

## 7 How to get around by mind and body

### Spatial thought, spatial action

*Barbara Tversky*

People draw on spatial knowledge when they find their ways back to their hotel while traveling as well as when they estimate the direction between their home town and their current one. Despite the clear relations among the tasks, they are studied by two disparate communities. The community that takes navigation in real space as its task is concerned with the determinants of accuracy, and in turn, the cues in the environment and the sensory-motor systems that make use of them. The community that takes spatial judgments as its task is occupied with systematic error, and in turn, the normal perceptual and cognitive processes that produce them.

How can these communities be integrated? Both accept the improvement and refinement that selection by learning or by evolution can achieve. The mystery, then, is to account for the existence of systematic errors. This requires two steps: first, showing that the errors are a consequence of normal and useful perceptual and cognitive processes; second, by showing why the errors are resistant to change for the better by learning or evolution.

#### 1 Space in mind, space in action

Spatial thinking is special. It is multi-modal, involving not just sight, but sound, smell, and touch; all these modalities and more reveal where we are and what is around us. Knowledge of space is essential to survival; our lives depend on knowing how to get home, where is safe ground, what to handle. Spatial thinking serves as a basis for other thought, it takes us from the concrete to the abstract, applying facility in reasoning about spatial size, distance, direction, and transformations to drawing inferences and constructing theories in abstract domains. Language reveals the spatial nature of abstract thought: we say a field is wide open, she's reaching for the stars, he has fallen into a depression, drawing away from friends.

Despite the ubiquity of space and the necessity for knowledge of it, people think about space differently from the way space is measured, from the way space is conceived in physics or geometry or engineering. In those cases, space itself is primary, and entities are located in it. For people, space begins with the entities; they are primary. They are located and oriented

with respect to each other and with respect to reference frames. These relations are not metric, but approximate, categorical, schematic. People interact in many spaces, the space of the body, the space around the body, and the space of navigation are prominent among them. Which objects and which reference frames are selected depends on the particular space, and the perceptions and actions it subserves. For the space of the body, body parts that are perceptually salient and functionally significant are prominent (Morrison and Tversky 2002; Tversky *et al.* 2002). For the space around the body, the three axes of the body and those of the world are critical (Bryant *et al.* 1992; Franklin and Tversky 1990). For the space of navigation, the primary focus here, paths and landmarks form the conceptual skeleton.

The space of navigation is the space that is too large to be seen at a glance. It has to be constructed, from different views, different encounters, even different modes, from experience, from maps, from language. Within psychology, two communities have studied the space of navigation. The community I call the *mind* community grew out of traditions in perception and cognition. The data of interest to this community come from studies of spatial judgments: what is the direction between Los Angeles and Algiers? The distance from Manchester to Glasgow? From Jerry's apartment to Times Square? Such questions were not chosen randomly; they were selected to induce error, and they succeeded. In fact, the major findings have been systematic errors in the judgments, evidence used to analyze normal cognitive processes (e.g., Tversky 1981, 1993, 2000a, 2000b). The community I call the *body* community grew out of traditions in learning and animal behavior. The data of interest to this community come from studies of spatial behavior, demonstrating that birds, bees, rats, and even people, can find their ways back to nest or home. The major findings have been accuracy of the behavior, evidence used to analyze the cues, and perceptual-motor systems that yield accuracy (see, for examples, Gallistel 1990 and papers in the volume edited by Golledge 1999). Even greater than the differences in situations and explanations are the differences in perspective between the communities. The perspective of the mind community on the mind is its limitations, its fallibility. The perspective of the body community on the body is its precision, its fine-tuning. The mind community strives to elucidate the normal cognitive processes that result in error; the body community strives to elucidate the behavioral systems that yield accuracy.

I plead guilty to exaggerating the positions of the two communities, heightening their differences. Naturally, there are similarities and points of contact. The mind folk and the body folk alike take learning and evolution for granted, and acknowledge that those processes can improve judgments and performance. If so, then the burden is on the mind community: why do systematic errors persist despite the selective pressures of years of learning and centuries of evolution? To answer this first requires a review of systematic errors and then an analysis of them.

## 2 Systematic errors in spatial memory and judgment

### 2.1 *Distortions due to hierarchical organization*

Although the space of navigation is for most intents and purposes flat, people group and organize space hierarchically. An example so famous it appears as a question in Trivial Pursuit® came from a study by Stevens and Coupe (1978). They asked students (in San Diego) to indicate the direction from San Diego to Reno. Of course all realized correctly that Reno is north of San Diego. But, most of the informants thought erroneously that Reno is east of San Diego, when, in fact, it is west. Stevens and Coupe generated that example from their theory. According to their theory, people do not remember all possible directions between pairs of cities. Instead, they remember the approximate locations of the states and what cities are in what states. They then use the remembered relative locations of the states to infer the directions between cities contained in them. Since Nevada is on the whole east of California, people infer that cities in Nevada are east of cities in California. Stevens and Coupe found similar effects for maps they constructed according to these principles.

Organizing space hierarchically distorts distance judgments as well as direction judgments. The general finding has been that distances within an entity, whether geographic entities, like a state or country, or conceptual entities, such as buildings differing in function or settlements differing by ethnicity, are underestimated relative to distances between entities (e.g., Hirtle and Jonides 1985; Portugali 1993). Hierarchical structure is reflected in reaction times to make judgments as well as errors of judgment; distance judgments for pairs of cities between states or countries are faster than distance judgments for pairs within the same geographic entity (Maki 1981; Wilton 1979).

Notably, grouping affects abstract judgments as well as judgments of proximity. People judge pairs of members of their own social or political groups to be more similar on features unrelated to the basis for grouping than pairs where one member is from one's own group and the other from another. This can be taken as evidence for the spatial basis of abstract judgments.

Hierarchical organization has useful consequences as well. It has clear benefits in memory, and it facilitates inference. Knowing that a loquat is a fruit allows people who have never encountered one to make good guesses about it; that it is sweet, that it grows on trees, that it has seeds, that it is within a certain size range, that it can spoil. Knowing that Reno is in Nevada allows us to infer that gambling is legal and that the climate is dry. Knowing that someone is an engineer or belongs to a feminist organization encourages yet other inferences.

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## 2.2 *Distortions due to perspective*

From a view point that allows us to see far away, the things we see in the distance appear telescoped, that is, they seem crowded relative to the things that are nearby. An analogous phenomenon occurs in judgment. For evidence, we move from San Diego to Ann Arbor, where students were asked to imagine themselves either in San Francisco or in New York City. Then they were asked to judge the distances between pairs of cities more or less equidistant on an east–west path across the United States: New York City, Pittsburgh, Indianapolis, Kansas City, Salt Lake City, and San Francisco. Those with the east coast perspective gave larger estimates for the east coast distances, especially New York–Pittsburgh, from those with the west coast perspective. Similarly, those with the west coast perspective gave larger estimates for the west coast distances, notably, San Francisco–Salt Lake City, from those with the east coast perspective (Holyoak and Mah 1982). Of course, this is one of the things Steinberg was telling us in his delightful *New Yorker* covers all those years. But the psychologists showed something more (whew!). Remember that all the informants were actually in Ann Arbor; the viewpoint was not their actual geographic position but rather an imagined one, and they were able to adopt either viewpoint with differing consequences.

As for hierarchical grouping, so for perspective, these effects occur for abstract judgments as well as spatial ones. We readily perceive the uniqueness and variability of those close to us, but glom all those others, from another social or political group, together, as all alike. And surely a case can be made for being more sensitive to the distances and differences that surround us than for the distances and differences that are far away.

## 2.3 *Distortions due to landmarks*

When someone local asks us where we live, we often respond with the closest landmark we think that person will know. Near DuPont Circle. Or the Bastille. Or Pombal. Landmarks seem to extend themselves to encompass whole neighborhoods. But ordinary buildings are just that. Consistent with this thinking, landmarks seem to draw ordinary buildings close to them, but not vice versa. A favorite cognitive sport at college campuses is to show the distorting effects of landmarks. People report that an ordinary building is closer to a landmark than the landmark to the ordinary building (Sadalla *et al.* 1980; McNamara and Diwadkar 1997). This robust phenomenon violates any metric account of spatial cognition; by a metric account, the distance from B to A must be the same as the distance from A to B. Like the previous distortions, the landmark effect occurs for abstract judgments as well as spatial ones; in fact, it was first demonstrated for abstract judgments. Rosch found that people judge magenta to be more similar to red than red to magenta, and an ellipse to be more similar to a circle than a

circle to an ellipse (Rosch 1975). Even more abstract, A. Tversky and Gati found that people think North Korea is more similar to Communist China than China to North Korea (Tversky and Gati 1978). Like landmarks, prototypes, such as red or circle or China, seem to define neighborhoods or categories, in this case, conceptual ones, including variations in them. Ordinary or variant cases do not.

#### 2.4 Other errors

These are but some of the systematic errors that have been documented; there are others. Route distances are judged longer when they have more turns (e.g., Sadalla and Magel 1980), or landmarks (e.g., Thorndyke 1981), or intersections (e.g., Sadalla and Staplin 1980) along the route. The presence of barriers that require detours along the route also lengthen estimates of route distance (e.g., Newcombe and Liben 1982). Curved features get straighter in the mind, for example, the Seine by Parisians (Milgram and Jodelet 1976) and the streets of Pittsburgh by well-seasoned taxi drivers (Chase and Chi 1981). Small angles and distances are overestimated while large ones are underestimated, as before, an error that appears in judgments of the abstract as well as of space (e.g., Kahneman and Tversky 1979; Poulton 1989).

### 3 An account of some errors

The errors highlighted are not consequences of randomness or ignorance. Rather, they are systematic, predictable consequences of ordinary perceptual and cognitive processes. Forming mental representations of environments has much in common with forming mental representations of scenes (Tversky 1981). An early process in scene representation is distinguishing figures from grounds, not always an easy task as volumes of reversible figures have illustrated. Once figures have been distinguished, they are located and oriented with respect to other figures and with respect to a frame of reference. Relating figures to other figures and to reference frames organizes a scene, but may also create error. When figures are related to each other, they are mentally brought into greater *alignment*, a phenomenon similar to the Gestalt principle of grouping by proximity. To demonstrate, students, this time, at Stanford, were asked which of a pair of maps of the world was the correct one. One map was correct; in the other, the relative positions of the continents were altered so that the United States was more aligned with Europe than it actually is and South America was more aligned with Africa than it actually is. A significant majority of students picked the incorrect map. Alignment works for north–south as well east–west. A significant majority of students selected an incorrect map in which South America was moved westwards to be more aligned with North America than it actually is. Alignment appears for direction estimates – Los Angeles is south, not

north, of Algiers – although the majority of students answered this and similar comparisons incorrectly. Alignment also appears in memory for artificial maps, and for meaningless blobs.

Figures induce their own set of axes, usually around an axis of elongation or of symmetry and that perpendicular to it. The axes induced by a figure may not correspond to the axes induced by a predominant external reference frame. According to *rotation*, the axes induced by the figure and those of the reference frame are mentally brought into greater correspondence. Thus, when asked to place a cut-out of South America in a north–south east–west reference frame, most students uprighted South America. Bay Area dwellers mentally upright the Peninsula, which runs north–west south–east. Consequently, they incorrectly report that Berkeley is east of Stanford, and Santa Cruz west of Stanford. As for alignment, rotation appears for artificial maps and meaningless blobs. Both these processes generating errors are, as noted, rooted in normal perceptual organization (Tversky 1981).

## 4 Accounting for the existence of error

### 4.1 *Schematization underlies comprehension and representation*

The perceptual and cognitive processes just described that underlie comprehension of scenes *schematize* the information that the world provides. That is, they omit some information, and simplify and approximate other information. An inevitable consequence of schematization is error. That schematization also has benefits shall soon be apparent.

### 4.2 *Schematization underlies integration*

Because the space of navigation is too large to be taken in at once, it comes in parts that must be integrated. How can the mind integrate different views, encounters, modalities into a sensible whole? One way would be to establish correspondences between the critical figures in each part, and then to organize them with respect to a common reference frame. Using reference objects and reference frames, of course, are exactly the processes that organize scene comprehension, and that have been shown to yield errors. Integrating across views, encounters, and modalities draw on the same processes as creating a representation. Perhaps the better way of putting it is the converse: the errors provide evidence for the processes.

### 4.3 *Schematization alleviates cognitive load*

Now we have, through schematization, formed representations of parts and integrated them into larger representations that have some degree of coherence. Given the nature of the errors that persist, complete coherence cannot be claimed. Although schematized, the representations preserve the import-

ant information, that of the relative locations and directions of the key figures. The next consideration is how the information is used to make spatial judgments, of, say, distance, direction, and size.

In making judgments like the direction between Los Angeles and Algiers or the distance from the subway stop to Fanueil Market, people cannot rely on a mental atlas the way cartographers, or the AAA, or webservers can rely on a physical one. People do not have a mental compendium of pre-stored integrated mental maps from which the relevant one can be extracted and inspected. What people seem to do is to draw on whatever knowledge they have that seems relevant, knowledge obtained from interaction in the environment, from maps, from language. That information has then to be integrated on the fly in ways just described. Then a judgment can be made on the integrated package. All this occurs in working memory, a network of brain activity notoriously limited in capacity (e.g., Baddeley 1990; Kahneman 1974). The more “things” held in working memory, the less capacity for computation; thus the richer the representation of the environment, the poorer the judgment. Schematizing representations leaves more capacity for judgment. Here’s a modern analogy that goes part way, instructively so: schematizing is like reducing bandwidth by compression. But in contrast to most current compression schemes, schematization compresses intelligently, by selecting the figures and relations that allow reconstruction of the world.

#### *4.4 Spatial judgments are armchair judgments*

Whereas wayfinding happens in an actual environment, rich with cues, spatial judgments are done in the mind, a piece of minimalist art. For tennis, the weight of the racquet in the hand, the ping of the ball on the strings, the tug and release of the muscles, the give of the asphalt on the feet, all support the swing, as does the sight of the opponent’s moves and the thump of ball on the court. For wayfinding, the texture of the pavement, the noise of traffic or birds, the wind between the buildings or trees, the smells emanating from the stores or the fields, support keeping on track, as well as the sights and views of the changing scene. The varied and multi-modal cues available in context provide information beyond what can be articulated or activated by the mind. Context promotes accuracy in more than one way. For one thing, it constrains behavior. The pedals of a bicycle constrain where the feet can go and how they can move. The roads and buildings in an environment constrain where we can turn and enter and exit. The mind can imagine, and, indeed, can believe, many things the world does not allow. For another thing, context provides cues to memory and performance. The decreasing traffic on the freeway reminds you that your exit is near; the sight of the bank on the corner prompts you to look for the subway entrance. The modern world even comes annotated, with street signs and directions to destinations. You don’t have to actively recollect these cues and signs as the world provides them for you. Another hi-tech analog: the

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world is a menu already pulled down; it turns a memory retrieval task into a simpler memory recognition task.

Context means that schematic information, though erroneous, may be sufficient to avoid error in spatial behavior. In fact, the sorts of sketch maps and route directions that people give each other can and do leave out much information, and these have undergone generations of informal user testing. Not accidentally, sketch maps and route directions omit or distort the same information that mental representations omit or distort, for example, metric information about distance and direction (Tversky and Lee 1998, 1999). What sketch maps, route directions, and mental representations do preserve is paths and nodes for action; the environment supplements what is missing and disambiguates what is schematic.

## 5 Accounting for the persistence of error

The case for the schematization processes that produce systematic errors in spatial judgments seems, if anything, to be overdetermined, much like the case for perceptual illusions. The very processes that produce error also facilitate the construction and integration of mental representations as well as inferences and judgments from them. Yet one might still wonder why such errors persist; should people learn to avoid not making errors? Accounting for the persistence of error is the next item on the agenda.

### 5.1 *Spatial judgments are rarely repeated*

The conditions for effective learning, such as learning one's way around a city or how to play a violin, typically require many trials in the same context. Context and repetition confer many benefits to increasing accuracy of behavior. Context constrains behavior, allowing some responses and not others. Context also provides rich cues to behaviors, where to turn, how to hold the fingers. Repetition with feedback provides the opportunity to correct errors and to learn the appropriate responses. Whereas those spatial behaviors that become accurate and finely-tuned do so under practice, spatial judgments are rarely repeated, especially with feedback. When they, they are likely to be learned. For example, I now know that Berkeley is west of Stanford and Los Angeles south of Algiers.

### 5.2 *Learning affects specifics, not processes or representations*

Knowing that Los Angeles is south of Algiers does not help me with the direction between Berkeley and Stanford or even the direction between Philadelphia and Rome. That knowledge is in the form of encapsulated footnotes, not generalized correctives to geographic regions. Learning corrects errors for specific facts, it does not affect the processes that generated the

errors. In fact, much of the data on alignment and rotation were collected immediately after a class lecture on systematic errors in spatial judgments.

The very mechanisms and processes that produce errors are general purpose mechanisms and processes. They function across a broad domain of content and are useful in a wide range of contexts. The mechanisms and processes applied to making spatial inferences are among those that function in perception and comprehension of the world around us.

### 5.3 *Correctives in context*

Thinking, indeed, believing that Rome is south of Philadelphia or that Santa Cruz is east of Stanford may never have consequences for me in the world. Even if I am asked and err, my questioner may have no reason to doubt me, indeed, may share my judgment. If I am driving from Stanford to Santa Cruz, I follow the highways, which do not err. Likewise, if I believe erroneously that a particular turn is a right angle, I will turn the direction the roads allow: if I believe a road or river is straighter than it is, I will again follow road or river rather than my erroneous beliefs. Many of the mechanisms that produce error are independent; consequently, so are the errors. The errors may conflict and cancel (e.g., Baird 1979; Baird *et al.* 1979). For the purposes of science, we ask only one question, provide only one cue, focus on one kind of error. But environments provide multiple cues, some of which may yield error, some not, and the errors are likely to be uncorrelated. The many affordances and cues available in context combined with a schematic overlay of the larger surrounding are likely to be sufficient for successful navigation.

## 6 A second look at spatial behavior in the wild

Now that the case has been made for the existence and persistence of error in spatial judgment, we need to take a second look at spatial behavior in the wild. Despite, or perhaps because of selection by evolution and refinement by learning, navigation in the wild is by no means perfect. As for spatial judgments, clever experimentation yields errors and, at the same time, reveals the mechanisms used in normal, error-free navigation. Path integration is the task most commonly studied. In path integration, a traveling organism is continuously updating its position and orientation relative to a point, usually a start or end point. Path integration can be accomplished in several different ways, notably by computing over changes in heading and distances traveled (Golledge 1999: 122). To study path integration, a navigator is blindfolded, then traverses a path, then turns and continues some more, and finally points to or returns to the starting point. Bees, ants, hamsters, even people perform fairly well at this task, but do make systematic errors. Hamsters and bees typically overshoot (Etienne *et al.* 1999). People overshoot small distances and small turns and undershoot large ones (Loomis

*et al.* 1999), a widespread error of judgment (Poulton 1989). But note what blindfolding has done. It has removed the cues in the environment that complement and typically correct the incorrect internal model. Notably missing are landmarks, and in fact, moving landmarks causes desert ants, and presumably others, to err (Muller and Wehner 1994). Path integration, then, is not perfect; it provides global information that is corrected by landmarks in the world.

## 7 Implications for rationality

How do people successfully navigate in the world? There are several possibilities, and like most biological systems, presumably all are realized. One is local, by routines, a well-learned sequence of local actions. This can take us on well-trodden routes, such as from home to office, sometimes without awareness. This will not work for getting between well-trodden routes without going back to “Go,” for old routes with detours, or for computing new routes. Then a global plan seems needed. The contrast between global and local is at least at three levels. Plans encompass a large environment, often conceived of from above an environment, whereas action representations are confined to a particular scene, usually conceived of from within an environment (for discussion with applications to robotics, see Chown *et al.* 1995; Kuipers 1978, 1982; Kuipers and Levitt 1988). Plans are general and schematic, incompletely specified; actions, by contrast, are both specific and specified. Finally, plans are amodal, whereas actions are precise movements of particular parts of the body in response to precise and specific cues. A route map can be likened to a musical score or sewing instructions; much is left to the artistry of the traveler, the conductor, the tailor, or seamstress.

The gap between the two research communities, those that study the mind’s judgments and those that study the navigator’s actions, appears to have narrowed. Both communities aim for an understanding of the complex mechanisms that underlie different spatial activities. Despite the emphasis of the mind community on systematic error and the body community on precise behavior, both find both erroneous and correct responding. For both, correct responding demonstrates the action of the proposed mechanisms, and errors, the boundaries of the theories and of the accurate behaviors.

Systematic errors of judgment and navigation have survived millennia of evolution and years of learning because they derive from general systems that serve cognition well in apprehending the world as well as behaving in it. The factors operating on these mechanisms are multiple, and the result is trade-offs that may work in general, but not in specific cases. These mechanisms serve to integrate information, to remember information, to retrieve it, and to manipulate it. These processes entail schematization of the information, eliminating some, exaggerating some, distorting some, processes that inevitably produce bias and error. Whatever correctives the world supplies affect local and specific judgments and actions; they do not affect the general

mechanisms that generate them. Humans, by their own account, make errors of judgment and action in domains other than space (see Tversky and Kahneman 1983 for errors in abstract domains, and a different account of them). At a global level, then, the cognitive mechanisms appear rational; at the local level of behavior, biased. The challenge, then, is to build an account of rationality, evolution, and learning that encompasses behavior that at one level of analysis appears reasonable and at another, replete with error.

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