Three Spaces of Spatial Cognition

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As we move about and interact in the world, we keep track of different spaces, among them the space of navigation, the space immediately around the body, and the space of the body. We review research showing that these spaces are conceptualized differently. Knowledge of the space of navigation is systematically distorted. For example, people mentally rotate roads and land masses to greater correspondence with global reference frames, they mentally align roads and land masses, they overestimate distances near the viewpoint relative to those far from it. These and other distortions indicate that the space of navigation is schematized to elements and spatial relations relative to reference frames and perspective. The space around the body is organized into a mental framework consisting of extensions of the major axes of the body. Times to report objects around the body suggest that the relative accessibility of the axes depends on their perceptual and functional properties and the relation of the body to the world. Finally, times to verify named or depicted body parts indicate that body schemas depend on perceptual and functional significance. Thus, these spaces (and they are not the only ones important to human interaction) differ from one another and are not conceptualized as Euclidean. Rather they are schematized into elements and spatial relations that reflect perceptual and conceptual significance. **Key Words: cognitive map, body schema, mental model, spatial thinking.**

All our lives, we interact with the space around us, from finding our way to a remote cabin in woods to reaching for a ripe apple in the tree beside the cabin to finding a comfortable position in the lounge chair beside the cabin to rest and snack after the hike. These three activities illustrate three spaces that people conceive of differently and that have been the focus of our research in recent years: the space of navigation, the space surrounding the body, and the space of the body. We interact with each of these natural spaces differently and they serve different functions in our lives. Concomitant with the differences in perception and function of these spaces, we also conceptualize them differently. Mental spaces are not simply internalized images of external spaces. Rather, they are schematized, eliminating detail and simplifying features. They are mental constructions, built around frameworks consisting of elements and the relations among them. Our research suggests that which elements and spatial relations are included and how they are schematized is different for each of these spaces in ways that reflect our experiences with the spaces. Although space may be all the same for geometry, for people, different spaces are perceived and interacted with differently, and therefore, schematized differently.

The space of navigation is too large to be seen from a single place (short of flying over it, but that is a different experience). To find our way in a large environment requires putting together information from different views or different sources. For the most part, the space of navigation is conceptualized as a two-dimensional plane, like a map. Maps, too, are schematized, yet they differ in significant ways from mental representations of space. The space around one's self stands in contrast to the space of navigation. It can be seen from a single place, given rotation in place. It is the space of immediate action, our own or the things around us. It is also conceptualized schematically, but in three dimensions. Finally, there is the space of our own bodies. This space is the space of our own actions and our own sensations, experienced from the inside as well as the outside. It is schematized in terms of the natural parts of our body, our limbs. Note that the concern here is not with the content of these three spaces, but rather with their structure, with the kind of elements, spatial relations, and reference frames that are used to mentally represent the spaces irrespective of content. In each of the three spaces, schematization leads to inevitable biases in the way the spaces are mentally structured. Knowledge of these three spaces—knowledge of the relative locations of the places in navigation space that are critical to our lives, knowledge of the relative locations of the objects around us in the space we are currently interacting with, and knowledge of the space of our bodies—is essential to finding our way in the world, to fulfilling our needs, and to avoiding danger. In short, this knowledge is necessary to survival.

There are other distinct and psychologically meaningful spaces than the three we explore here. For example, we have not distinguished the spaces learned by actual navigation from the spaces learned from maps, whereas others have. We do not distinguish those spaces because we are concerned with mental representations and most of the evidence on mental representations of those spaces points to similarities rather than differences. In a comprehensive review of previous work on categorization of space, Freundschuh and Egenhofer (1997) distinguish six spaces, based on manipulability, locomotion, and size. Moreover, they use that framework to embed previous categorizations of spaces in the geography literature, for example, those of Lynch (1960), Ittelson (1973), Canter (1977), Downs and Stea (1977), Kuipers (1978), Couclelis and Gale (1986), Garling and Golledge (1987), Zubin (1989), Mark (1992), and Montello (1993). Neuroscientists might categorize mental spaces differently, based on sensory receptive fields, action patterns, and the brain pathways linking them, and linguists might use yet another taxonomy, based on language of spatial reference systems. The trichotomy we investigate is surely incomplete. Although it is correlated with size, and thus overlaps with some of the categories distinguished by geographers, the essential differences among the three spaces are in the way that they are mentally represented.

The Space of Navigation

We encounter the space of navigation in many different ways. The prototypical way is by exploring the environment. As we explore the environment, the salient features of the environment change. But if we are to learn the environment, we must find a way to link the different features in space. In addition to integrating different views from different locations, we often need to integrate different forms of information, remembered journeys, descriptions, maps, and more. Using a description to get from one place to another, say the trail to the cabin in the woods, or your house to mine, is not just a modern problem, but is probably something our hunter-gatherer ancestors accomplished. In this case, what needs to be integrated is the description with the environment as viewed. Even maps were used in antiquity, and using them requires integrating them with the visible world. Sometimes, we use all these sources of information, our memories of the environment, descriptions, and maps. Of course, there are important differences among these three media, but there is also important common ground. Clearly, the easiest way to integrate these different representations is to use a common schematization for all. From the earliest work on environmental psychology, environments have been schematized to nodes and links, landmarks and the paths among them, elements and their spatial relations, often from a particular perspective (e.g., Lynch 1960; Kuipers 1978; Levelt 1982; Tversky 1992; Daniel et al. 1996; Tversky and Lee 1998). Linking different views or representations is possible when there is a common reference frame, such as the canonical directions or large environmental features, and when elements are schematized similarly.

That people's mental representations are schematized and that landmarks, paths, reference frames, and perspective are important in generating them has been supported by myriad studies. Many of these have also shown that people's conceptions of space are not only schematized, but also distorted in systematic ways. The distortions arise from the fundamental

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components of the representations themselves, from the elements, landmarks and paths, the reference frames, and the perspectives. Schematization and consequent loss of detail allow for efficient memory storage, rapid inference-making and integration from multiple media, but the loss of detail is replaced by simplifying distortion.

Effects of Other Elements on Distance and Direction Judgements

We do not remember the space of navigation in an absolute way. One way we remember the locations and directions of elements is in relation to the locations and directions of other elements. Moreover, locations and directions seem to be schematized so that the grouped elements are drawn closer together. Hirtle and Jonides (1985) asked one group of University of Michigan students to sort buildings in the campus area into groups. Most students put university buildings in one group and town buildings in another. A second group of students was asked to judge the distances between pairs of buildings, without explicitly grouping them. The grouping by function is apparently implicit as the second group's distance judgements were distorted by the grouping into town and university structures. Distances between buildings in the same group, town or university, were underestimated relative to the distances between buildings in different groups.

In addition to being grouped, elements in the environment are typically related to other elements. Environmental elements are not cognitively equal; some are larger, or older, or better known, or more central to our activities. These "good" landmarks are often selected as reference elements for less salient elements. When asked where we are from, for example, we answer differently to different people, depending on what we believe they know of our environment. But in each case, we pick a nearby landmark that we think our questioner will know, and say near that (Shanon 1983). These local salient landmarks also distort our conceptions of our surroundings. People judge the distance from an ordinary structure to a good landmark to be shorter than the distance from a landmark to an ordinary structure (Sadalla et al. 1980; Couclelis et al. 1987; McNamara and Diwadkar 1997). The presence of other elements affects direction judgements as well as distance judgements. When asked to choose the "correct" map, more people select a map in which South America has been moved westward so that it is closer to due south of North America than the veridical map of the Americas. People also prefer a map in which Europe and Africa have been moved southwards to be aligned with the USA and South America to the true map. In addition, people's judgements of directions between pairs of cities show the same distortion (Tversky 1981).

Effects of Frame of Reference on Distance and Direction Judgements

Stevens and Coupe (1978) posed a question whose answer is so surprising that it has made it to *Trivial Pursuit*. They asked students in San Diego to indicate the compass direction between San Diego and Reno. Most thought, incorrectly, that Reno was east of San Diego. From this and similar examples, Stevens and Coupe argued that people's conceptions of the space of navigation are hierarchical, even though space is not. Instead of remembering the locations of all cities, they argued, people remember the relative locations of states, the larger units containing cities. They also remember which cities are in which states, and use the locations of the states to infer the locations of the cities. Evidence for hierarchical encoding of large spaces also comes from the time it takes to make direction judgements. People are faster to say that one city is east or north of another if the two cities are in different geographical entities, states or countries, than if they are in the same geographical entity (Wilton 1979; Maki 1981).

Thus, one reference frame for remembering the location and orientation of an entity is the surrounding geographical entity. Another reference frame is the canonical directions surrounding a geographical entity. That also distorts direction judgements. People see a natural orientation in shapes, including geographical entities, so, for example, South America, Israel, Japan, and Italy, whose natural axes are tilted relative to north-south east-west are natural candidates for mental uprighting. In fact, they are uprighted in memory so that their natural axes are closer to the canonical axes. When asked to orient a map of South America, people place it more upright than it actually is (Tversky 1981), and when asked to give directions between pairs of cities in Israel, Japan, or Italy, people's judgements are distorted as if they had uprighted those countries (Cornoldi, unpublished data; Glicksohn 1994; Tversky, unpublished data).

Effects of Perspective

Yet another factor in organizing the space of navigation is the viewpoint adopted on a space. Holyoak and Mah (1982) asked students in Ann Arbor to imagine themselves either on the east coast or the west coast. They were then asked to judge the distances between pairs of cities more or less equidistant on an east-west trajectory across the United States. Those imagining themselves on the east coast judged the distance between New York and Pittsburgh to be larger than those imagining themselves on the west coast. Conversely, those on the west coast thought the distance between San Francisco and Salt Lake City was larger than those on the east coast. Each group judged the nearby distances to be relatively larger than the faraway distances, much like the popular posters of a New Yorker's (or San Franciscan's) view of the country.

The organizing effects of elements, reference frames, and perspectives have been revealed in many other studies as well. Together, they suggest we schematize the space of navigation in terms of elements, reference frames, and perspectives. Our use of these organizing structures not only schematizes but also distorts our conceptualizations of these spaces. This brief and schematic review has simplified and omitted, hence distorted, many of the fascinating findings on navigation that have been accumulating. Fortunately, there are a number of excellent reviews printed elsewhere (see, for example, the special issue of *Geoforum* in 1992, and Portugali 1996).

The Space Around the Body

As we move about the world, we seem to keep track of the objects around us effortlessly, so that even without looking we are aware of what is behind, to the sides, above, below, and in front of us. In contrast to the space of navigation, the space around the body can be viewed from a single place. Also, in contrast to the space of navigation, the space around the body is conceptualized in three dimensions. How do we keep track of the space surrounding us?

Franklin and Tversky (1990) investigated people's mental models of their surroundings using descriptions of environments. In the paradigmatic situation, participants read descriptions of themselves as observers in settings, such as an opera house, museum, or barn, surrounded by objects at all six sides of the body. After learning the environments, participants were informed that they were now facing another object. They were then presented with direction terms, front, back, left, right, head (or above), feet (or below), and asked to respond with the object currently in that position. Three models were proposed to account for the times to retrieve objects in the probed directions. According to the Equiavailability Model, no one direction is privileged, so retrieval times to all directions should be identical (Levine et al. 1982). Research on imagery (e.g., Shepard and Podgorny 1978; Kosslyn 1980) suggested the Mental Transformation Model, according to which participants imagine themselves in the position of the observer in the narratives, facing forward. To retrieve another direction, participants imagine themselves turning to face the probed direction to ascertain what object is located there. If so, retrieval times should increase with the angular disparity between forward and the probed direction, so that times to front should be fastest, times to objects displaced 90 degrees to left or right or head or feet should be next fastest, and objects displaced 180 degrees to the back should be slowest.

Neither the Equiavailability nor the Mental Transformation models accounted for the data. Instead, the data could be accounted for by the Spatial Framework Model developed by Franklin and Tversky (1990). The model posits that in order to keep track of the objects around the body, people construct a mental spatial framework from extensions of the three axes of the body and associate objects to it. The body has three essential axes, that formed by head and feet, that formed by front and back, and that formed by left and right. The accessibility of objects lying in different directions depends on characteristics of the body and the world. The head/feet and front/back axes of the body are asymmetric, whereas the right/left axis lacks any salient asymmetries. Of the three axes of the world, only the up/down axis defined by gravity has a salient asymmetry. The other two axes are defined arbitrarily relative to a position. When the observer is upright, the characteristics of the body and of the world work together to make the head/feet axis the most accessible, followed by the front/back, and last, the left/right. In fact, the retrieval times correspond to this pattern. When the observer reclines and turns from front to side to back, no axis of the body is correlated with gravity. In this case, the head/feet axis loses its primacy to the front/back axis, which separates the world that can be readily seen and manipulated from the world that cannot be readily seen or manipulated. In fact, for the reclining observer, retrieval times to front/back are faster than those to head/feet, corresponding to this analysis (Franklin and Tversky 1990).

In subsequent studies, the situation was varied, yielding systematic similarities and differences in the pattern of data. For example, the same pattern arises when participants recall spatial arrangements around a central object instead of a central person, as if they adopt its perspective, and a similar pattern arises when they recall spatial relations of objects arrayed in front of them, instead of surrounding them (Bryant et al. 1992). The same pattern arises when participants judge spatial relations around two characters, as long as the characters are in separate scenes (Franklin et al. 1992). In all of these cases, the central person is described as moving in the scene to face different objects. This is the natural way that the world is explored and experienced, through our own movements (or the movements of the vehicles that transport us). When the environment is described as rotating rather than the central person, a situation formally identical to the moving person case, it takes participants twice as long to perform the mental transformations (Tversky et al., in press). After readjusting to the new orientation, retrieval times in the various directions are biased in the same ways. These biases in retrieval are not limited to environments learned by description. When participants learn scenes from observation rather than narrative and are tested from memory, the spatial framework pattern still emerges (Bryant et al. In press). This is also the case when participants learn the scenes from models of them (Bryant and Tversky 1999).

In keeping track of the immediately surrounding space, then, people seem to construct mental spatial frameworks from the three major axes of the body, and to associate objects to them. Ascertaining the locations of objects surrounding the body is accomplished through this framework, amongst other tasks. However, the axes are not equally accessible or discriminable. Relative accessibility and discriminability is determined by enduring characteristics of the body and of the world, as we perceive them. In the upright case, the front/back axis most accessible, due to the confluence of body asymmetry and world gravity. Left/right is least discriminatable, supported by the high frequency of right-left confusions (e.g., Maki and Braine 1985) as well as the absence of the use of these terms for describing location in many languages (Levinson and Brown 1994). When a person reclines and turns from side to side, no body axis is correlated with the axis of gravity, so accessibility depends solely on characteristics of the body. In this case, the perceptual and behavioral asymmetries of the front/back axis render it the most accessible. Thus, the way in which surrounding space is schematized biases the speed of information retrieval as well as memory for, and description of, locations in space (e.g., Franklin et al. 1995).

The Space of the Body

As we perform our various daily activities, we keep track of the various parts of our bodies, of where they are, what they are doing, how they are feeling. Of course, the human body is a familiar one in our visual world as well, but unlike other objects in the world, we know bodies from the inside as well as from the outside. In order to better understand people's conceptions of the space of the body, Morrison and Tversky (1997) have begun exploring mental maps of the body. The first step in investigating mental maps of the body was to see which parts of the body were more accessible, more rapidly recognized.

Morrison and Tversky began with the body parts that span the body and that are most frequently named with single common morphemes across languages (Brown 1976; Andersen 1978). These include: head, arm, hand, chest, back, leg, and foot. The first task was a body part identification task. Participants saw the name of a body part on the screen and then a body with a part highlighted by a uniform white dot. Their task was to respond as rapidly as possible whether the highlighted part was the same or different from the named part. The bodies were realistic renderings in a variety of natural positions (and unnatural orientations).

Three theories make different predictions about the speed of identifying the body parts. A theory derived from research on imagery (e.g., Kosslyn 1980) would predict that larger parts would be named faster than smaller ones, as they can be detected faster when scanning the object. This would mean that leg and back, for example, would be identified faster than hand and arm. Object recognition theories could also be used to predict the outcome of a body part verification task. For recognizing objects, contours or shapes seem to be critical (e.g., Rosch et al. 1976). Shapes, in turn, can be divided into their parts. Contour discontinuities (inflection points) seem to be used to partition objects into parts (e.g., Hoffman and Richards 1984; Biederman 1987). From the work on contour discontinuities, it could be predicted that parts with greater contour discontinuities would be identified faster. Thus, for example, foot should be identified faster than chest.

A third theory, the part significance theory, derives from the observation that bodies are experienced from the inside as well as the outside, so that information about sensations and actions combines with information about appearance to constitute our knowledge of bodies. Some support for this position comes from research of Reed and Farah (1995). Their participants were asked to decide whether pairs of bodies depicted in complex positions but at different angles were in fact the same position. When participants made judgements while waving their arms in random movements, they were faster to judge differences in depicted arm positions; conversely, when participants moved their legs randomly, they were faster to judge differences in depicted leg positions. For objects, part size, salience and functional significance are highly correlated (Tversky and Hemenway 1984). For bodies, these can be somewhat dissociated. The index we used for body part significance was relative size on sensory-motor cortex, reasoning that parts that have relatively greater sensory feedback and motor control would be relatively more significant in human interactions with the world. According to part significance, head and chest should be identified faster than leg.

In the study described, measuring times to verify named and highlighted body parts, part identification times in fact correlated best with part significance. Verification times were fastest to head, next to chest, hand, foot, and arm, and last to leg and back. Part discontinuity was second best, which is not surprising as the rankings for part significance and part discontinuity are themselves correlated. Nevertheless, part significance can account for the relatively rapid verification times for chest but part discontinuity cannot. There was no support for part size. In fact, some of the largest parts, leg and back, were slowest. This is somewhat surprising as the task was primarily a visual one that did not arouse any body sensations, such as those that might be aroused had participants been asked to verify touched or moved body parts. Apparently the names of the body parts call to mind the meanings of the parts, that is, their functions, actions, and sensations, as well as the visual features of parts, notably their contours. This position is supported by a second study in which participants compared two depictions of bodies with the same or different parts highlighted. In this task, which can be performed by visual comparison without naming, part discontinuity was the best predictor of reaction times, better than part significance. As before, part size correlated negatively with verification speed.

While this work is only preliminary, it does suggest that mental maps of the space of our bodies depend on both function and appearance, on sensation and action as well as on visual salience. In the case of the space of the body, the elements are the body parts, the spatial relations are their configuration, and the bias is toward parts with greater salience defined by contour discontinuity for a purely visual situation and toward parts with greater significance when function or action is aroused.

Three Functional Spaces

Knowing how to get from where we are to where we need to be, being aware of our immediate surroundings irrespective of where we are looking, and keeping track of what our bodies are doing and feeling is essential to our very survival. These three spheres of knowledge correspond to three different arenas of interaction with the spatial world and to three different schematizations of the world. Are there other spaces of import to the human mind? Certainly. For example, neuroscientists might subdivide the space surrounding the body into the space that limbs can reach and the space that can be seen but not reached without moving, that is, into the space that can be manipulated and the space that can be seen but not manipulated. This distinction may be more important for the limbs and sensory-motor interaction than for conceptions of space. After all, the space that can be seen but not manipulated can be easily reached by navigation. A related space, the space of objects that can be manipulated, seems to have cognitive import. Although objects and scenes are both composed of parts in spatial configurations (cf. Tversky and Hemenway 1984), people are surrounded by scenes while they are larger than (most) common objects. People interact with scenes by moving around in them, but they interact with objects by manipulating them, and people's mental representations reflect those differences in experience.

Similarly, the space of navigation can be divided into the space of experienced navigation and the space that is known only through maps (e.g., Montello 1993). There are many similarities between these spaces. For one thing, the space of experienced navigation is often learned vicariously, from maps and descriptions, as well as from actual experience. For many kinds of information and judgements (but not all; see, for example, Taylor et al. 1999), environments learned by maps, description, and navigation are indistinguishable. For example, the errors derived from reliance on other elements and frames of reference occur for environments acquired by actual navigation as well as those learned from maps (Tversky 1981) suggesting that the underlying mental representations are similar in character. However, some tasks, notably updating orientation, are performed quite differently under actual navigation than under imagined navigation or maps (e.g., Presson and Hazelrigg 1984; Presson et al. 1989; Rieser 1989).

Because the three spaces, the space of navigation, the space around the body, and the space of the body are experienced differently, interacted with differently, and serve different functions in our lives, it makes sense that they are schematized differently, forming different kinds of mental representations. In each case, the schematization reflects the typical kinds of interactions that human beings have with their surroundings. For large-scale navigation, we need to keep track of the important landmarks and routes in the environment and to patch together different views, different modalities, and different experiences into a larger whole that will allow seamless interaction among parts that have been cognitively separate. Using elements such as landmarks, paths, cities, and countries, and reference frames, such as surrounding geographic entities or north-south-east-west, gives us a way to patch those separate segments together. For the space around the body, we need to keep track of the objects surrounding us, objects that may be obstacles to our movements or that may be useful for our activities. Because their danger or utility depends in part on their locations relative to our bodies, we keep track of them relative to our bodies. For this situation, our bodies are schematized by our body axes, which vary in accessibility in systematic ways. Finally, for the space of the body, we need to keep track of our own body parts and those of others in close proximity. Body parts that are more significant both perceptually and kinematically are those that are more accessible.

The mental representations for each of these spaces differ in critical ways from classical views of imagery. The mental space of navigation does not seem to be Euclidean. Rather, this space seems to be represented qualitatively, in terms of elements and the coarse spatial relations among them. The space around the body is not searched in analog fashion, from viewpoint to probed direction. Instead, it is searched categorically, through the three body axes. Finally, for the space of the body, part size does not determine part verification times. Rather, when part verification requires comparing two depictions, times are determined by part salience, which is based on contour discontinuity. However, when part verification requires comparing a named part to a highlighted part, times are determined by part significance, which is based on functional significance as well as perceptual salience, as indexed by relative projection size in sensory-motor cortex. Although these spaces are conceptualized differently, all three are used, apparently seamlessly, as we interact with the world. ■

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Organization of Feature-, Time-, or Location-Based M Models*

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This study considers how mental models are encoded into memory by viewing visual displays like
is an internal representation of a situation that links objects or concepts to other objects or con
indicated location-based mental models are encoded when a series of propositional statements s
location are read from a text. Evidence that locations were being used as the basic container for an
models is provided by a significant *fan effect*. A *fan effect* shows an increase in reaction time with
considered when making a decision. Features, times, and locations were considered as possible c
models. Subjects created location-based mental models, but also encoded feature-based mental
effect for time, found for a map animation, suggested the order of the presentation of maps c
structure of learned information.

Key Words: mental models, spatial cognition, map anima

Introduction

Considerable progress has been made in distinguishing the various encoding processes people use to acquire spatial information and the systematic errors evident in many cognitive maps (Stevens and Coupe 1978; Tversky 1981; Holyoak and Mah 1982; Hirtle and Jonides 1985; Lloyd 1989). The types of information we are likely to encode into cognitive maps seems predictable, but how this information will be organized and structured in our memories is less obvious. Knowledge concerning how learned information is represented in memory may help to explain common patterns found in cognitive maps and lead to a better understanding of spatial decision-making processes. Research on memory structures can benefit geographers and others who want to successfully communicate environmental knowledge and cartographers who wish to design interactive and animated maps that efficiently provided needed information to users.

When we travel through the environment or watch a map animation we encounter objects embedded in time and space. Most objects are forgotten quickly, but others are encoded into our long-term memories (Kahneman et al. 1992). It is possible to encode information about when and where objects are encountered as well
as the many perceptual feat
objects. The internal structu
memory when learning such i
useful in making fast and ac
the future (Jih and Reeves 19
lead to unwanted and syste
and Mathews 1996; Patton 1

Map animations have obje
features that interact in time
sent information to the viewe
For some types of cognitive p
and *where* information is not v
example, when basic-level ca
learned, the focus is on using
mation for objects to genera
these categories (Rosch et al.
1996).[1] Maps could be conside
form a basic-level category.
about the category *map* gener
the *map* category from all the
ences they have had with spe
They have encountered maps
and at different geographic l
mon understanding of the nat
ever, should be encoded in
features shared by the objects
as part of the *map* category. T
mation is part of our general
mantic memory (Martindale 1
in semantic memory is not tir

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