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CHAPTER 12

Spatial Cognition

Embodied and Situated

Barbara Tversky

What does it mean to say that cognition is situated? Like many interesting questions, this one has many answers, probably at least one for every paper in these volumes (for an early one, see Varela, Thompson, & Rosch, 1991). Cognition is inescapably affected by the immediate who, what, where, when, and perhaps why. Walking past a gift store is a reminder to buy a birthday present; leftovers in the fridge inspire a new recipe; fingers are handy for counting. The world serves not just our own minds but also our communications with the other minds: a glance at the door tells a partner it is time to leave; the salt and pepper shakers on a dinner table act as props in a dramatic retelling; *here*, *that*, and *this way* can be understood efficiently but only in context. This kind of cognition can be called "on-line" situated cognition.

Based in part in on collaborative work with, in order of mention: Julie Morrison, Nancy Franklin, David Bryant, Holly Taylor, Jeffrey M. Zacks, Bridgette Martin Hard, Paul Lee, Julie Heiser, and Angela Kessell. I am grateful for the opportunity to work with such a talented set of individuals.

Less immediately, that is, off-line, cognition is situated by facts about our bodies and the world they inhabit. Bodies and the world have properties that afford, enable, and constrain perception and action. These affordances, enablings, and constraints have enduring, biasing effects on cognition. Here are some of them. We are upright creatures with three axes, an elongated, asymmetric head-to-feet axis that is aligned with gravity, which is a strong asymmetric axis of the world, and two axes that are not aligned with gravity, a front-back axis that is asymmetric, and a left-right axis that is for the most part symmetric (these ideas draw on and expand ideas articulated by Clark, 1973, and Shepard, 1984). We have four mobile appendages, two legs that can move us preferentially in one direction on the ground, the direction we call "forward," and two arms that are free to manipulate objects in the world, preferentially in the forward direction. We have a set of sense organs oriented in the direction of movement. Our actions in the world are for the most part goal directed and hierarchically so.

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Those actions as well as the structure and movement of the other things in the world are constrained by gravity and the other things in the world. Of primary importance among those other things are other beings like us. We are deeply social creatures, dependent on others to fulfill our needs and desires throughout our entire lives. Coordinating our needs and desires with those of others depends on communication, verbal and nonverbal, explicit and implicit.

These facts about the world, in constraining perception and behavior, bias and constrain mental representations of space and of action. The interactions of the body in the external world not only bias perception and action but also craft symbolic perception and action, and form the basis for abstract thought. This view follows from the ideas that the brain and the body evolved, among other things, to manage perception and action in the world, and that evolution builds new functions from old structures. Cognition is not just situated, it is also embodied, in ways that are hard to untangle.

These are heady ideas. To develop them, two questions will be addressed: How does the body in the world shape thought? How does the body in the world shape communication? The answers will come from research in our laboratory, neglecting many of the rich contributions of others, only some of whom are represented in these pages. We begin at the beginning: thinking about space.

Shaping Thought: Space and Action

Spaces for Thought

SPACE IS SPECIAL

Spatial thinking is essential for survival. Elementary to survival is knowing where to go to find food, water, and shelter and knowing how to return, as well as how to gather the food and water when they are located. Perhaps because of its centrality for survival, spatial thinking forms a foundation for other thought, amply illustrated in the ways we talk (e.g., Clark, 1973; Lakoff & Johnson, 1980; Talmy, 1983), the ways we depict (e.g., Tversky, 1993, 2001), and the ways we reason (the previous, and too many to list, some herein and some in the companion chapters of this handbook). We say that our thoughts run in circles, we hope that the Dow Jones tops the charts, we give a thumbs-up to a performance. External representations as well as internal ones reflect spatial thinking: charts of social networks, like family trees or organizations; depictions of religious ideas, like mandalas or Kabbalah; diagrams of scientific theories, like the structure of an atom or the expression of a gene, are spatial whether in the mind or on paper.

Space for the mind is not like space for the physicist or surveyor, where the dimensions of space are primary and things in space are located with respect to those dimensions. For people, the things in space are primary and the reference frames are constructed out of them. Which things and which reference frames depends on which space, how it is perceived, and how it serves. Because spatial thinking is central in existence, all people become expert in it – which is far from saying that they are perfect at it; on the contrary, spatial memory and cognition have systematic biases (e.g., Tversky, 1981, 2000).

The thesis to be developed is that people's conceptions of space differ for different spaces and are a joint product of perception and action appropriate for those spaces. People act differently in different spaces: the space of the body, the space immediately around the body, and the space of navigation, the space too vast to be seen from a single viewpoint. Because perception and action in each space differ, so conceptions of these spaces differ. One reason the mind creates mental spaces is to understand perception and action; another reason is to enable perception and action. Correspondingly, the discussion will shift emphasis from space to action.

Space of the Body

The body is the first space encountered, even before birth. Experience of other spaces is channeled through the body, through perception and action. Like other objects, bodies have parts. Decomposing an object into

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parts is an important way to know an object, as different parts have different appearances and different functions, and the appearance of parts can serve as clues to their functions (Tversky & Hemenway, 1984). Prominent among body parts are those named frequently across many languages, including head, chest, back, arms, hands, legs, and feet (Andersen, 1978; Brown, 1976). They are prominent, in part, literally because they extend from the contour of the body; they literally stick out. They are the parts drawn by children all over the world, the familiar tadpole figures (e.g., Goodnow, 1977; Kellogg, 1969). For objects in general, the parts that are defined by discontinuities in object contour are perceptually salient (e.g., Hoffman & Richards, 1984), are frequently named, and are rated as good parts (Hemenway & Tversky, 1984). They are also parts with functional significance. Consider the legs of tables and jeans and horses, the handles of hammers and suitcases. It is noteworthy that the parts of objects that enjoy perceptual distinctiveness also enjoy functional significance. This supports inferences from perception to function (Hemenway & Tversky, 1984), a fact that children use in bootstrapping from categories based on perceptual similarity, like shape and color, to categories based on function, like clothing and tools (Tversky, 1989).

Viewed from the outside, bodies are like other objects. But bodies are also experienced from the inside. The body parts that extend from the body contour act on the world and sense the world. They are overrepresented for their size in the sensorimotor cortex, as depicted in the homunculus popular in textbooks. These correspondences are a striking contrast to physical measurement: the brain, naming across languages, and children's drawings across cultures converge to suggest that large parts are not the most significant for bodies. Other evidence indicates that bodies are perceived differently from objects. Detecting differences in body configurations is easier when participants move the relevant half of the body, top or bottom, but detecting differences in Lego figure configuration is not facilitated by movement (Reed, 2002; Reed & Farah, 1995). For bodies, apparent motion follows biomechanical trajectories rather than the shortest path, as for other objects (Chatterjee, Freyd, & Shiffrar, 1996; Shiffrar and Freyd, 1993). Size, however, enjoys support in object cognition. In imagery, large parts of animals, such as the back of a rabbit, are verified faster than small distinctive parts, such as the ears of a rabbit (Kosslyn, 1980). Intuitively as well, large parts should be detected faster, just as finding a large person in a crowd is easier than finding a small person.

Does part distinctiveness and function or part size dominate the body schema? To address this, Morrison and Tversky (2005; see also Tversky, Morrison, & Zacks, 2002) investigated a body-part verification task, using the parts named across cultures: head, front, back, arm, hand, leg, and foot. In some experiments, the body-body task, participants saw pairs of realistic profiles of bodies in different orientations, each with a part highlighted by a white dot. In other experiments, the name-body task, participants saw the name of a body part followed by a picture of a body with a part highlighted. In both tasks, participants were to respond as quickly and accurately as possible whether the indicated parts were same or different. The data of interest were the same reaction times to the different body parts.

In all experiments, size lost. The parts high in distinctiveness and function were verified faster than the large parts; for example, verifying head was faster than verifying back. The body-body task and the name-body task differed in a subtle way, corresponding to the differences between part distinctiveness and part significance. Although part distinctiveness and functional significance are correlated, the correlation is not perfect. In particular, the chest is regarded as a relatively significant body part even though it lacks perceptual distinctiveness. Its significance seems to derive from the fact that it is the forward part of the body, the direction of perception and action, and the fact it encases important internal organs. In the body-body verification task,

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chest was relatively slow, reflecting the perceptual nature of the task. In the name-body verification task, however, chest was relatively fast. The compelling explanation for the advantage of functional significance is that language is abstract, so names are more likely to prime functional features than perceptual ones. This explanation is consonant with other situations, where naming calls attention to abstract features, notably function (Tversky, Zacks, Morrison, & Hard, 2008).

The space of the body serves us to keep track of where body parts are relative to one another, either our own bodies, through proprioception, or other bodies, through vision. Where body parts are relative to one another affects and provides clues to what body actions are possible and likely. On the whole, though not always, the parts that are perceptual distinctive are also those that are functionally significant. Surprisingly, it is not the large parts but those that are salient and significant that people recognize most quickly and that appear to dominate the terrain of the space of the body.

Space around the Body

Now we venture outside the body, to the space immediately surrounding it. This is the space of actual or potential perception and action, the space in reach of hand or eye. Of course, not all things in view can be readily reached or acted on; Daedalus could not fly to the sun. People are remarkably adept at keeping track of the positions of things in the world as they move about, even when things are out of view, like the stores they have just passed while running errands. Storytellers rely on this ability by invoking imaginary characters moving in imaginary worlds. How do people keep track of locations of things as they move?

To study how people keep track of the things around them as they move, Franklin and Tversky (1990) devised constrained worlds, objects around the body in natural scenes, and constrained movements rotating in place. We instilled these worlds with words, not with experience (though we later replaced descriptions with scenes, described subsequently), simultaneously showing that worlds that are described rather than experienced could be imagined and updated. We proposed that people keep track of the relative positions of the objects around them as they move by constructing a spatial-mental framework out of the three axes of the body and appending objects to it, updating it as the situation changes. We reasoned that accessibility of objects should reflect characteristics of the body axes and the world relevant to perception and action. The head-feet axis has salient asymmetries both perceptually and behaviorally; moreover, for the canonically upright observer, it correlates with the only asymmetric axis in the world, the up-down axis of gravity. The front-back axis separates the world that can be easily perceived and acted on from the world that cannot be easily perceived or acted on, but the left-right axis has few salient perceptual or behavioral asymmetries. This analysis predicts that, for the upright observer, things located along the head-feet axis should be fastest to retrieve, followed by things located on the front-back axis, followed by things located on the left-right axis. For the reclining observer, no body axis correlates with gravity, so accessibility depends entirely on the body axes. In this case, things located along the front-back axis should be fastest because of the forward bias of perception and action.

The spatial framework pattern of reaction times was compared to patterns predicted by two other theories in several dozen experiments. According to a theory based purely on the physical situation, the equiavailability model, no region of space has special status, so all directions should be equal. According to an account derived from theories of mental imagery (e.g., Kosslyn, 1980; Shepard & Podgorny, 1978), the mental transformation model, participants should imagine themselves in the scene. When a direction is probed, they should imagine themselves turning to face that direction to determine what object is there. Looking should take longer the greater the angle from forward. This model predicts that front

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should be fastest, followed by left, right, head, and feet, with back the slowest.

The spatial framework pattern of reaction times, derived from an analysis of perception and action, has been found in numerous variations (e.g., Bryant, Franklin, & Tversky, 1992; Franklin, Tversky, & Coon, 1992; Tversky, Kim, & Cohen, 1999). Although the pattern of data does not fit the analog view of mental imagery, nor does it fit a propositional account (e.g., Pylyshyn, 1981). In particular, participants readily reorient under instructions that the observer turns to face a new object, but participants find it difficult to reorient under instructions that the room rotates so that the observer is facing a new object, even though formally, the two kinds of instructions require identical transformations (Tversky et al., 1999). Under normal conditions, people turn but environments do not, and those expectations affect updating mental worlds.

IMAGINARY ACTIONS IN IMAGINARY WORLDS

The first investigations of the space around the body followed the example of storytellers and used prose to instill the worlds and changes in it. Later studies used models, diagrams, and real spaces to instill the worlds (Bryant & Tversky, 1999; Bryant, Tversky, & Lanca, 2001). Models induce observers to take the view of the central figure, a perspective embedded in the imaginary world. Diagrams induce observers to take a view from above, a perspective external to the imaginary world (Bryant & Tversky, 1999). One set of studies showed differences between locating objects from perception and from memory (Bryant, Tversky, & Lanca, 2001). When a scene is responded to from perception, the pattern of reaction times conforms to what might be termed the *physical transformation model*. Specifically, objects directly in front are fastest, those displaced by ninety degrees next – head, feet, left, and right – and objects behind are slowest. In this case, observers are turning to look at the probed locations to determine what is in the probed direction. However, once participants learn the environment, they cease to look even though they could. Instead, they respond from memory, and their reaction times fit the spatial framework pattern; that is, responses to head and feet were fastest, followed by responses to front and back, and then responses to left and right.

The fact that responding from perception and responding from memory were different demonstrates that imagery is not simply internalized perception; rather, it is a construction, and sometimes a reconstruction of perception. The advantage of using spatial frameworks in memory rather than the particular views of perception is generality. The more abstract spatial framework representation allows for easy computation of many views as well as easy transformation between views.

Conceptions of the space around the body do not depend on the physical situation per se. Instead, as for the space of the body, conceptions of the space around the body derive from and are biased by enduring characteristics of perception and action of the human body in the world, the asymmetries of the body that affect how the body can act and perceive, and the asymmetries of the gravitational axis of the world, which also affect human action and perception. The next space to be considered, the space of navigation, is also a constructed mental space that is biased by perception and action.

Space of Navigation

The space we experience as we hike in the mountains or go from home to work or wander through a museum is the space of navigation. It is too large to be perceived from a single place, so it must be constructed from separate pieces. The pieces can be views from experience, they can be descriptions we have heard or read, or they can be maps we have studied. How are the different pieces and different modalities combined, the smaller spaces to form a large one? To put the pieces together requires a common reference frame and reference objects. These allow the separate pieces to be integrated, scaled, arranged. But the very

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factors that allow integration also produce distortions.

Consider first reference objects. Cities or landmarks or landmasses are located and remembered with respect to one another. North America is north of South America. Philadelphia is west of Rome. Grouping of landmarks follows the gestalt principle of grouping by proximity. However, when people remember landmarks or landmasses relative to one another, they remember them as more aligned than they actually were. As a consequence, a significant majority of observers chose a map in which North America is more directly north of South America than the true map in which South America barely overlaps North America (Tversky, 1981). Likewise, a significant majority of respondents think that Boston is east of Rio de Janeiro, though it is not. Landmasses oriented east-west are similarly distorted. A significant majority of observers chose a map in which Europe is located directly west of the United States rather than the true map, in which Europe is north of the United States. Likewise, a significant majority think that Philadelphia is north of Rome, though it is not. This error occurs for artificial maps as well as true ones, and it holds for blobs not viewed as maps. Alignment, then, is an inevitable consequence of grouping.

A similar error, termed *rotation*, arises when reference frames are used to organize elements within them, another prominent gestalt perceptual organizing principle. When students were asked to place a cutout of a map of South America in an NSEW frame, they placed South America upright. As it is, South American looks tilted; as an elongated shape, it generates its own set of axes, which are at odds with the geographic ones. Another example comes from the San Francisco Bay Area. The region runs west as it goes north. Yet, the overall conception is that the Bay Area runs from north to south, so residents are surprised to learn that Berkeley is west of Stanford, and Santa Cruz is east of Stanford.

Alignment and rotation are widespread; they occur for landmasses, for roads, and for cities; they also appear in memory for meaningless blobs, in children as well as adults. They reflect general perceptual organizing principles, with effects in memory for geography as well as other domains, such as graphs (e.g., Schiano & Tversky, 1992; Tversky & Schiano, 1989).

Other systematic errors in memory for the space of navigation help to characterize how that space is constructed. In natural spaces, some elements are naturally more prominent than others. In geographic space, these are landmarks, the Golden Gate Bridge in San Francisco, Times Square in Manhattan, the Eiffel Tower in Paris. Every city, every town, every campus, has them. Our lives, too, have temporal landmarks: family events, educational achievements, and the like. When asked to estimate distances from an ordinary building to a landmark, people give smaller distances than the distances from a landmark to an ordinary building (e.g., Sadalla, Burroughs, & Staplin, 1980). Thus, distances in the mind are not symmetrical! These asymmetries hold for metaphoric spaces as well as physical ones. For example, people think a son is more like his father than the father like his son (Tversky & Gati, 1978). Mental representations of abstract spaces, like mental representations of real spaces, have landmarks and prototypes.

When conceptual spaces get too large, the mind divides them into parts and subparts – so, too, for geographic spaces. Geographic spaces can be subdivided and grouped, by geographic, political, and other categories. People judge distances between entities within a group to be less than distances between entities situated in different groups (e.g., Hirtle & Jonides, 1985). Perspective also affects distance judgments, whether imagined or real. Students imagining themselves in San Francisco estimated the distance from San Francisco to Salt Lake City to be larger than those imagining themselves in New York City. Conversely, students imagining themselves in New York City estimated the distance from New York City to Pittsburgh to be greater than did students imagining themselves in San Francisco

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(Holyoak & Mah, 1982). Of course, Steinberg had spoofed this distortion on the covers of the *New Yorker* long before. Both distortions due to grouping and distortions due to perspective have analogues in abstract thought, for example in judgments about in-group and out-group members (e.g., Quattrone, 1986).

These are not the only systematic errors in spatial judgments. The errors discussed so far could be called "perceptual errors," based on perceptual processing. However, there are errors from action or potential action as well. For example, routes that have more turns or landmarks are judged longer than routes with fewer turns or landmarks (Sadalla & Staplin, 1980a, 1980b). Trying to put together all these systematic distortions would not likely yield a cognitive map that is consistent and coherent. For this reason, a better metaphor for mental conceptions of large spaces is a cognitive collage (Tversky, 1993). Like collages, mental conceptions of space are constructed from fragments, from different perspectives, and from different modalities.

WHY ARE THERE SYSTEMATIC ERRORS?

At first thought, it is mystifying that that the mind distorts the world. Further thought reveals that there are good reasons that it does so. Take, for example, the visual system. The world does not give us edges, corners, and contours, yet these are efficient for identifying the objects of importance. It is the nervous system that gives us edges, corners, and contours by sharpening and leveling – distorting – incoming information. For the space of navigation, what is important is integrating different views and different modalities into wholes that have some coherence. Integrating requires both extracting the entities that are important from all the views and modes and coordinating reference frames. This process has two consequences that lead to distortions: focusing on some information at the expense of other and integrating approximately or schematically, as the exact information is often missing or unnecessary (for a more detailed discussion of these issues, see Tversky, 2003, 2005b).

TALKING ABOUT LARGE ENVIRONMENTS

Humans are talkative beings, and undoubtedly one of the early topics of conversation in the evolution of language was talking about space, telling others where to find food and shelter and where to avoid danger. Space is usually described from a perspective, as a perspective allows locating things relative to one another and a frame of reference. Spontaneous descriptions of large spaces take one of two perspectives or, interestingly, a combination of both (Taylor & Tversky, 1992, 1996). In a route perspective, speakers take the imagined point of view of a traveler in an environment and describe the locations of landmarks relative to the changing position of the traveler in terms of left, right, front, and back. In a survey perspective, speakers take a bird's-eye view of an environment, as if from a tree or mountaintop, and describe the locations of landmarks relative to one another in terms of north, south, east, and west. Each of these perspectives is situated; that is, each is a familiar way of viewing and interacting with an environment.

Significantly, survey and route perspectives have parallels in thinking about the landscape of time, yielding a bias familiar to academicians. When events are far in the future, we find room for them the survey-like representation we use for the vast future, but when events are located in the near future, we think about them as routes from now to then, from here to there. Suddenly, the time and effort to get to that gorgeous spot remote in a mountain range looms large, especially against the other time-consuming events already scheduled (e.g., Trope & Liberman, 2003). More abstract parallels to route and survey perspectives abound. A good information-systems designer needs to plan the overall configuration of computers, servers, printers, and at the same time, take into account the set of possible procedures users are likely to need (Nickerson, Tversky, Corter, Zahner, & Rho, in press). Similarly, determining the

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organization of a manufacturing plant must include both the divisions of operation and the tasks to be performed. The survey perspective consists of wholes, parts, and subparts, and the route perspective of sequences within. More on sequences when we get to events.

Spatialmental Transformations

In cognitive science talk, representations are static mappings of elements and relations in the world to elements and relations in the mind. Representations, though conceived to be static, can be used in mental actions. They can be mentally scanned (Kosslyn, 1981) or searched or, importantly, transformed. Mental transformations of or in mental representations again have situated and embodied origins (Shepard, 1984); that is, they reflect and derive from common perceptual experience. There are many (e.g., Tversky, 2005d), but two seem to be primary: imagining changes in objects, most notably, changes in orientation or mental rotation (Shepard & Cooper, 1982) and imagining changes to one's own orientation in space (e.g., Bryant & Tversky, 1999; Parsons, 1987; Wraga, Creem, & Proffitt, 2000; Zacks, Mires, Tversky, & Hazeltine, 2000). These two spatialmental transformations are independent, producing different patterns of reaction times and using different brain pathways (e.g., Bryant & Tversky, 1999; Parsons, 1987; Wraga et al., 2000; Zacks et al., 2000; Zacks, Vettel, & Michelon, 2003). In the course of their daily lives, people naturally change orientations in space themselves and naturally observe other objects changing orientation. These spatial transformations can be performed mentally and applied to representations of the concrete and the abstract, providing a spatial basis for imagination. Mental spatial transformations underlie a range of mental feats: figuring out a route from a map and enacting a route while navigating; constructing a laparoscopic surgical procedure; inventing acrobatics on ice, sea, or land; or designing the next great museum (see Shepard, 1978).

Situated Mental Spaces

Three spaces crucial to human interactions in the world have been discussed: the space of the body, the space around the body, and the space of navigation. There are other spaces and spatial reference frames, notably, the space around the jaw or the hand (e.g., Gross & Graziano, 1995). Each of these spaces subserves different perceptual-motor interactions, and conceptions of those spaces differ from physical measurements of the spaces in concordance with those interactions. For the space of the body, functional significance rather than size determines accessibility of body parts. For the space around the body, the axes of the body form a reference frame, in three dimensions, and the accessibility of axes depends on their significance in perception and action. The space of navigation is pieced together from different experiences by selecting common entities – landmarks – and a unifying frame of reference. The use of reference landmarks and reference frames lead to systematic errors in judgments of distance and direction. These spaces are used for thinking about other things, time, value, power, and a multitude of other abstract concepts, as revealed in language, gesture, and graphics. The use of space for general thought is especially evident in the spaces people create to serve as tools to augment their own cognition, spaces in the world that serve internal spaces in the mind. This discussion will be continued later, when we get to diagrams. But first we move from space to time, to the events that take place in time.

Action

PACKAGING LIFE INTO EVENTS

The world is never static. To make sense of the constant flux, the mind captures change in packets, called "events." Clues to those packets come from the ways we talk about them: go to work, eat dinner, see a movie. Thus, the continuous events that occur in time are segmented and categorized, much as the tremendous variation of things in the world are grouped and categorized (e.g.,

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Rosch, 1978). For ordinary everyday events, like making a bed or doing the dishes, event packets are perceived as a sequence of hierarchical action-object couplets, culminating in achievements or accomplishments (for an analysis and review, see Zacks & Tversky, 2001). When asked to give play-by-play descriptions of films of everyday events like making a bed or doing the dishes, at coarse and fine levels, people provide a sequence of actions on objects that are hierarchically organized into goals and subgoals (Zacks, Tversky, & Iyer, 2001). The same occurs when people describe the units and subunits of generic events (Zacks et al., 2001) and of remembered events, like going to the doctor (Bower, Black, & Turner, 1979). The units of events are not actions, but action-object couplets; *put* is not a unit, but *put on the bottom sheet*, *put the dishes in the sink*, and *put the clothes in the washing machine* are units of making a bed, doing the dishes, and doing the laundry, respectively (e.g., Tversky, Zacks, & Hard, 2008). *Put* is not the same for *put on the bottom sheet* or *put the clothes in the dryer*. As sequences of action-object couplets, events are inherently situated, not just in the objects they entail but also in their characteristic actors and settings. The bed is made in the bedroom and the dishes are done in the kitchen, by household residents or by their helpers. Events are the stuff of our lives, and our understanding of them is situated in the appropriate settings, objects, and actors. Hierarchical organization of action serves as an action plan, a mental simulation of the action that embodies the action (cf. Gallese, 2005; Goldman, 2005).

ACTION UNDERSTANDING AND PERSPECTIVE TAKING

Events performed by people, in contrast to natural events like hurricanes or earthquakes, are of special importance to people. We need to understand the actions and intentions of others to understand what they are doing, to react to what they are doing, and to perform those actions ourselves. Learning the action-object hierarchies that constitute events performed by people is often a social process, which occurs from observing others perform actions. How might this happen? Recall the play-by-play descriptions of events like making a bed. They describe the actions of the actors and are from the perspective of the actor, not the perspective of the person who is viewing and describing the scene. Understanding the actions and inferring the intentions of others may begin with taking their perspective.

Neurophysiological evidence lends support to this possibility. There is ample evidence that watching others' actions and imagining one's own actions activate brain areas associated with action planning and performance (e.g., Cross, Hamilton, & Grafton, 2006; Decety & Grèzes, 2006; Koski, Iacoboni, Dubeau, Woods, & Mazziotta, 2003; Rizzolatti, Fadiga, Fogassi, & Gallese, 1999; Ruby & Decety, 2001). What is more, the motor activation appears to correspond to an anatomical mapping of the actor's body to the observer's body (Aziz-Zadeh, Maeda, Zaidel, Mazziotta, & Iacoboni, 2002). As Aziz-Zadeh et al. note, merely observing action seems to induce motor resonance or motor simulation on the part of the observer, a possible mechanism for action understanding and learning, one that effectively embodies observed behavior. Actively describing or imitating actions from the actor's perspective may promote action learning and understanding by enhancing these natural processes.

Shaping Communication: Gestures and Diagrams

Gestures: External Spaces

GESTURE IS EFFECTIVE IN COMMUNICATION

The hands serve not just to perform actions but also to explain them. When people tell stories or explain things, they use their hands, especially when they relate how things are arranged in space or how to do something or how something works (e.g., Goldin-Meadow, 2003; Mc Neill, 2005). Of course, people gesture for many other reasons as well. Gestures appear to have

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benefits both for those making the gestures and for those watching them. For performers of gestures, gestures serve to find words; when speakers sit on their hands, they are less fluent (Krauss, Chen, & Chawla, 1996; Krauss, Chen, & Gottesman, 2000). Children blind from birth gesture when describing a spatial layout, suggesting that gestures help to organize thought (Iverson & Goldin-Meadow, 1997). For viewers of gestures, gestures clarify meanings and facilitate comprehension (e.g., Alibali, Flevares, & Goldin-Meadow, 1997; Goldin-Meadow, 2003; Kelly & Church, 1998; McNeill, Cassell, & McCullough, 1994; Valenzeno, Alibali, & Klatzky, 2003). These many roles of gestures are a testament to the varieties of embodied cognition in thinking, in expressing thought, and in understanding thought.

GESTURES IN SPATIAL DESCRIPTIONS

Evidence for how gestures organize and express thought comes from a study in which participants were asked to describe environments they had learned from maps (Emmorey, Tversky, & Taylor, 2000), modeled on the previous work of Taylor and Tversky (1996). As before, some environments elicited primarily route descriptions; others, primarily survey descriptions; and others, mixed descriptions. The gestures corresponded to the description perspective, suggesting that both embodied gestures and symbolic language reflected the way speakers thought about the environments. Frequently, speakers used series of related gestures to create models of the environments. They virtually sketched the environments in the air, anchoring them with some places and indicating locations of other places relative to the anchors. The set of gestures, sometimes as long as fifteen gestures in a row, formed a coherent interrelated sequence.

GESTURES PLACE THINGS IN MEMORY

Remarkably, gestures occur in the absence of speech and in the absence of communication, strong evidence that they serve thought by embodying it. One activity people engage in throughout their lives is solving problems. Participants were asked to solve a series of spatial problems, some easy and some difficult. After they solved them, they were asked to explain their solutions to a video camera so that someone watching the video would understand the solution (Kessell & Tversky, 2005). In explaining their solutions to the problems, nearly all participants gestured for all problems. Their gestures served to represent the problem, by using iconic gestures reflecting the spatial layout, and their gestures served to demonstrate the solutions to the problems – again, typically iconic gestures showing the transformations needed for solution.

More surprising was the finding that alone in a room, not speaking, many participants gestured when trying to solve certain problems. Only two of the problems elicited gestures in most participants. Those that elicited gestures were the problems with high demands on spatial working memory, keeping track of many rungs on a ladder or the locations and properties of six glasses. In these cases, the gestures represented the problems; they corresponded to the spatial layouts, vertical for the ladder and horizontal for the glasses, with the appropriate numbers for each. In a second parallel study, other participants were given paper and pencil when solving the problems. These participants used paper and pencil for exactly the same problems that had elicited gestures in participants without paper and pencil. Together, the findings suggest that gestures were used to offload and organize spatial working memory when internal capacity was taxed. Using paper to off-load and organize working memory makes sense; it is permanent and can be referred to during problem solving. Using gestures to off-load working memory is more puzzling, as gestures are fleeting. Why might gestures facilitate working memory?

One possible explanation for why gestures are used to off-load working memory is that people remember where they put things. Or they remember better if they put the things somewhere than if someone else did. People remember routes when they navigate better than when they are taken somewhere. They remember actions better if they do them themselves (Engelkamp, 1998). The physical acts of placing or navigating appear to be intimately involved in spatial memory. Gesturing, putting, and placing, then, may invoke the same cognitive networks in the service of conceptual memory.

Thinking can be regarded as action, internalized. Indeed, we talk about thinking as actions: we frame our thoughts, we pull ideas together or take them apart; we buy ideas, we sell them, we build one idea on another. This simple example, placing imaginary objects to support memory of them, shows how thinking can involve the body acting in the world.

Diagrams: External Spaces

It seems that humans have always created artifacts. It is well known that many of these were intended to increase physical well-being, such as tools for harvesting and preparing food. But many are intended to increase mental well-being, such as to augment memory and facilitate information processing. Trail markers, tallies, pictographs, and maps are some of the cognitive tools created by cultures all over the globe. Often people do not have to create artifacts to augment cognition; they just co-opt what is there. Fingers get used for counting, and hands and feet for measuring.

Maps serve as a paradigm for a created cognitive tool. Maps have dozens of uses, not just to guide navigation but also to proclaim territory or to promote inferences about flows of populations, weather, or pollen. They use elements and spatial relations among elements on stone, clay, sand, or paper to convey elements and spatial relations in a larger world. But they do not just shrink the world, they omit much of the world and distort the world. Paths and landmarks are included that would not be visible at the scale of the map. Paths are straightened, turns are schematized to ninety degrees, distances are approximate. The reader will observe that these simplifications to external representations of space parallel the simplifications of internal representations of space. As noted, that may be one reason why they work; they include the information important to people and capture the way people think. That information in maps is frequently omitted and distorted often does not matter, as the environment supplements and disambiguates it.

Given that people think about abstract concepts spatially, as evident in language like *getting close* to someone, *feeling upbeat*, *arriving at* an insight, *entering* a new field, *wrapping one's head around* an idea, it seems surprising that external representations for abstract ideas were not common until the late eighteenth century (e.g., Beniger & Robyn, 1978; Carswell & Wickens, 1988; Tufte, 1983). Like maps, visualizations of the abstract use elements and spatial relations among them, but they use them metaphorically to represent abstract elements and relations. Part of their success is that they rely on human facility in understanding spatial information and making spatial inferences (e.g., Larkin & Simon, 1987; Tversky, 1993).

NATURAL CORRESPONDENCES

Spatial relations in graphics are readily produced and understood, even by preschool children. In one experiment, preschoolers, children, and adults were asked to arrange stickers on paper to express various spatial, temporal, quantitative, and preference concepts, for example, a TV show they loved, a TV show they were indifferent to, and a TV show they disliked (Tversky, Kugelmass, & Winter, 1991). Most of the youngest children arranged the stickers on a line, showing that they saw a dimension underlying the elements, and ordered them accordingly. For preference and quantity, they mapped more to up or left or right but almost never to down. That more goes up goes along with language and reflects the asymmetry of that axis in the world. Similarly, that more equally goes left and right reflects the symmetry of the horizontal axis. Preteen children also represented interval and ordinal relations among elements. These results – from children from a variety of language cultures – suggest that the correspondences of

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proximity and direction in an abstract space to proximity and direction on paper are natural and spontaneous.

The use of elements on paper to represent elements in the world or the mind also seems to have natural correspondences. Early written languages provide examples, as they depicted meanings rather than recorded language as spoken (e.g., Gelb, 1963). Wherever possible, resemblance was used, but many concepts are difficult to depict. Then, figures of depictions, analogous to figures of speech, synecdoche (association represents element; e.g., *scales* for scales of justice) or metonymy (part of element represents element; e.g., horns of a sheep) are used (e. g., Tversky, 1995, 2001, 2005a). Diagrams and interfaces use similar techniques; think of icons in airport signs or on computers. Another readily comprehended kind of element is common in diagrams, schematic geometric forms like lines, arrows, and blobs (Tversky, Zacks, Lee, & Heiser, 2000). In quantitative graphs, for example, lines connect; they show that two (or more) variables share an underlying attribute but have different values. Bars contain and separate. The justification for using bars or lines relies on assumptions about the underlying data, lines for interval data and bars for categorical data. People's interpretation and production of bars and lines appears to derive from the natural graphic meanings of bars and lines. People, then, should readily interpret lines as trends and bars as discrete comparisons, and they do. What is more, they produce lines for trends and bars for discrete comparisons. For both interpretation and production, the graphic forms are stronger than the actual underlying dimensions (Zacks & Tversky, 1999). Arrows are asymmetrical lines and suggest asymmetrical relations. Arrows are frequently added to diagrams to suggest a variety of meanings: order, cause, motion, outcome, and more. When asked to interpret diagrams that do not have arrows of mechanical systems like pumps and brakes, people provide structural descriptions of the spatial arrangement of the parts. When asked to describe diagrams with arrows, people provide step-by-step causal relations (Heiser & Tversky, 2006.).

USING MENTAL MAPS AND SKETCH MAPS

When asked to produce a map to aid a traveler to get from one place to another, people usually produce rudimentary maps (e.g., Tversky & Lee, 1998, 1999). Most of the detail is left out, and what is left in, typically, the paths that form the route, is distorted. Intersections are usually drawn at right angles and distances are approximate. Like mental maps of environments, sketch maps are distorted, and they are distorted in similar ways. Nevertheless, both mental maps and sketch maps serve their purpose; they help people find their destinations. How is that? Like mental maps, sketch maps are situated, used in context, in environments, and the environments disambiguate and correct (Tversky, 2003). If a turn is eighty or one hundred degrees instead of ninety, the traveler will turn the way the road goes. The traveler will turn upon reaching the next landmark, whatever the distance. All that is needed from the map is where to turn and which way, and in fact, that is the information included in verbal directions. Intersections and turns can be checked against the world. Actual navigation is even more deeply situated. After checking the landmarks and turns of either mental or paper maps against the world, successful navigation depends on coordinating eye and body to make the turns correctly.

Although these schematic elements – lines, arrows, blobs – have meanings that are readily interpreted in context, they have languagelike properties. Like words, they are categorical and can be combined to create many possible graphics, for example, route maps and networks. Context disambiguates them – a line in a graph has a different meaning from a line in a map. Context is necessary to disambiguate the words that parallel these forms. An occupational line and a train line are not likely to be confused in context, nor are mathematical and romantic relationships. Yet, unlike words, the meanings of these forms are readily available.

External spaces serve cognition, both individual and group, in a multitude of ways. They off-load the contents of memory, freeing working memory to manipulate external

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tokens instead of internal ones. They relieve working memory further by allowing externalization of intermediate products of mental manipulations. They promote organization and reorganization of the contents of memory. They can be viewed and manipulated by groups, thereby ensuring common understanding and facilitating collaboration. Because they are based on natural cognitive correspondences, external spaces both reflect and support human thought, concrete and abstract.

Situated Thought

We cannot get out of our bodies and we cannot get out of the world. We can do so only in our imaginations, but as we have seen, the imagination is constrained by our bodies and the world. Spatial thinking comes from and is shaped by perceiving the world and acting in it, be it through learning or through evolution. The embodied and situated cognitive structures and biases of thought about space and about action limit and bias abstract thought as well. Thought is grounded in the world and in the body. Our bodies not only sense but also participate in thought; we use our bodies to locate, to refer, to measure, to arrange and rearrange, to transform. Imagination is not limited by the body and the world; it is enabled by the body and the world. The representations and processes used to understand the spatial world and act in it are those that allow invention, creativity, and discovery.

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