Theories of Memory
Volume II

edited by

Martin A. Conway
Susan E. Gathercole
&
Cesare Cornoldi

Psychology Press
a member of the Taylor & Francis group

1998

11

Three Dimensions of Spatial Cognition

Barbara Tversky
Stanford University, CA, USA

SPATIAL KNOWLEDGE

Our knowledge of the spatial world comes not just from vision, but also from hearing, touching, smelling, and from the feedback from our own bodies. From hearing, we can know where to look; from seeing, we can know where to reach. Spatial knowledge, then, is multimodal, and in part, supra-modal. Knowing the location of our bodies in space is essential for survival, as is knowing other critical locations, such as our homes. Spatial knowledge serves as a basis for thinking about other things, such as time, or mood, or ability, or ideas (e.g. Clark & Clark, 1977; Lakoff & Johnson, 1980). This is evident in uses of language that are so entrenched that to call them metaphoric seems overly poetic: "We're behind schedule"; "He's down in the dumps"; "She's at the top of the heap"; "That field is waiting for someone to enter".

Our knowledge of space is not like geometry or physical measurement. Rather, our knowledge of space seems to be constructed out of the things that are in space, not out of space itself. Moreover, our knowledge of space is not absolute or metric; rather it is relative, primarily, as we shall see, to other things in space as well as to a more global reference frame.

Bodies and the Surrounding World

One of the first aspects of space that we confront is our own bodies. Our bodies have three axes, that formed by our heads and feet, that formed by our fronts and backs, and that formed by our left and right. The head/feet axis is asymmetric, as is the front/back axis. In addition, the front/back axis separates the world we can readily see and manipulate from the world that we cannot easily see or manipulate. The left/right axis of our bodies has no salient asymmetries. Our bodies exist in and interact with the world, which also has three axes; first, a vertical axis that is asymmetric due to gravity, and has a natural origin in the ground. Gravity has profound effects on the way things in the world look, for example a long vertical axis and vertical symmetry for many natural objects, and the way they behave, for example moving or even growing downwards or sideways more easily than upwards. The world we experience also has two horizontal axes with arbitrary origins, such as Greenwich. Experientially, their origins are in our incidental and varying viewpoint in the world. For the most part, these horizontal axes define the world we navigate. From our viewpoint, the world in front of us has a weak asymmetry in that things that are nearer appear larger and clearer than things that are far; the sideways horizontal axis has no essential asymmetries (parts of this analysis derive from similar analyses of Clark, 1973; Fillmore, 1975; Levelt, 1984; Miller & Johnson-Laird, 1976; and Shepard and Hurwitz, 1984). Thus, space as we perceive and experience it is not equipotential or arbitrary as it might be in a formal abstract treatment; rather space as we perceive and experience it is anchored, asymmetric, and biased.

These facts about the space of our bodies and the world they interact with form the basis for our conceptions of the spatial world. In the following pages, I will describe their implications for three different domains of spatial thinking. The first domain is the three-dimensional world around our bodies that we seem to keep track of effortlessly as we move about the world. Accessing objects in different directions from our bodies is biased in ways accounted for by the asymmetries of our bodies and by the relation of our bodies to the world. People keep track of the things around them by constructing a mental spatial framework derived from the body axes. The second domain is the primarily two-dimensional world that we navigate, which is thought to be captured by "cognitive maps". People's memory for the plane of navigation is systematically distorted. Those distortions indicate that people remember locations relative to each other and to a reference frame. The third domain is the two-dimensional plane of diagrams and charts; the issue of interest is the way space in graphics is used to convey abstract meanings. As for the other phenomena, so for this one, the reference frame naturally adopted yields biases.

SPATIAL FRAMEWORKS:
THE WORLD AROUND OUR BODIES

Learning from Description

As we move about the world, we seem to keep track of the relative locations of our surroundings effortlessly, so that we know where things are relative to our bodies without having to look at them. As noted earlier, space is not uniquely visual. It is accessed by many modalities, and by language as well. In fact, it seems likely that one of the earliest uses of language was to describe the spatial world, to inform others how to find their way to water or food and how to avoid danger. Franklin and I (Franklin & Tversky, 1990) wanted to know whether this ability to keep track of surroundings under navigation could be tapped by language alone as well as by experience. The vivid imagery experienced by many in reading suggests that language can instil a rich mental world that can be mentally traversed and revised as the described situation changes.

In a series of experiments designed to capture those phenomena in a laboratory setting (Franklin & Tversky, 1990), participants read narratives describing themselves in settings such as an opera house or barn surrounded by objects such as a bouquet of flowers or a bucket beyond their head, feet, front, back, left, and right. After learning the environments, participants were reoriented to face another object and queried by direction terms such as "head", "front", and "left", for the objects currently lying in those directions. Participants performed this task quickly and accurately. However, the times to access objects varied considerably depending on the directions of the objects from the body. Many participants reported imagining themselves in the environments and imagining themselves looking at the specified direction to find the object, a position consonant with classical work and theory in imagery and mental transformations, a pattern we termed the *Mental Transformation* pattern (e.g. Finke & Shepard, 1986; Kosslyn, 1980; Shepard & Podgorny, 1978). According to this theory, responses should be fastest to identify objects directly in front of the observer, next fastest to those displaced 90 degrees, that is, those to left, right, head, and feet, and slowest to objects displaced by 180 degrees, that is, the object behind. These subjective reports notwithstanding, the pattern of retrieval times did not correspond to the Mental Transformation pattern. In particular, time to retrieve objects behind, requiring a 180-degree mental transformation, were shorter than times to retrieve objects to left and right, requiring 90-degree mental transformations.

For the upright observer, the times to retrieve objects in various directions from the body corresponded to the *Spatial Framework* analysis. According to this analysis, readers construct mental spatial frameworks from extensions of the axes of their own bodies and associate objects to them. Accessibility of the axes depends on the relative salience of the axes in context. For the upright observer, the head/feet axis is most salient because of its asymmetries and because it is aligned with the only asymmetric axis of the world, the axis of gravity. The front/back axis is second because of its asymmetries, and the left/right axis is slowest because it has no essential asymmetries. The obtained retrieval times corresponded to this pattern. When the observer in the scene is described as reclining and turning from front to back to side, no axis of the body is aligned with gravity. In this case, only the asymmetries of the body should determine retrieval times. Like the head/feet plane, the front/back plane is asymmetric, but in addition it separates the world that can be perceived and manipulated from the world that cannot be easily perceived and manipulated, so it should be more salient. In fact, when the observer is described as reclining, retrieval times to front/back are faster than those to head/feet.

These findings have been replicated and extended in several variations of the described scenes, including third-person rather than second-person descriptions (Bryant, Tversky, & Franklin, 1992), central objects as well as central persons (Bryant et al., 1992), external as well as internal perspectives (Bryant et al., 1992), multiple viewpoints in a scene (Franklin, Tversky, & Coon, 1992), and probing for directions from objects rather than probing for objects from directions (Bryant & Tversky, 1992). The basic pattern has also been found in experiments describing the room as moving rather than the person as turning in the scene (Tversky, in press). In that case, participants take twice as much time to reorient when the room rather than the observer is described as turning even though these transformations are formally identical. Because the two situations, that of the room turning and that of the observer turning, are formally identical but psychologically different, this result is not readily accounted for by a propositional model.

Learning from Experience

In the previous experiments, environments were instilled by discourse, not by actual experience with an environment. From a description of space, it is necessary to construct a mental representation of space, but from direct experience of space, it may not be necessary to construct a mental representation—memory may suffice—or a different sort of mental representation might be constructed. To investigate this, Bryant, Lanca and I (Bryant, Tversky, & Lanca, 1996) put participants in environments where they were surrounded by objects on all sides. Participants learned the environments from experience, from looking around themselves at the objects in the scene. At testing, they were either provided the objects in the specified directions from memory as before, or they answered while they were in the environments and could actually scan the scene.

This design—responding from memory versus responding from perception—allowed testing of another tenet of the classical view of imagery, that imagery is like internalised perception (Kosslyn, 1980; Shepard & Podgorny, 1978). According to the view that imagery is like internalised perception, the patterns of retrieval times should be the same for responding from memory as those for responding from perception. In fact, they were not. When participants responded from perception of the scene, their retrieval times corresponded to what we termed the *Physical Transformation Model.* Participants were fastest to respond to objects directly in front, next fastest to respond to objects displaced by 90 degrees, to head, feet, left, or right, and slowest to respond to objects located

behind, displaced by 180 degrees. This pattern is exactly what the *Menta Transformation Model,* derived from prior work on imagery and menta transformations, predicted for the original task. However, when participant responded from memory of the scene, their retrieval times corresponded to th Spatial Framework model. Thus, the mental representations constructed fro experience are functionally different from the mental processing that underlie responding while looking, but functionally the same mental representations a those constructed from descriptions.

Interestingly, when participants responded from perception of the scenes, the quickly learned the scenes. As they learned the scenes, they ceased scannin them and began to respond from memory, without looking. When participan ceased looking, their response times corresponded to the Spatial Framewor model. Thus, even when perception is available, it may be more efficient to rel on memory.

Neither Imagery nor Propositions

These findings are difficult to accommodate within either a classical imagery account or a classical propositional account. The general pattern of retrieva times in memory to different directions from the body does not depend on th degree of displacement from frontwards, and the pattern of times from memory does not correspond to that from perception. Both these findings contradict th classical imagery position. On the other hand, propositional accounts do no naturally predict biases in directions nor do they predict slower reorientatio when an environment rather than an observer is described as moving. Rather tha depending on our internalised perceptions of space, the patterns of times in thes tasks depend on our long-standing conceptions of the space of our bodies as they interact with the space of the world. In order to keep track of the objects surrounding us as we navigate the world, we construct schematic mental representations. The components of these mental representations are a framework, in this case, mental extensions of the natural axes of the body, and elements, tokens for the surrounding objects. Furthermore, the axes are biased in ways corresponding to our mental conceptions of the spatial world.

COGNITIVE MAPS: THE WORLD WE NAVIGATE

Now we turn to mental representations of the primarily two-dimensional plane of navigation, a domain of knowledge captured by the term "cognitive map". One prevalent view of cognitive maps is that they are like images, fairly veridical mental representations of the true state of things, preserving even metric information about the world. The well-known experiments of Kosslyn, Ball, and Reiser (1978) are taken as support for that view; in those experiments, times to scan between two points on a mental image of a memorised map correlated with ıal distances between the points on the map. This view is appealing for its ıplicity: internal representations are like external ones, and distances are ıtured metrically (Kosslyn, 1980; Shepard & Podgorny, 1978). The view can ıasily refuted by demonstrations of systematic errors or biases in memory, but find systematic rather than random errors requires careful construction of ıerimental tasks. Evidence for systematic errors in memory and judgement for ps and environments has accumulated.

As we navigate the world, we see the world from different viewpoints and ferent distances. In addition, some knowledge of the whereabouts of things in world comes from maps and descriptions in addition to or instead of direct ception. Given multiple views and multiple information sources, encoding ct metric positions from each experience does not seem to be the best way to ıember space, nor does it seem to be what our cognitive apparatus does. her, we seem to remember elements relative to each other and to a frame of ırence. Elements may be landmarks, roads, cities, countries, depending on the ıation, and frames of reference may be the canonical axes, relatively large ironmental features such as highways, borders, rivers, and mountain ranges. correspondence with this analysis, errors and biases in memory for maps and ironments can be divided into those due to other elements and those due to ırence frames (Tversky, 1981, 1992, 1993, 1996a).

her Elements: Landmarks

ıen someone asks us where we live, we often answer relative to the nearest ent geographic feature we think our interlocutor is likely to know (Shanon, 33). To a European, I might answer "California", to a New Yorker, I might wer "near San Francisco", to a local, I might answer "on Stanford campus". ıs, our information about regions is organised around landmarks. At the same e that they help to organise spatial knowledge, landmarks also distort spatial ıceptions in ways that are inconsistent with any metric representation of space. ıcifically, people judge distances to a landmark to be less than distances to an inary building (Sadalla, Burroughs, & Staplin, 1980). That mental distances asymmetric defies any metric account of mental representation (Tversky, 77), in particular the traditional view of cognitive maps.

her Elements: Alignment

ing other elements of a spatial scene as a reference object can distort gements of location as well as distance. According to the Gestalt principle of ıximity, people mentally group together similar elements in a visual scene. nilar geographic elements, like North and South America, are likely to be ntally grouped. Consistent with this analysis, when asked to judge which of two maps of the Americas is the correct one, a significant majority of those questioned picked the incorrect map in which South America had been moved more directly "below" or more aligned with North America (Tversky, 1981). In actuality, South America is for the most part west of North America, but people group them and judge South America to be relatively more east than it actually is. The same error arises for North America and Europe and South America and Africa; a significant majority of viewers pick the incorrect map in which Europe and Africa have been moved southwards relative to North and South America. The error also occurs for judgements of directions between cities and for artificial maps, indicating that it is based in processes underlying organisation of spatial scenes.

Frame of Reference: Hierarchical Organisation

In remembering locations of elements, we use reference frames as well as other elements as organisers. A readily available reference frame for spatial elements is the larger spatial region in which the element is embedded, for example, states for cities. Stevens and Coupe (1978) asked students in San Diego to draw a line indicating the direction between San Diego and Reno. Most participants indicated that Reno was east of San Diego when, in fact, it is west of San Diego. Stevens and Coupe reasoned that rather than remembering the directions between all pairs of cities, people organise geographic knowledge hierarchically. They organise cities into states and remember the relative directions between states. When queried about directions between pairs of cities, they infer that information from the directions of the states in which the cities are contained. Because California is generally west of Nevada, people infer that Reno is west of San Diego. Stevens and Coupe demonstrated effects of hierarchical organisation on artificial maps as well as real-world examples.

Since then, others have demonstrated effects of hierarchical organisation in other tasks. Wilton (1979) and Maki (1981) have shown that reaction times to judge north–south or east–west directions between pairs of cities are faster when the cities are in different geographic units aligned with the directions, even when distances are closer than pairs of cities within the same geographic unit. Hirtle and Jonides (1985) found that people underestimate distances between pairs of locations within the same conceptual group relative to pairs of locations between conceptual groups. For example, students at the University of Michigan underestimated distances of pairs consisting of two campus buildings or two town buildings relative to the distances between pairs consisting of one campus and one town building. Thus, hierarchical organisation has been demonstrated to affect time and errors to make judgements of both distance and direction for natural and artificial stimuli (see also Chase, 1983; Hirtle & Mascolo, 1986; McNamara, 1986, 1992; McNamara, Hardy, & Hirtle, 1989).

Frame of Reference: Perspective

The next investigation seems to have been inspired by the famous cartoons of the New Yorker's view of the world, where Manhattan is large and differentiated, and the world in any direction from it is shrunken and hazy. In point of fact, this is how we see; the things that are closer to us loom larger and are more distinct than the things that are far away and appear telescoped together. Holyoak and Mah (1982) investigated the effects of mental perspective on distance estimates. They asked students in Ann Arbor to imagine themselves as either in New York or San Francisco, and then to make judgements about the relative distances between pairs of cities more or less equidistant across the country. Those with an east coast perspective judged the distance between New York and Pittsburgh to be relatively larger than those with the west coast perspective, whereas those with the west coast perspective judged the distance between San Francisco and Salt Lake City to be relatively larger than those with the east coast perspective. The students who were given no perspective and presumably adopted one from Ann Arbor gave estimates intermediate between the east and west coast perspective participants.

Frame of Reference: Rotation

A natural frame of reference for geographic entities is the north–south–east–west framework provided by the canonical axes. Geographic regions, however, may also induce their own local frame of reference from their own shape. In perception of objects, people extract the longer axis, often assuming symmetry around it, and further assume that the axis is aligned with vertical or horizontal (Rock, 1973). When the frame of reference induced by a region is not perfectly aligned with the external frame of reference provided by the canonical axes, the two seem to be mental-rotated more in correspondence. Thus, for example, South America seems to be tilted relative to north–south on a world map. Consistent with this, when students were asked to place a cutout of South American into a north–south east–west frame, they tended to position it upright (Tversky, 1981). Similar distortions occur for artificial maps and for judgements of directions between pairs of cities or roads in regions that are not quite aligned with the canonical axes for both real and artificial environments.

Organisation of Space

In organising spatial knowledge, people appear to extract the major elements or figures, be they buildings or roads or cities or countries. The locations and orientations of these elements are not remembered directly but rather relative to each other and relative to certain natural reference frames, such as those provided by larger geographic units or those provided by the canonical axes. The effects of the reference objects and frames are distorting; they anchor the element in question, drawing it closer in distance or orientation. It may then be impossible to put together all the parts into a consistent whole, that is, the result need not be consistent with any metric representation. Cognitive maps can be impossible figures (Tversky, 1981), although the more constraints imposed, the less the error as the constraints are often uncorrelated (Baird, Merril, & Tannenbaum, 1979). Thus, the term "cognitive map" is misleading; it implies a unitary mental representation that is Euclidean. Because spatial knowledge does not necessarily conform to metric assumptions and because knowledge of space comes from many different modalities—verbal, visual, kinesthetic, and more—a cognitive collage seems a more appropriate metaphor than cognitive map to capture people's knowledge of space (Tversky, 1993).

These systematic biases and errors are not restricted to the domain of space. Analogous biases and errors can be found in memory and judgements in social, political, and other abstract domains (e.g. Nisbett & Ross, 1980; Quattrone, 1986; Taylor, 1989; Tversky & Gati, 1978; Tversky & Kahneman, 1974). For example, people perceive members of groups far from their own to be more similar to each other than members of their own groups, an effect analogous to the effect of perspective on distance estimates for near and far locations (Quattrone, 1986). People prefer to say that red is like magenta than vice versa (Rosch, 1975) and prefer to think that a son is like a father than a father like a son, an asymmetry effect like that of estimating distances to landmarks or ordinary objects (Tversky & Gati, 1978). The prevalence of these biases across domains of thought suggests that decomposing a domain of knowledge into elements and larger units, and structuring elements with respect to other elements and with respect to reference frames, is the result of general cognitive processes and not restricted to spatial thinking.

GRAPHICS: THE CONSTRUCTED WORLD BEFORE OUR EYES

Graphics, on paper, wood, stone, sand, clay, or bone, are ancient human artifacts, far more ancient than written language. They have been used to portray animals, environments, tallies. Although the oldest extant map, a clay tablet from Mesopotamia, dates back more than 4000 years (Wilford, 1981), visualisations of inherently nonvisual relations are a recent invention, beginning with economic and political graphs in the late eighteenth century by Playfair and Lambert (Beniger & Robyn, 1978; Tufte, 1983). With increased contact among diverse language communities and with advances in graphic technologies, graphics are increasingly prevalent in more aspects of our lives, from signs in public places to graphical user interfaces. An interdisciplinary set of researchers has begun to study diagrammatic reasoning (e.g. Glasgow, Narayanan, & Chandrasekeran, 1995).

lements and Spatial Relations: Elements

tudying the graphic inventions adopted across time and space, by different ultures, eras, and ages, reveals some universals that seem to be rooted in ognition (Tversky, 1995). Graphics consist of elements and the spatial relations mong them. In depictions, the elements are the people or animals or objects ortrayed; in writing, the elements are letters or pictographs; in graphs, the lements are lines, dots, numbers, and letters. Most writing systems began with ons as elements. The icons bore resemblance to what they represented but ecame schematised, conventionalised, and often symbolic with time and use Coulmas, 1989; Gelb, 1963). For objects and some activities, it is relatively easy construct icons that are readily interpreted. However, for abstract concepts, electing icons is less natural and often relies on "figures of depiction" such as etonymy, where a concrete associate to a concept stands for the concept.

patial Relations: Levels of Preserving patial Information

hese observations about icons have been noted many times. What is less bvious is how space, usually the space among elements, is used to convey eaning. The basic metaphor underlying meaning in graphics, as well as gestures nd similar uses of space in communication, is that distance in space reflects istance in some abstract concept or dimension. The mapping from the con-eptual dimension to space can preserve information from the conceptual imension at different levels: at the nominal or categorical level, where only the eparation into groups is meaningful; at the ordinal level, where the order of lements is meaningful; at the interval level, where the distances among elements re meaningful; and at the ratio level, where the ratios of the distances are eaningful.

A simple example of using space meaningfully at a categorical or nominal vel is the separating of letters belonging to different words with spaces. recursors of modern alphabetic languages did not always do this. Rows and olumns also use space to group similar items together and separate them from issimilar items. A simple example of an ordinal spatial device is an ordered st—children in order of age, baseball players in order of batting average, roceries in order of encounter in the grocery store. Indenting successively ubordinate entries in an outline is also a meaningful ordinal use of space. lierarchical trees, such as an organisation chart of a company or an evolutionary ee, are other examples of using space to convey ordinal information. In such ees, only one dimension, the vertical or horizontal dimension conveying time or ower for example, is meaningful, depending on how the tree is rooted. The equence on the perpendicular dimension is not interpretable. A simple example using space meaningfully at the interval level is the x–y graphs found

commonly in newspapers, magazines, and textbooks. Those graphs with a meaningful zero, such as plots of money, may preserve information at a ratio level. Pie charts are another ratio spatial device.

Spatial Relations: Directionality

In addition to spatial proximity, direction in space is often used to convey meaning. Consistent with its asymmetry both in the body and in the world, the horizontal dimension seems to be neutral, but consistent with its asymmetry in the body and in the world, the vertical dimension is not. For the vertical dimension, more, better, and stronger are associated with up; and less, worse, and weaker with down, in space as in language—remember top of the heap and feeling low—and in gesture—think of thumb's up and high five. This bias was evident in a survey conducted of tree diagrams that appear commonly in scientific texts, diagrams of evolution, of geological ages, and of linguistic families. For the diagrams of evolution, 17 out of the 18 texts with such diagrams found in texts in the Stanford main library portrayed human beings at the top of the chart. For the geological charts, 15 out of 16 portrayed the present era at the top. Thus, for both these topics, there is a strong tendency to place the present time, the best time so far, and people, the best species so far, at the top. For the linguistic trees, 13 out of 14 displayed the proto-language at the top. For linguistic trees, then, in contrast to biology and geology, the present time is at the bottom and the past at the top. However, at the top is the proto-language, the idealised language from which the others derived. The same holds for family trees, where the ancestor establishing the family sits firmly at the top.

Children's Use of Space to Convey Abstract Concepts

In order to learn how space is used spontaneously to convey nonspatial concepts, we asked children from different language cultures to use space on paper to express concepts of time, quantity, and preference (Tversky, Kugelmass, & Winter, 1991). The basic task for the children was as follows. The child and the experimenter sat side-by-side in front of a square piece of paper, thus sharing the same perspective. The experimenter put a dot sticker down in the centre of the page, stating that this stood for the time for eating breakfast (for example). The child was asked to put down stickers for the time to eat lunch and the time to eat dinner. One of the quantitative tasks asked about the amount of candy in a handful, the amount in a bag of candy, and the amount collected on Halloween. One of the preference tasks asked about a food loved, a food neither liked nor disliked, and a food that was disliked. Each child was first warmed up with a spatial task, representing the positions of tiny dolls in front of the child, and then given two temporal, two quantitative, and two preference tasks.

The children ranged in age from kindergarten through college. The task was simplified for the high school and college students. Participants included large samples of Hebrew-speaking Israelis, Arabic-speaking Israelis, and English-speaking Americans. Both Hebrew and Arabic are written from right to left, so this allowed us to examine the effects of writing direction on graphing direction. However, the right to left tendency is stronger in Arabic than in Hebrew for several reasons. In Arabic, letters are connected and formed from right to left, whereas in Hebrew, letters are not connected and most are drawn from left to right. In Arabic, at least until late in elementary school, numbers go from right to left, whereas in Hebrew, numbers go as they do in English, from left to right. Finally, Hebrew-speaking Israelis are more likely to have early exposure to a language written from left to right than are Arabic-speaking children.

There were several questions of interest. First, what information would the children's mappings preserve? Next, what direction would be used to represent increases? Third, is there a general graphing schema; that is, would the mappings be content-free? For information preserved, older children's mappings preserved more information than younger children's. Some of the youngest children treated the separate times, quantities, and alternatives as exactly that, as separate groups not on a single dimension. Their dots did not form a line; rather, they were placed seemingly randomly on the page. Most of the children did put the dots on a line, preserving order. To test for preservation of interval, in a separate study, we chose new examples where scale differences were blatant, for example, breakfast, morning snack, and dinner. We also elicited and then demonstrated the use of interval mapping for a spatial array. Despite these manipulations, only at about fifth grade did a large portion of the children preserve interval in their mappings. With age, then, children's use of space to map nonspatial relations preserved more information about the relations.

In contrast to information preserved, the use of the different directions to indicate increases showed no effect of age. For indicating time, there was an effect of language. A large portion of English-speaking children mapped time as increasing from left to right and a large portion of Arabic-speaking children mapped time as increasing from right to left. Hebrew-speaking children were in between. This was expected. Interestingly, the directionality of time did not change with age, suggesting that even college students did not bring their knowledge of graphing to this task, but rather treated each task for what it was, a request to use space to express a nonspatial relation.

Although writing culture affected direction of indicating increases for time, it had no effect on indicating increases for quantity or preference. Across cultures and ages, approximately equal numbers of participants indicated increases in quantity or preference as going from left to right, right to left, and down to up. [illegible] direction that was not used to indicate increases was up to down. This finding is consonant with the observation that the vertical dimension has a natural asymmetry but the horizontal one does not. Increases are indicated as goin upwards, or leftwards or rightwards, but not as going downwards. There ar some "negative" relations that increase upwards; inflation and employment ar examples. But these cases preserve the direction of the numbers even if they d not preserve the direction of the valence of the relation.

These findings indicate that children from diverse language cultures us space to express nonspatial relations in much the same way that graph inventions do, suggesting that these graphic inventions and conventions ar based at least in part on natural cognitive biases rooted in people's conceptions o space. Distance in space is used to convey distance on nonspatial relations, an the vertical dimension of space, but not the horizontal dimension, is us asymmetrically so that upwards is associated with more and with positivity. N all uses of space to convey other meanings are culture-free; the direction representing time is affected by the dominant direction of writing. This may b because time is frequently incorporated into writing, as in "the meeting will b between 2 and 4". Cross-cultural research on inventions of writing by pre schoolers (Ferreiro & Teberosky, 1982; Levin & Tolchinsky Landsman, 198 and inventions of arithmetic notation by children and throughout histor (Hughes, 1986) illustrate similar uses of space to convey nonspatial meaning and other ones as well.

IN CONCLUSION

Knowledge of the world begins with the world of our bodies and the world w inhabit and interact with. The spatial world and the things it contains are thre dimensional, but unlike mathematical abstractions, the three dimensions of ou phenomenal world are not perfectly symmetric or equipotential. Gravity define the vertical axis of the world. It imposes a major asymmetry in the world, wit profound effects on the way things appear and the way things behave. In contras the two horizontal axes of the world are arbitrary and symmetric except wit respect to a particular viewpoint in the world. From a particular viewpoint, th axis perpendicular to it is symmetric, but the axis defined by the viewpoint has weak near/far or front/behind asymmetry. For our own bodies, the head/feet an front/back axes have strong asymmetries of both appearance and behaviou whereas the left/right axis does not. These enduring facts about our bodies an the spatial world are incorporated in our enduring conceptions of space. I hav discussed their implications for three domains of spatial knowledge, th knowledge we have of the three-dimensional space around our bodies as w move about; the knowledge we form of the two-dimensional spaces we navigat formed from navigation or maps or language, spaces that are often too large to b seen from a particular position; and the two-dimensional space of externa graphic devices that we construct to represent, remember, and conceptuali information.