *Journal of Experimental Psychology: Human Perception and Performance*, 22, 916-929.

Hirtle, S. C. and Jonides, J. (1985). Evidence of hierarchies in cognitive maps. *Memory and Cognition*, 13, 208-217.

Holyoak, K. J. and Mah, W. A. (1982). Cognitive reference points in judgments of symbolic magnitude. *Cognitive Psychology*, 14, 328-352.

Horn, R. E. (1998). *Visual language*. Bainbridge Island, WA: MacroVu, Inc.

Huttenlocher, J. Hedges, L. V., and Duncan, S. (1991). Categories and particulars: Prototype effects in estimating spatial location. *Psychological Review*, 98, 352-376.

Jellema, T., Baker, C. I., Oram, M. W., and Perrett, D. I. (In press). Cell populations in the banks of the superior temporal sulcus of the macaque and imitation. In Meltzoff, A. and Prinz, W. (Editors), The imitative mind: Evolution, development, and brain bases.

Kaiser, M. K., Proffitt, D. R., Whelan, S. M., & Hecht, H. (1992). Influence of animation on dynamical judgments. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 669-690.

Kanwisher, N., McDermott, J. and Chun, M. M. (1997). The fusiform face area: A module in human extrastriate cortex specialized for face perception. *The Journal of Neuroscience*, 17, 4302-4311.

Karnath, H-O, Ferber, S. and Himmelbach, M. (2001) Spatial awareness is a function of the temporal not the posterior parietal lobe. *Nature*, 411, 950-953.

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

Kosslyn, S. M. (1980). *Image and mind*. Cambridge: Harvard University Press.

Kosslyn, S. M. (1989) Understanding Charts and Graphs. *Applied Cognitive Psychology*, 3, 185-223.

Kosslyn, S. M. (1994a) *Elements of graph design*. Freeman

Kosslyn, S. M. (1994b). Image and brain: The resolution of the imagery debate. MIT PRess, Cambridge, MA

Lakoff, G. and Johnson, M. (1980). *Metaphors we live by*. Chicago: University of Chicago Press.

Larkin, J. H. and Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, 11, 65-99.

Lee, P. U. and Tversky, B. (submitted). Switching perspective in spatial descriptions.

Levy, I., Hasson, U. Avidan, G., Henler, T. and Malach,R. (2001). Center-periphery organization of human object areas. *Nature Neuroscience*, 4, 533-539.

Levinson, S. (1996). Frames of reference and Molyneux's question: Cross-linguistic evidence. In P. Bloom, M. A. Peterson, L. Nadel, & M. Garrett (Eds.), Space and language (pp. 109-169). Cambridge: MIT Press.

Lowe, R. (1999). Extracting information from an animation during complex visual processing. European Journal of the Psychology of Education, 14, 225-244.

McNamara, T. P. and Diwadkar, V. A. (1997). Symmetry and asymmetry of human spatial memory. *Cognitive Psychology*, 34,, 160-190.

Maguire, E. A., Frackowiak, R. S. J., and Frith, C. D. (1997). Recalling routes around London: Activation of the right hippocampus in taxi drivers. *Journal of Neuroscience*, 17, 7103-7110.

Mani, K. & Johnson-Laird, P. N. (1982). The mental representation of spatial descriptions. Memory and Cognition, 10, 181-187.

Morrison, J. B. and Tversky, B. (1997). Body schemas. In M. G. Shafto and P. Langley (Editors), *Proceedings of the Meetings of the Cognitive Science Society*. Pp. 525-529. Mahwah, NJ: Erlbaum.

Morrow, D. G., Bower, G. H. and Greenspan, S. (1989). Updating situation models during narrative comprehension. Journal of Memory and Language, 28, 292-312.

Newcombe, F., Mehta, Z., and de Haan, E. H. F. (1994). Category specificity in visual recognition. In M. J. Farah and G. Ratcliff, Editors, *The neurpsychology of high-level vision.* Pp. 103-132. Hillsdale, N. J.: Erlbaum.

Newcombe, N., Huttenlocher, J., Sandberg, E., Lee, E., and Johnson, S. (1999). What do misestimations and asymmetries in spatial judgement indicate about spatial represntation? *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 25, 986-996.

Palmiter, S., & Elkerton, J. (1993). Animated demonstrations for learning procedural computer-based tasks. *Human-Computer Interaction, 8*, 193-216.

Pani, J. R., Jeffres, J. A., Shippey, G. T., & Schwartz, K. T., (1996) Imagining projective transformations: Aligned orientations in spatial organization. Cognitive Psychology, 31, 125-167.

Pinker, S. (1990). A theory of graph comprehension. In R. Freedle (Ed.), Artificial intelligence and the future of testing. Pp. 73-126. Hillsdale, N. J.: Erlbaum.

Portugali, Y. (1993). Implicate relations: Society and space in the Israeli-Palestinian conflict. The Netherlands: Kluwer.

Reed, C. L. and Farah, M. J. (1995). The psychological reality of the body schema: A test with normal participants. Journal of Experimental Psychology: Human Perception and Performance, 21, 334-343.

Rieser, J. J. (1999). Dynamic spatial orientation and the coupling of representation and action. In R. G. Golledge (Editor). Wayfinding behavior: Cognitive mapping and other spatial processes. Pp. 168-191 Baltimore: Johns Hopkins Press.

Rinck, M., Hahnel, A., Bower, G. H., and Glowalla, U. (1997). The metrics of spatial situation models. Journal of Experimental Psychology: Learning, Memory, and Cognition, 23, 622-637.

Rizzolatti, G., Fadiga, L, Fogassi, L, and Gallese, V. (In press). From mirror neurons to imitaiton: Facts and speculations. In Meltzoff, A. and Prinz, W. (Editors), The imitative mind: Evolution, development, and brain bases.

Robertson, L. C. and Rafal, R. (In press). Disorders of visual attention. In M. Gazzaniga (Editor), The cognitive neurosciences, Second edition. Cambridge, MA: MIT Press.

Rock, I. *Orientation and Form*. N.Y.: Academic Press, 1973.

Rosenbaum, R. S., Priselac, S., Kohler, S., Black, S. E., Gao, F., Nadel, L., & Moscovitch, M. (2000). Remote spatial memory in an amnesic person with extensive bilateral hippocampal lesions. Nature Neuroscience, 3, 1044-1048.

Sadalla, E. K., Burroughs, W. J., and Staplin, L. J. (1980). Reference points in spatial cognition. *Journal of Experimental Psychology: Human Learning and Memory*, 6, 516-528.

Schiano, D., & Tversky, B. (1992). Structure and strategy in viewing simple graphs. *Memory and Cognition*, 20, 12-20.

Schwartz, D. L. (1995). The emergence of abstract representations in dyad problem solving. *The Journal of the Learning Sciences*, 4, 321-354.

Shah, P. and Carpenter, P. A. (1995). Conceptual limitations in comprehending line graphs. *Journal of Experimental Psychology: General*, 124, 43-61.

Shanon, B. (1983). Answers to where-questions. *Discourse Processes*, 6, 319-352.

Shelton, A. L., Burrows, J. J., Tversky, B., and Gabrieli, J. D. E. (2000). Effects of route and survey perspectives on brain activation during scene recognition. Thirtieth Annual Meeting of the Society for Neurosciences, New Orleans, LA, November.

Shelton, A. L. and McNamara, T. P. (2001). Visual memories from nonvisual experiences. *Psychological Science*, 12, 343-347.

Shelton, A. L., Tversky, B. and Gabrieli, J. B. E. (2001). Switching between route and survey perspectives in spatial memory. Paper presented at meetings of Cognitive Neuroscience Society, New York, March.

Shepard, R. N. (1994). Perceptual-cognitive universals as reflections of the world. *Psychonomic Bulletin and Review*, 1, 2-28.

Shepard, R. N. and Cooper, L. (1982). *Mental images and their transformation.* Cambridge: MIT Press.

Shepard, R. N. & Podgorny, P. (1978). Cognitive processes that resemble perceptual processes. In W. K. Estes (Ed.), *Handbook of learning and cognitive processes*. Vol. 5. Pp. 189-237. Hillsdale, N. J.: Erlbaum.

Shiffrar, M. M. & Shepard, R. N. (1991). Comparison of cube rotations around axes inclined relative to the environment or to the cube. *Journal of Experimental Psychology*: *Human Perception and Performance*, 17, 44-54

Shin, S-J (1995). *The logical status of diagrams*. Cambridge: Cambridge University Press.

Simkin, D. and Hastie, R. (1987). An information analysis of graph perception. *Journal of the American Statistical Association*, 82, 454-465.

Simons, D. J. and Levin, D. T. (1997). Change blindness. *Trends in Cognitive Science*, 1, 261-267.

Southworth, M. and Southworth, S. (1982). *Maps: A visual survey and design guide*. Boston: Little, Brown and Company.

Stenning, K. and Oberlander, J. (1995). A cognitive theory of graphical and linguistic reasoning: Logic and implementation. *Cognitive Science*, 19, 97-140.

Taylor, H. A., Naylor, S. J. and Chechile, N. A. (1999). Goal-specific influences on the representation of spatial perspectives. Memory and Cognition, 27, 309-319.

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

Taylor, H. A. and Tversky, B. (1992b). Spatial mental models derived from survey and route descriptions. *Journal of Memory and Language*, 31, 261-282.

Taylor, H. A. and Tversky, B. (1996). Perspective in spatial descriptions. *Journal of Memory and Language*, 35, 371-391.

Thorndyke, P. and Hayes-Roth, B. (1982) Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology*\ 14, 560-89.

Tufte, E. R. (1983). *The visual display of quantitative information*. Chesire, Connecticut: Graphics Press.

Tufte, E. R. (1990). *Envisioning information*. Cheshire, CT.: Graphics Press.

Tufte, E. R. (1997) *Visual Explanations*. Cheshire: Graphics Press.

Turnbull, O. H., Denis, M., Mellet, E., Ghaem, O., Carey, D. P. (2001). The processing of visuospatial information: Neuropsychological and neuroimaging investigations. In M. Denis, R. H. Logie, C. Cornoldi, M.,de Vega, and J. Englelkamp (Editors), *Imagery, language and visuo-spatial thinking*. Pp. 81-108. Hove, UK: Psychology Press.

Tversky, B. (1981). Distortions in memory for maps. *Cognitive Psychology*, 13, 407-433.

Tversky, B. (1985). Categories and parts. In C. Craig & T. Givon (Eds.), *Noun classes and categorization* Pp. 63-75. Philadelphia: John Benjamins.

.Tversky, B. (1991) Spatial mental models .In G. H. Bower (Ed.), *The Psychology of Learning and Motivation: Advances in Research and Theory*.Vol. 27 (pp. 109-145). N. Y.: Academic Press.

Tversky, B. (1992). Distortions in cognitive maps. Geoforum, 23, 131-138.
.
Tversky, B. (1993). Cognitive maps, cognitive collages, and spatial mental models. In A. U. Frank and I. Campari (Editors), *Spatial information theory: A theoretical basis for GIS.*
Pp. 14-24. Berlin: Springer-Verlag.

Tversky, B. (1995a). Cognitive origins of graphic conventions. In F. T. Marchese (Editor). *Understanding images*. Pp. 29-53. New York: Springer-Verlag.

Tversky, B. (1995b). Perception and cognition of 2D and 3D graphics. *Human Factors in Computing Systems*. P. 175. New York: ACM.

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

Tversky, B. (2000b). Levels and structure of cognitive mapping. In R. Kitchin and S. M. Freundschuh (Editors). *Cognitive mapping: Past, present and future*. Pp. 24-43. London: Routledge.

Tversky, B. (2000c). Remembering spaces. In E. Tulving and F. I. M. Craik (Editors), *Handbook of Memory*. Pp. 363-378. New York: Oxford University Press.

Tversky, B. (2001). Spatial schemas in depictions. In M. Gattis (Editor), *Spatial schemas and abstract thought*. Pp. 79-111 Cambridge: MIT Press.

Tversky, B. (In press.). Multiple mental spaces. *Proceedings of Wittgenstein Society.*

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

Tversky, B., Kim, J. and Cohen, A. (1999). Mental models of spatial relations and transformations from language. In C. Habel and G. Rickheit (Editors), *Mental models in discourse processing and reasoning*. Pp. 239-258. Amsterdam: North-Holland.

Tversky, B., Kugelmass, S. and Winter, A. (1991) Cross-cultural and developmental trends in graphic productions. *Cognitive Psychology*, 23, 515-557.

.

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

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

Tversky, B.,Morrison, J. B. and Betrancourt, M. (in press). Animation: Does it facilitate? *International Journal of Human-Computer Studies*.

Tversky, B. Morrison, J. B. and Zacks, J. (In press). On bodies and events. In A. Meltzoff and W. Prinz (Editors), *The imitative mind.* Cambridge: Cambridge University Press.

Tversky, B., & Schiano, D. (1989). Perceptual and conceptual factors in distortions in memory for maps and graphs. *Journal of Experimental Psychology: General,* 118, 387-398.

Ullmer-Ehrich, V. (1982). The structure of living space descriptions. In R. J. Jarvella and W. Klein (Eds.), *Speech, place and action*. Pp. 219-249. N. Y.: Wiley.

Ungerleider, L. G. & Mishkin, M. (1982). Two cortical visual systems. In D. J. Ingle, M. A. Goodale, and R. J. W. Mansfield (Editors). *Analysis of visual behavior.* Cambridge, MA: MIT Press.

Winn, W. D. (1987). Charts, graphs and diagrams in educational materials. In D. M. Willows and H. A. Haughton (Eds.). *The Psychology of illustration*. N. Y.: Springer-Verlag.

Woodward, D. and Lewis, G. M. (1994) *The history of cartography. Volume 2, Book 2: Cartography in the traditional East and Southeast Asian societies*. Chicago: University of Chicago Press.

Woodward, D. and Lewis, G. M. (1998). *History of cartography. Vol. 2 Book 3: Cartography in the traditional Africa, America, Artic, Australian, and Pacific societies*. Chicago: University of Chicago Press.

Zacks, J. and Tversky, B. (1999). Bars and lines: A study of graphic communication. *Memory and Cognition*, 27, 1073-1079.

Zacks, J., Levy, E., Tversky, B., and Schiano, D. J. (1998). Reading bar graphs: Effects of depth cues and graphical context. *Journal of Experimental Psychology: Applied*, 4, 119-138.

Zacks, J., Levy, E., Tversky, B., and Schiano, D. (2001). Graphs in use. In Anderson, M., Meyer, B. & Olivier, P. (Editors), *Diagrammatic Reasoning and Representation.* Pp. 187-206. Berlin: Springer.
.
Zacks, J., Rypma, B., Gabrieli, J. D. E., Tversky, B., and Glover, G. H. (1999). Imagined transformations of the body: An fMRI study. *Neuropsychologia, 37(9)* 1029-1040.