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## Mental Models of Spatial Relations and Transformations from Language

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When we read a vivid description of a social encounter or a journey, we often are able to imagine where the characters and objects are in the scene and how they move about as the action proceeds. Researchers studying how people use and understand language have come to agree that language comprehension entails construction of a situation model or mental representation of the situation described by the discourse in addition to mental representations of the words and sentences (e.g., Bransford, Barclay, & Franks, 1972; van Dijk & Kintsch, 1983; Mani & Johnson-Laird, 1982). At about the same time, researchers studying spatial cognition began to investigate the power of language alone to instill complex internal representations of space (e.g., Ehrlich & Johnson-Laird, 1982; Tversky, 1991b). The confluence of these fields has enriched both. For example, language researchers have often assumed that people's mental representations of space are Euclidean-like and veridical, for example, that distance information is represented analogically (e.g., Wilson, Rinck, McNamara, Bower, and Morrow, 1993). However, a long history of research in spatial cognition has demonstrated that people's mental representations of space are qualitative and piecemeal, thus likely to be inconsistent and distorted (e.g., Hirtle & Jonides, 1985; Holyoak & Mah, 1982; Sadalla, Burroughs & Staplin, 1980; Tversky, 1981, 1991a, 1992, 1993, 1996a). Interestingly, these aspects of mental representations of space are reflected in the language people spontaneously use to describe space. That language is qualitative and piecemeal as well (e.g., Denis, 1996; Ehrlich & Koster, 1983; Levelt, 1984; Talmy, 1983; Taylor and Tversky, 1996).

*Mental Representations of Space from Experience*

It is reasonable to assume that situation models constructed from text are based on the mental representations formed from actual experience with the world. The accumulating evidence for systematic distortions in memory for the spatial world gives some insight into the nature of those mental representations. The view that these are like maps or even schematic maps is giving way to the view that they are more like mixed media, collections of related information, some of which is more visual or spatial, some of which is more linguistic (e.g., Kuipers & Levitt, 1988; Tversky, 1993). Mental representations of environments seem to be put together in an ad hoc way to suit current purposes, rather than being retrieved as unitary wholes. Such mental representations are better characterized as cognitive collages than as cognitive maps (Tversky, 1993). They differ systematically from the two-dimensional Euclidean diagrams that typify maps.

One critical way in which mental representations of environments and environments differ is that mental representations are hierarchical (e.g., Chase, 1983; Hirtle & Jonides, 1985; Maki, 1981; McNamara, 1986, 1992; Stevens & Coupe, 1978; Wilton, 1979). People group cities into states or countries, they group buildings by function. These groupings distort judgments of distance as well as of direction. Distance judgments are also distorted by clutter, that is, the number of entities, for example, buildings or intersections (e.g., Sadalla & Magel, 1980; Sadalla & Staplin, 1980; Thorndyke, 1981), by viewpoint, near or far (Holyoak & Mah, 1982), and by whether the distance is estimated relative to a landmark or to an ordinary building (Sadalla, Burroughs & Staplin, 1980). Direction judgments are distorted by alignment to other proximal elements and by rotation to the horizontal or vertical in a frame of reference (Tversky, 1981). Horizontal and vertical have privileged status in the world as well as in perception (Howard, 1982).

Given these widespread distortions, how can mental representations of the spatial world be characterized? The distortions in distance estimation indicate that mental representations do not directly represent space or distance, but rather represent the entities that exist in space. The distortions in direction estimation indicate that mental representations of directions are not continuous, but rather, tend toward the categorical. Together, these findings suggest that spatial elements are organized relative to each other and to a reference frame, and assimilated toward these. And together, these distortions are unreconcilable in a map-like or Euclidean representation.

*Mental Representations of Space from Descriptions*

*Spatial Relations.* For the most part, research examining spatial mental representations established from description alone has examined simple spatial layouts, with the expectation of finding effects of distance and spatial relations. A number of experiments have demonstrated that people can mentally construct simple scenes composed of familiar objects from description alone (e.g., Clark & Chase, 1972; Glushko & Cooper, 1978; Franklin & Tversky, 1990; Mani & Johnson-Laird, 1982; Taylor & Tversky, 1992; Tversky, 1975). In all these cases, the descriptions specified the spatial relations categorically, using terms like "left," "above," and "in front of." Establishing continuous spatial relations from language alone is complicated by the fact that everyday language is inadequate for expressing continuous spatial relations. Continuous spatial relations can be conveyed by technical language using degrees and meters, but such language is neither produced nor comprehended precisely by ordinary users of language (Flin & Shepherd, 1986; Leibowitz, Guzy, Peterson, & Blake, 1993). Morrow and his collaborators have conveyed distance information using a combination of diagrams and text (Morrow, Bower, & Greenspan, 1989; Morrow, Greenspan, & Bower, 1987). However, recent work examining verification times for described routes is more consistent with the view that described distance is represented in gross categories defined by entities, rather than metrically (Franklin, 1989; Rinck, Hahnel, Bower, and Glowalla, in press).

*Spatial Transformations.* Mental representations of space derived from descriptions, then, seem to capture approximate but not metric distances and spatial relations, just as mental representations of space derived from experience do. Yet, situation models do not just represent static distances and spatial relations, they are also updated as the described situation changes. That is, they incorporate mental transformations as well as spatial relations. Spatial mental transformations on experienced objects have been extensively studied (e.g., Finke & Shepard, 1986; Shepard & Podgorny, 1978). The mental transformations that people readily perform on actual objects should form the basis for those that can be performed on described objects. This is not to say that everything that people can do in imagination on real objects they can also do on described objects, but rather suggests that transformations that are difficult to do on real objects should also be difficult to do on described ones.

Numerous mental transformations on real objects have been explored, beginning with the now classic experiments on mental rotation (Shepard & Cooper, 1983) and mental scanning (Kosslyn, Ball, & Reiser, 1978). In addition to mentally rotating and mentally scanning objects, people are also adept at mentally shrinking or enlarging them (Bundesen & Larsen, 1975; Larsen & Bundesen, 1978). In solving geometric analogies, people imagine objects not only rotating, reflecting, enlarging, and shrinking, but also splitting in half, doubling, and changing position (Novick & Tversky, 1987). People are able to imagine their own bodies rotating in space (Parsons, 1987). People can also imagine parts of their bodies, such as their hands and feet, moving in space. In this case, they imagine hands and feet moving in paths that are physically possible (Parsons, 1994). Interestingly, people can imagine objects rotating in space, but are more accurate when the objects are aligned with horizontal and vertical, a result reminiscent of rotation to frame of reference in mental representations of space (Pani, Jeffres, Shippey, & Schwartz, 1996; Pani, William, & Shippey, 1995). Other research suggests that mental transformations are not always smooth and analog, as in mental rotation and mental enlargement. When people are queried about the directions of successive pulleys in a system, they appear to mentally animate the system in discrete steps rather than all at once (Hegarty, 1992). Thus, mental transformations seem to be biased in at least two ways: toward transformations that are possible in the world and toward transformations that are aligned with the horizontal and vertical axes of the world. Moreover, they are not necessarily continuous analog transformations, but in some cases are more categorical, much like the evidence for spatial relations.

To date, the mental transformations in space evoked by language that have been studied have been relatively simple and straightforward. Denis and Cocude (1989) have replicated the studies of Kosslyn, Ball, and Reiser (1978) on mental scanning of maps using only descriptions of maps. Just as in the studies of memorized maps, they found increases in scanning time with distance, though the effects were on the whole weaker. Several studies have observed effects of describing a character as moving in a scene (Glenberg, Meyer, & Lindem, 1987; Morrow, Bower, & Greenspan, 1989; Morrow, Greenspan, & Bower, 1987). Other research has found that participants are able to mentally construct

images from descriptions of its' parts, for example, attaching a capital letter J to the bottom of an upsidedown grapefruit half and realizing that that forms an umbrella (Finke, Pinker, & Farah, 1989). These simple mental transformations have been readily accomplished by participants. One caveat comes from research inducing mental turning in place from descriptions (Franklin & Tversky, 1990). Although people readily mentally turned in place, this transformation did not have the smooth, continuous character of mental rotation. Turning 180 degrees did not take longer than the whole than turning 90 degrees. Along the same line, there are popular thought problems requiring spatial transformations that seem quite difficult, for example: Think of a sugar cube tilted diamond-like being slowly lowered into a cup of coffee. When it is half-way immersed, what does a cross-section of the cube look like? With so few examples of research, it is difficult to know the constraints of imagination of described spatial transformations. After an introduction to the paradigm, I will describe one modest endeavor in this direction.

### *Spatial Frameworks*

Whether through nature or through nurture or both, people's mental representations of space seem to be derived from their typical experience in it (e.g., Clark, 1973; Fillmore, 1975; Miller and Johnson-Laird, 1976; Shepard and Hurwitz, 1984; Tversky, 1991)b. Language, in turn, can draw on, evoke, or reconstruct those mental elements. The world we inhabit is three-dimensional, with an asymmetric vertical dimension determined by gravity and two horizontal dimensions that are unbiased except with respect to a specified viewpoint or origin. Our own bodies, through which we perceive, explore, and experience the world, are more constrained. We have an asymmetric vertical axis defined by head and feet, an asymmetric horizontal axis defined by front and back, and a symmetric left- right axis. Moreover, our experience with the spatial world is not just visual, it is auditory, tactile, kinesthetic, and more, so that our mental representations of space are not just multi-modal, but likely to be, at least in part, supra-modal. These facts about the spatial world we perceive and interact with might be expected to constrain mental representations of space and the mental transformations that can be performed on them, and they do.

In order to study people's mental representations of themselves in the world surrounding them, Franklin, Bryant and I have been investigating how people keep track of the objects around them under simple movements, turning in place, lying down, and standing up. Our initial research used narratives to convey these worlds, and we found that people had no trouble constructing mental representations of them as well as updating them as the described situation changed (Franklin & Tversky, 1990). The narratives described you, the reader, in a three-dimensional environment, such as an opera house, museum, or hotel lobby, surrounded by objects particular to the environments located beyond your head, feet, front, back, left, or right. Once participants had studied and learned the environments, they turned to a computer that redirected them to face another object in the scene, and then queried them for the current locations of the other objects with successive direction probes, randomly ordered, left, right, front, back, head, and feet. Performance was highly accurate; the data of interest were the reaction times to the various directions.

We considered several models to account for the times to retrieve objects in the probed directions about the body. Because the environments did not favor any direction over any other, the *Equiavailability Model* would predict equal reaction times to all directions (Levine, Jankovic, & Palij, 1982). The data did not corroborate this account, nor did they support an account based on classic theories of imagery (e.g., Kosslyn, 1980; Shepard & Podgorny, 1978). According to the latter account, participants would imagine themselves in the described situations, facing forward. To ascertain which object was lying in the probed direction, they would imagine themselves turning to search that direction. The *Mental Transformation* account would predict fastest reaction times to front, next fastest to directions 90 degrees from front, namely, head, feet, left, and right, and slowest times to back, 180 degrees removed from front.

Although the Equiavailability and Mental Transformation accounts did not fit the data, the data did conform to the *Spatial Framework* analysis. According to Spatial Framework analysis, participants construct a mental spatial framework out of the three body axes and associate objects to them. The axes differ in accessibility, depending on asymmetries of the body and of the world. For an upright observer, the head/feet axis should be most readily accessed because of its' asymmetries

and because it is correlated with the only asymmetric axis of the world, that defined by gravity. Front/back should be next, due to its' asymmetries, and left/right, lacking prominent asymmetries, should be slowest. This pattern of reaction times has been found in dozens of experiments (e.g., Bryant, Tversky & Franklin, 1992; Franklin & Tversky, 1990; Franklin, Tversky & Coon, 1992). Further support for the model comes from the case where the observer in the scene reclines and turns from front to side to back. In this case, no axis of the body is correlated with gravity, so locating objects depends only on the relationship to the body. In this case, we argued that the front/back axis should be fastest as the front/back asymmetries in perception and behavior are especially important; that axis separates the world that can be observed and manipulated from the world that cannot. In fact, for the reclining observer, times to locate objects to front and back are faster than times to locate objects to head and feet (Franklin & Tversky, 1990).

Since the initial studies, we have gone on to explore a number of variations of the original situation. Variants of the spatial framework analysis account for patterns of retrieval times to probed directions for variants in the situation, including points of view external to the scene as well as internal (Bryant, et al., 1992) and scenes with more than one viewpoint (Franklin, et al., 1992). In yet another variant, participants learned the scenes from observing them rather than from narrative, and responded from memory just as participants in the experiments where scenes were described had done (Bryant, Tversky, & Lanca, 1998). The experiments reported here investigate yet another extension, one where instead of describing the person in the scene as turning in place and the surrounding environment as stationary, narratives describe the person as stationary and the surrounding environment as turning.

There are reasons for expecting that the case of imagining spatial transformations of an environment would be more difficult than the case of imagining spatial transformations of one's own body. Except for earthquakes, in nature, it is people who move in environments, not environments that move around people. Of course there are haunted houses and other such dubious pleasures in amusement parks, but they are atypical and recent inventions, accounting for their attraction. Train and automobile travel can give the impression of being stationary while the world passes by but these are also recent inventions in our evolutionary history, though a small elite has probably been carried going farther back in our history. Even so, classic research on kittens carried in baskets yoked to kitten who performed movements has shown that the carried kittens learned little compared to the mobile kittens (Held & Hein, 1963). Formally, however, the situation where the person is turning in a stationary environment and the situation where the environment is turning around a stationary person are identical, so that a propositional account of behavior would predict that there should be no differences between the two cases.

#### Experiment 1: Turning Person vs. Turning Environment

The narratives for this experiment described the participants as floating in a weightless space house designed by NASA, visiting different rooms. Movement could be accomplished either by describing the participant as moving or by describing the room as moving around the participant (Kim, 1992). In what turned out to be a pilot experiment, two types of movement were described, turning on the same plane, or rotating from plane to plane. Although participants in the moving person condition had no difficulty carrying out this experiment, participants in the moving room condition were unable to do so. They quickly got disoriented. Many of them realized that imagining themselves turning or rotating in one direction was equivalent to imagining the room turning or rotating in the opposite direction, but they said they were still unable to perform the rotations. Therefore, we carried out an experiment where participants were described as only turning on a horizontal plane and not also rotating to another plane.

There were two sets of reaction times of interest: the times to reorient to a new facing, and, after the reorientation, the times to retrieve objects at the probed directions. The expectation was that for this conceptually easier situation, participants would be able to perform the task, but that reorientations would be more difficult, that is, take more time, when the room was described as moving rather than the observer. Once the reorientations had been accomplished, it was expected that the spatial framework pattern of times to retrieve objects in the probed directions would emerge for both cases.

### Method

*Participants.* Twenty-four Stanford undergraduates participated either for cash or for credit in an introductory psychology class. Six males and 6 females participated in the moving person condition and five males and seven females participated in the moving room condition.

*Procedure and Descriptions.* Participants first read and signed a consent form. Then they were given general instructions about the nature of the experiment. Following this, participants in the moving person condition read the following general description of the situation:

"You are visiting a large space museum created by NASA. The purpose of this museum is to show people what it would be like to live in outer space. The largest exhibition in the museum is the newly build "spacehouse," a full-scale model house created as a prototype that may eventually be used to colonize the moon. It looks like a normal contemporary style house. However, there is very little gravity in the house, and most of the objects are bolted to the floors, ceilings, and walls to keep them securely in place. You enter the house and find yourself floating in mid-air, a few feet above the floor. You are in an upright position, *but discover that you can change the position of your body by shifting your weight in the desired direction. You can rotate your body in three ways. You can rotate your body to the left 90 degrees, so that you face the object that was previously to your left, or you can rotate to your right 90 degrees, so that you face the object that was previously to your right. You can also rotate your body around 180 degrees so you face the object that was previously at your back (behind you).* At all times, your body is in a straight, upright position. The most striking feature you notice is that objects are not where you are accustomed to seeing them. Some objects are even attached to the ceiling. This seems appropriate since the lack of gravity allows you to move equally well (or with equal difficulty) in all directions. You decide to explore the house."

Participants in the moving room condition read the same general description, with the section below substituting for the section in italics above:

*and it is difficult to move. In the house is a small hand-held device which looks like a remote control. It has several buttons on it. The buttons are labeled "left," "right," and "180 degrees." You discover that the rooms in the spacehouse rotate, so that you do not need to change positions, and that the hand-held device controls the rotation of the room. For instance, if you press the "left" button, the room rotates to the left 90 degrees, so that the wall which used to be in front of you is now to your left. Pressing the "right" button causes the room to rotate 90 degrees to the right, so that the wall that was previously in front of you is now to your right. If you press the "180 degrees" button, the room rotates 180 degrees, so that the wall which used to be in front of you is behind you."*

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 Insert Figure 1 about here  
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Following this, participants read descriptions of visits to each room, preceded by a list of the objects in that room. For example, the living room contained a lamp, a newspaper, a plant, a portrait, a stereo, and a television. The objects for each of the six rooms were selected to be common, distinctive, appropriate to the setting, and approximately the same size. They were described as being beyond the observer's head, feet, front, back, left, and right, with particular positions determined randomly. A diagram of the situation appears in Figure 1. The description of the living room located the objects relative to the observer as follows:

"You are in the living room of the spacehouse. The living room is spacious, and the ceiling is made of glass, giving it the appearance of a greenhouse. You are in an upright position, suspended several feet above the floor. Above your head hanging from the ceiling is a plant. It is plastic, and is full of leaves. Below your feet on the ground is a lamp. It opens up at the top, giving it the appearance of a torch. In front of you, built into the wall is a television. It is turned on and a soap opera is playing. To your right, there is a newspaper attached to the wall. The cover story is about a civil war that has broken out on Mars. You turn to your left and there is a stereo on top of a shelf which is attached to

the wall. It is made up of several components. You look behind you and see a portrait on the wall. It pictures a family with two children and a dog.

Participants were allowed to study each story as long as they wished, until they felt they knew the locations of the surrounding objects. Then they turned to an IBM-AT computer for the continuation. Participants read sentences on the screen one at a time, striking a key to read the next sentence.

The first sentence reoriented the participant by describing either the participant or the room as rotating in one direction or another. When participants judged that they had been reoriented, they pressed a key to continue the experiment. The time from presentation of the reorientation sentence to pressing the key was the reorientation time. This was followed by a statement describing the object currently faced, and then a filler sentence not related to the object now faced to eliminate any priming effects for that object. Following this, one of the the six direction probes appeared in random order: head, feet, front, back, left or right. Participants were instructed to press any key as soon as they knew which object was in that directions. The time between the direction probe and the key press was called RT1. After the key press, a list of the six objects appeared on the screen, and participants pressed a key corresponding to the number of the objects. This was called RT2. In most of the experiments run so far, RT1 reflects the times to respond to each of the directions and to determine the appropriate object whereas RT2 reflects only the time to find the name of the appropriate object in the list. RT2 has usually not varied systematically with direction, although in some studies, it has, indicating some spillover from RT1 processes.

A new detail sentence, filler sentence, and question followed. After all six directions had been probed, the participant was again reoriented to face a different object, followed by another block of six probes. This was repeated until all four horizontally-arrayed objects had been faced. At the end of the probes for a given story, the computer informed the participant. The participant was then given a written description of another room in the spacehouse and the configuration of objects around the observer in that room. Then the participant turned to the computer and was repeatedly reoriented to face new objects and probed for the directions of all objects, as before. There were a total of seven rooms visited: bathroom, bedroom, den, dining room, kitchen, and living room. The first story served as practice. The order of subsequent stories was counterbalanced across participants.

### Results

*Reorientation times.* It took nearly twice as long for participants in the moving room condition to reorient to face a new object (8.5 s) as for participants in the moving person condition (4.4 s;  $t(21) = 1.84$ ,  $p < .05$ ). For both conditions, larger reorientations to 180 degrees were faster than reorientations to 90 degrees (for moving person,  $t(10) = 3.55$ ,  $p < .005$ ; for moving room,  $t(11) = 3.37$ ,  $p < .01$ ).

*Direction times.* Because an ANOVA on the RT2 data yielded no significant effects, only the RT1 data will be discussed. Medians were calculated for each subject and the means of the medians used in the statistical analyses, avoiding the need to eliminate outliers. The direction times for participants in the two conditions, moving person and moving room, did not differ. Nevertheless, the data were analyzed separately for each condition. In each condition, the spatial framework pattern of data appeared: head/feet was faster than front/back which was faster than left/right. The means of the median times are displayed in Table 1. For the moving person condition, effects of axis were highly significant ( $F(2, 10) = 16.53$ ,  $p < .0001$ ), with head/feet significantly faster than front/back ( $t(11) = 2.32$ ,  $p < .05$ ) and front/back significantly faster than left/right ( $t(11) = 3.23$ ,  $p < .01$ ). For the moving room condition, effects of axis were also significant ( $F(2, 10) = 10.54$ ,  $p < .005$ ), with head/feet marginally faster than front/back ( $t(11) = 1.68$ ,  $p < .12$ ) and faster than left/right ( $t(11) = 3.83$ ,  $p < .005$ ) and front/back faster than left/right ( $t(11) = 2.85$ ,  $p < .05$ ).

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Insert Table 1 about here  
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### *Discussion*

Both predictions were supported. Reorientation was faster for participants performing the more natural task, those who were told to think of themselves as moving, not those who were directed to think of the room as moving. Contrary to what might be expected from mental rotation (Shepard & Cooper, 1982), reorientations to 180 degrees were faster than reorientations to 90 degrees. However, in this experiment, the direction of reorientation to 90 degrees was specified but the direction of reorientation to 180 degrees was not. Once participants had reoriented, there were no remaining effects of how they had accomplished the reorientation. Times to locate objects in specified directions did not differ between the groups. In both groups, retrieval times followed the spatial framework pattern for upright observers. Participants were fastest to locate objects to head and feet, next to front and back, and slowest to left and right.

### Experiment 2: Turning and Rotating Person vs. Turning and Rotating Room

This experiment was a replication of the previous one and also included rotations to other planes, in particular, reclining and upside down relative to the initial posture. In an earlier version, participants in the moving room condition were not able to perform rotations although participants in the moving person condition were. In the present experiment, the moving room condition was augmented by adding explanatory information to the instructions and by increasing practice in each plane in the hopes of enabling participants to perform successfully. As before, participants in the moving room condition were expected to take more time to reorient than participants in the moving person condition. Reorientations to other planes, called rotation, were expected to take longer than reorientations on the same plane, called turning. Turning in place is familiar daily activity. The previous experiments have shown that people seemingly effortlessly keep track of the locations of objects relative to themselves as they turn in the real or imaginary world. Rotating to reclining or upside down is not common, and people may not be as adept at keeping track of relative locations under rotations.

After reorientation, the groups were expected to perform similarly in retrieving the objects lying in different directions from the body. All other things being equal, the upright and reclining spatial framework patterns of retrieval times to directions would be expected. However, in this situation, there is no natural upright in the world, so it would be natural for participants to treat themselves as if they were always upright. The world is described as without gravity, though because a gravity-free world has only been experienced by a handful of astronauts, none of whom participated in the experiment, it is not obvious that participants can conceptualize a gravity-free world.

### *Method*

*Subjects.* Twenty-eight Stanford undergraduates participants served in the experiment for cash or for course credit in the introductory psychology course. Six males and 16 females participated in the moving person condition and 5 males and 7 females participated in the moving room condition. An additional 23 participants from the moving room condition and 9 participants from the moving person condition were dropped from the data analyses either because their error rate exceeded the criterion of 10% or because of technical problems logging data.

*Procedure and Descriptions.* The procedure and descriptions were similar to those of the first experiment, with the following changes. Participants were presented detailed instructions explaining that they would be reading descriptions of encounters with rooms in a weightless space house designed by NASA. In each room, they would be surrounded by objects, oriented toward one of them, and asked to identify the objects at all directions around their bodies. The instructions went on to explain exactly how the reorientations would occur for the two conditions, moving person and moving room. Reorientations on the same plane were described as "turns" and reorientations to another plane were described as "rotations." Rotations were like cartwheels; that is, the movement was toward the left or right. Reorientation descriptions always identified the object faced as a consequence of the reorientation to facilitate comprehension. There were two reorientation times, the time to readjust to a new facing on the same plane and the time to readjust to a new facing on a

different plane. They were measured as before. Participants read a total of 10 descriptions of rooms. The first was for practice.

*Design.* The design was similar to that of the previous experiment with the following changes. For half the participants, in each room, the first rotation was 180 degrees, to upside down relative to the initial posture; when all the turning orientations for that posture had been probed, there was a second rotation of 90 degrees to reclining relative to the initial posture. For the other half of the participants, in each room, the first rotation was 90 degrees to reclining relative to the initial posture, and the second rotation was another 90 degrees to upside down relative to the initial posture. Thus, each subject had 4 facings at each of 3 postures. This yielded for each subject: 72 direction trials, 12 per direction; 9 turning reorientations, 3 for each plane; but only 2 rotating reorientations.

### Results

*Reorientation times.* For both types of reorientations, turning on the same plane and rotating to a different plane, participants in the moving room condition took longer than participants in the moving person condition. For turning on the same plane, participants in the moving person condition averaged 8.37s to reorient whereas participants in the moving room condition averaged 14.35s to reorient ( $F(1, 592) = 26.56, p < .00001$ ). The degrees turned had no effect on reaction time; that is there were no differences between turning 90 and turning 180 degrees. For rotating to a different plane, participants in the moving person condition averaged 9.28s to reorient and participants in the moving room condition averaged 22.06s to reorient ( $F(1, 160) = 38.95, p < .00001$ ).

*Direction times.* An ANOVA on the RT2 data did yield significant effects. These effects were smaller, as were the reaction times, than the RT1 effects and in the same directions. Moreover, combining RT1 and RT2 yielded the same pattern of effects. For simplicity, only the data for RT1 will be reported here. There was a small but significant residual effect of condition ( $F(1, 3854) = 13.60, p < .001$ ). Over all directions and all postures, participants in the moving person condition took 4.55s to respond whereas participants in the moving room condition took 5.08 to respond. There was also an effect of plane ( $F(1, 3843) = 6.06, p < .01$ ). Times for upright (4.49s) were slightly faster than those for reclining (4.76s) which were faster than times for upside down (5.97). Moreover, there was an effect and some interactions with sex ( $F(1, 2843) = 11.87, p < .001$ ). Women were faster than men, but this was primarily due to a single slow male.

The main effects of interest were those of direction queried ( $F(1, 3854) = 37.24, p < .00001$ ) and the interaction of plane and direction queried ( $F(10, 3843) = 4.19, p < .00001$ ). Reaction times by condition, plane, and direction are displayed in Table 2. For upright and upside down, the upright spatial framework pattern emerged, that is, head/feet was fastest followed by front/back and then left/right. This replicates the pattern found by Bryant, et al. (1998). The same pattern emerges for reclining, though the differences between head/feet and front/back are reduced as revealed in the interaction between plane and direction queried. Typically, for reclining retrieval times, front/back is actually faster than head/feet (Franklin & Tversky, 1990). Faster times for head/feet than front/back for the reclining condition may be due to the lack of an environmental upright; participants may have conceptualized the scene so that they were always upright in it.

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Insert Table 2 about here  
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*Discussion.* The results replicated and extended those of the first experiment. The new procedures made it possible for participants in the moving room condition to conceptualize rotations to new planes. As before, reorientations on the same plane took longer for the moving room condition than the moving person condition. The same was true for reorientations, that is, rotations, to a new plane. Even after reorientation, participants in the moving room condition took slightly longer to answer the direction questions than participants in the moving person condition, suggesting that not all of the difficulty of reorientation was absorbed in the reorientation times. This same result was obtained in a third study, similar to this one. Despite the slight differences in overall times, the pattern of times to direction probes was the same in both conditions. Reorientations on the same plane did

not take longer for 180 degrees than for 90 degrees, contrary to expectations from mental rotation and consistent with the results of the first experiment and some previous research (e.g., Franklin & Tversky, 1990). However, the same caveat applies; 180 degree reorientations did not specify direction whereas 90 reorientations did.

For retrieving objects in the probed directions, the upright spatial framework pattern emerged for all postures for both conditions. The advantage of head/feet over front/back was reduced in the reclining posture, but it did not reverse, as is typically the case (e.g., Franklin & Tversky, 1990). This may be because the described environment had no natural upright, so participants may have thought of themselves as upright at all times. The results for the upside down case replicate those of Bryant and Tversky (in press).

### General Discussion

The experiments described were first attempts at finding constraints on the spatial mental transformations that can be induced by description rather than experience. Exploring spatial imagination through description is often, particularly in this case, simpler technically than exploring spatial imagination through experience. In many cases, the effects are the same (e.g., Bryant, et al., 1998). Because in the normal course of events people move through stationary environments it was expected that describing people as stationary and environments as moving would be more difficult to comprehend than describing people as moving in stationary environments. This effect was evident in two experiments. It took nearly twice as long to reorient when the environment was described as moving than when the person was described as moving. This is not simply due to an inability to conceptualize movement of anything but one's own body. People are as adept at conceptualizing movements of objects as of their own bodies (Bryant, et al., 1992).

These results support the claim that people's experience of their bodies interacting with the spatial world underlies their mental representations of space which in turn support comprehension of spatial language. The results also add support to the claim that people's mental representations of space are not like internalized perceptions of space, but depend rather on people's conceptions of space (Bryant & Tversky, in press; Franklin & Tversky, 1990; Tversky, 1991b). People's conceptions of space include knowledge not immediately evident from perception, for example, knowledge about gravity and knowledge about the mobility of things in the world.

We began with the observation that people are able to form mental representations of space from descriptions of space. Mental representations established from description can be functionally the same as those established from experience. The question at hand is what spatial information is captured by representations established purely from language. Because mental representations of space from descriptions appear to be constructed out of mental representations of space from experience, we began by examining the nature of mental representations of space from experience. Spatial information can be separated into information about static spatial relations and information about dynamic spatial transformations. Findings relevant to the mental representation of spatial relations from discourse come from research on what have been called cognitive maps. Rather than being like maps or internalized perceptions, mental representations of space are mental constructions formed from elements and their spatial relations to each other and to a reference frame. The evidence for this position has come from pervasive demonstrations of systematic errors and bias in memory and judgment. Mental representations of spatial relations, like spatial descriptions, seem to be categorical and relative, to other elements and to reference frames (e.g., Tversky, 1996b).

Research relevant to the nature of mental representations of spatial transformations from discourse come from research on imagery. People are able to perform a variety of simple spatial transformations, including linear motion, rotation, enlarging, mental animation, and construction of a spatial array, though there has been some suggestion that the kinds of spatial transformations that can be performed are constrained or biased to motions that are possible in the world and to transformations that are aligned with the dominant axes of the world. There is also indication that mental transformations are not necessarily analog, but may lean toward categorical in some cases. Most of the research using descriptions of space has been aimed at demonstrating the existence of

spatial information in mental representations rather than testing the efficacy of various types of spatial information that is represented.

Here, we reported experiments testing the efficacy of language to evoke spatial transformations. Language that captures the normal, everyday experience of people interacting in the world is more readily comprehended than language that does not. Of course, participants were able to comprehend descriptions of environments moving around stationary observers, it just took them longer than comprehending descriptions of observers moving in stable environments. Most likely, comprehending that language was also based on interactions with the perceptual world. Participants for whom the environment was described as moving realized that the situation was equivalent to a reversal of the normal situation in which they move and the environment is stationary. Imagination can overcome the limitations of experience, though it is rooted in it.

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Table 1. Mean RT1 by Direction and Plane for Experiment 1

	Head/feet	Front/back	Left/right
Moving Person	1.56	1.76	1.98
Moving Room	1.44	1.51	1.93

Table 2. Mean RT1 by Direction and Plane for Experiment 2

Moving Person	Head/feet	Front/back	Left/right
upright	3.92	4.24	5.07
reclining	3.89	3.97	5.60
upside-down	3.86	4.22	6.38
Moving Room	Head/feet	Front/back	Left/right
upright	3.97	4.28	5.56
reclining	4.15	4.55	6.91
upside-down	4.24	4.78	7.68