Multiple Systems for Spatial Imagery: Transformations of Objects and Bodies

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Problem-solving often requires imagining spatial changes. *Object-based transformations* allow imagining an object in a different orientation. *Perspective transformations* allow imagining changes in one's viewpoint. Three experiments tested the hypothesis that these two transformations are dissociable and specialized for different situations, by manipulating instructions and task parameters and measuring response times, errors, and introspective reports. Human experience with small objects such as telephones and clothes irons consists mostly of manipulation or observed manipulation, which is characterized by object-based transformations. Consistent with this experience, when participants made judgments about small manipulable objects, they showed a strong tendency to use object-based transformations. Experience with human bodies is more varied, including both object-like interactions and interactions in which one must estimate another's perspective. Accordingly, when making judgments about pictures of bodies, participants' selection of a spatial transformation depended on the type of judgment that needed to be made. When instructions violated these natural mappings, performance was impaired. These data argue for the view that multiple spatial transformation systems evolved to solve different spatial reasoning problems.

Keywords: Imagery, visuospatial, mental rotation, perspective-taking.

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Introduction

The spatial structure of the world is complex and dynamic. Objects move, and observers move within the environment. Each new movement gives rise to a complex cascade of visual, kinesthetic, proprioceptive, and auditory signals. This poses major potential challenges for understanding perceived spatial transformations, and for imagining potential spatial transformations

Happily, different classes of movement events give rise to systematically different patterns of sensory input (Gibson, 1950). For example, consider a soccer player watching a teammate's shot. As the ball speeds toward the goal, movement of the object causes a local flow field on the retina of the player. If the player turns back to check on the other team's players, movement of the player's perspective produces a global flow field, and is accompanied by vestibular and proprioceptive signals. This natural partitioning of the space of sensory signals leads to a natural partitioning of motion events into transformations involving the motion of external objects, which we will term *object-based transformations*, and transformations involving the motion of one's personal point of view, which we will term *perspective transformations*.

Soccer players and other observers are not merely passive perceivers, however. People entertain plans for any number of actions that can lead to both object-based spatial transformations and perspective transformations, as well as blends of the two. In planning such actions, or in solving spatial reasoning problems, one may imagine the spatial transformations involved. The abilities of people to imagine spatial transformations are impressive for their power, flexibility and ubiquity—but at the same time for their failings. Spatial brain-teasers are easy to construct and excruciating to solve, puzzles can soak up hours, and people get lost in familiar cities.

One possibility is that various spatial reasoning problems are performed by a unitary spatial transformation operation or system (Rock, Wheeler, & Tudor, 1989). However, another possibility is that the brain contains systems specialized for performing different classes of mental spatial transformation. This is the view that has motivated the present research.

We propose that spatial reasoning can be better understood by considering the relationship between classes of imagined spatial transformations and the real physical transformations to which they correspond. This view depends on several assumptions. First, we assume that perception and imagery are coupled (Finke & Shepard, 1986). Second, we assume that different physical transformations give rise to systematically different patterns of sensory stimulation. As the soccer example suggests, actual object-based transformations tend to be associated with local visual flow transients, whereas perspective changes tend to be associated with global flow fields and proprioceptive and vestibular transients. Third, we assume that observers are also actors, and they imagine different mental spatial transformations for different action situations, each involving a particular combination of typical actions and objects. Finally, we assume that mental imagery arose from

selective pressures that simultaneously shaped neural systems for perception and for action (Shepard, 1994). These four assumptions lead to the proposal that the human brain and mind contain multiple systems for performing imagined spatial transformations, each with its own computational structure, and each shaped for specific tasks and stimuli. The research described here is informed by this *multiple systems framework* (Zacks & Michelon, in press).

In particular, the research described here focuses on two families of spatial transformation introduced in the soccer example: object-based spatial transformations and perspective transformations.[1] Object-based transformations and perspective transformations both involve updating the relationship between three spatial reference frames: an *egocentric reference frame*, which codes objects' locations relative to the observer; one or more *object-centered* (or "intrinsic") reference frames, which code locations relative to an object; and an *environmental* (or "allocentric") reference frame, which codes things relative to the local environment (McCloskey, 2001). Both transformations depend on all three reference frames, but each transformation consists of a different form of updating the relationship between the reference frames. In an object-based transformation, the reference frame of an object is updated relative to the egocentric and environmental reference frames. In a perspective transformation, the egocentric reference frame is updated relative to the environmental reference frame and the reference frames of one or more salient objects (Zacks & Michelon, in press).

Object-based transformations and perspective transformations produce different patterns of behavior. Evidence for this comes from two quite different approaches. The *direct instruction* approach asks participants to imagine a particular transformation, and then make a spatial judgment based on that transformation (e.g., "Imagine yourself turning 90 degrees to the left and tell me what you see"). The *judgment task* approach directs participants to make different spatial judgments without any special instructions, and infers the spatial transformation performed from response times and errors.

Inducing Transformations by Instructions

In the direct instruction approach, participants typically are asked to imagine a rotation of an array of objects (an object-based transformation), or asked to imagine themselves rotating around or within the array (a perspective transformation). In one set of studies, Huttenlocher and Presson (1973; 1979) asked children to perform one of these two types of transformation. The participants were then asked either to identify which of multiple pictures matched the transformed view, or where (relative to the participant's egocentric

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[1] These two are by no means exhaustive; movements of the limbs constitute a third important class of transformation, one which is likely closely coupled to the two studied here (Schwartz & Holton, 2000; Sirigu & Duhamel, 2001; Wexler, Kosslyn, & Berthoz, 1998; Wohlschläger & Wohlschläger, 1998).

reference frame) a given item would appear after the transformation. They found that array rotation tasks could be easier or harder than viewer rotation tasks, depending on the exact question asked. When participants reconstructed an array to correspond to the imagined view or reported the positions of objects in the array, imagined array rotations were faster and more accurate than imagined viewer rotations. However, when participants reported which item would be at a particular location, imagined viewer rotations were faster and more accurate (Huttenlocher & Presson, 1979; Presson, 1982).

More recently, Wraga and colleagues (2000) have extended this paradigm, again finding that the relative difficulty of viewer and array rotations depended on the particular spatial judgment required, though in none of their experimental conditions were array rotations superior to viewer rotations. (See also Amorim & Stucchi, 1997; Presson, 1982.) In these experiments the two transformations were sensitive to stimulus manipulations: Array rotations improved relative to viewer rotations when the array was a single familiar object. Array rotations also improved when haptic information was provided. Another recent study showed that the relative difficulty of viewer and array rotations depended on the plane of rotation (Carpenter & Proffitt, 2001). In addition to overall difficulty differences in a given task configuration, array rotations and viewer rotations showed different relationships between orientation and response time in these studies: For array rotations, response times increased monotonically from 0 to 270 degrees. However, for viewer rotations, 270 degree trials were typically as fast as or slightly faster than 180 degree trials.

Correlates of these behavioral patterns have been studied with functional neuroimaging. One recent study found left-dominant parietal activity during viewer rotations (Creem, Downs, Wraga, Proffitt, & Downs, 2001). Another directly compared viewer and array rotations (Zacks, Vettel, & Michelon, 2003). This study replicated the finding of greater left posterior increases for viewer rotations, and found greater right posterior increases for array rotations (as well as greater left parietal decreases).

In short, when participants are directly instructed to imagine a spatial transformation and make a spatial judgment, the pattern of performance depends on whether the transformation is an object-based spatial transformation or a perspective transformation. Object-based transformations seem overall to be more difficult, but this depends on the spatial judgment required, the stimulus used, and the plane of rotation. In addition to overall difficulty, the relationship between orientation and response time differs depending on the spatial judgment required. Directly instructing object-based and perspective transformations leads to different patterns of neural activity.

Inducing Transformations Without Direct Instruction

In the judgment task approach, the experimenter manipulates features of the spatial judgment task in ways hypothesized to affect the transformation evoked, and tests for predicted effects on patterns of performance (Shepard & Cooper, 1982). Zacks, Tversky, Mires, and Hazeltine (2002) used a paradigm
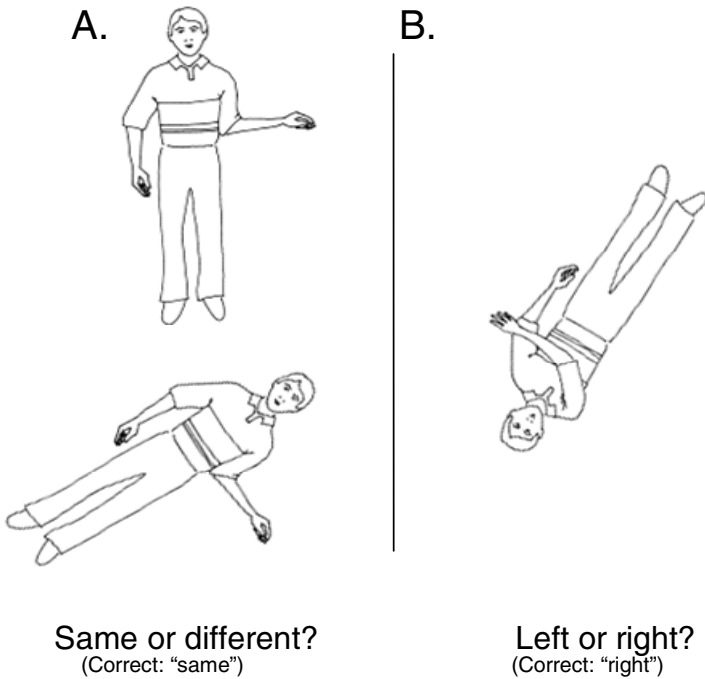
A.   **B.**

Same or different?   **Left or right?**
(Correct: "same")   (Correct: "right")

Figure 1. Tasks and stimuli for judgments about bodies in Experiments 1-3. Panel A shows one trial of the same-different task, and panel B shows one trial of the left-right task. The two panels also demonstrate the two different poses used, and three of the twelve orientations used. (The task instructions and correct answers below each pane are provided for illustration; they did not appear during the experimental trials.)

exemplifying this approach. We will describe it is some detail because the present experiments build on the method they used. Participants made spatial judgments about pictures depicting a human body with one outstretched arm. Bodies were chosen because they are associated in perception with both object-based and perspective transformations.   People experience object-based transformations of bodies when they observe others' motion, and experience perspective transformations of their own body as they move around the world.

   In the Zacks et al. (2002) study, pictures of bodies with one arm outstretched were presented at varying picture plane orientations, always facing the viewer (see Figure 1). The *same-different* task was designed to evoke an object-based transformation when performed with pictures of bodies, and was adapted from Shepard and Metzler (1971). Participants viewed two pictures, one above the other, and judged whether the two were identical or mirror images. It was

hypothesized that participants would perform an object-based transformation to align the reference frame of one of the bodies with that of the other. The *left-right* task was based on a task employed by Parsons (1987). In it, participants judged whether a picture of a human body had its left or right arm outstretched. It was hypothesized that this would elicit a perspective transformation to align the participant's reference frame with that of the body.

The multiple systems view predicts that if the same-different task evoked an object-based transformation, it should lead to an approximately linear increasing relationship between stimulus orientation and response time. This is because the imagined object-based transformation, that is, mental rotation, is isomorphic to the corresponding physical rotation (Shepard & Metzler, 1971). However, for perspective transformations this relationship need not obtain. Parsons (1987) asked participants to imagine themselves in the position of similar figures, that is, a directly instructed perspective transformation. In this task, response times were independent of orientation for picture plane rotations. The same pattern held for left-right judgments performed on the same figures. Based on theory and these previous results, Zacks et al., (2002) predicted that, for picture plane rotations, object-based transformations should yield reliable increases in response times with increasing rotation of the figure; however, perspective transformations should yield essentially no relationship between orientation in the picture plane and response time. Both predictions were strongly supported by the data: Response time increased monotonically with orientation for the same-different task, but did not vary with orientation for the left-right task. It is important to note that Parsons' (1987) data did *not* support the view that perspective transformations are always independent of orientation. On the contrary, when pictures of bodies were rotated through oblique planes, different response time patterns were observed for directly instructed perspective transformations, some increasing with degree of rotation and some not. What matters for the current argument is not that response time be independent of orientation for left-right judgments, only that the pattern differs clearly from that for object-based transformations. For the present experiments, front-facing picture plane rotations were utilized to capitalize on this known difference.

These two tasks also were studied with functional MRI (Zacks, Ollinger, Sheridan, & Tversky, 2002). Areas in right parietal, temporal and occipital cortex, as well as a portion of the superior cerebellum, were more active when performing the same-different task than the left-right task. This was true after task differences in response time patterns were controlled. (No regions were found showing the opposite pattern, greater activity in the left-right task.) These results converge with other neurophysiological and neuropsychological studies, which have associated right posterior cortex with object-based transformations, particularly mental rotation (Corballis, 1997; Ditunno & Mann, 1990; Harris et al., 2000; Pegna et al., 1997; Tagaris et al., 1997; Yoshino, Inoue, & Suzuki, 2000). (However, other studies have failed to find right hemisphere

lateralization for mental rotation tasks, e.g., M. S. Cohen et al., 1996; Jordan, Heinze, Lutz, Kanowski, & Jancke, 2001.)

   In short, a task manipulation predicted to selectively elicit object-based or perspective transformations affected both patterns of behavioral performance and neural activity.

Converging Approaches

The direct instruction and judgment task approaches complement each other. The direct instruction approach uses instructions to encourage participants to imagine a given spatial transformation and then to make a spatial judgment, and analyzes response time and error data in an exploratory fashion. This makes the resulting behavioral patterns directly interpretable, but is subject to the possibility that participants' performance might be influenced by task demands and tacit knowledge about the time course of different types of transformation (Pylyshyn, 1981). In the judgment task approach, features of the task are manipulated to affect the mental spatial transformation performed in a hypothesis-driven fashion. Judgment task manipulations are less subject to concerns about task demands, because they do not establish a task demand to respond in any particular way, but they require specific predictions about the resulting patterns of performance and sufficient data to test those predictions, in order to justify inferences about what spatial transformations are being executed. There are a few examples in the literature of attempts to combine these two approaches. For example, in the study by Parsons (1987) described above, participants imagined themselves in the position of pictured bodies (the direct instruction approach) and also made left-right judgments about the same stimuli (the judgment task approach). Based on the similarity of the behavioral profiles for these two tasks, Parsons argued that people used the imagined transformation in order to perform the left-right judgments.

Bodies and Objects

The multiple systems framework proposes that people's use of object-based and perspective transformations is shaped by their habitual interactions, forming associations between spatial transformations and features of the situations in which they occur. The data we have reviewed provide evidence for associations between spatial transformation use and two variables: the spatial judgment required, and the instructions provided to a participant. The multiple systems framework makes a further prediction, that the use of object-based and perspective transformations is shaped by patterns of interaction with different classes of stimuli. As noted previously, bodies have an interesting duality: We experience the bodies of others as objects that move independently, but also experience our own bodies undergoing perspective transformations as we move about the world. As a result pictures of bodies afford both object-based and perspective transformations. We also interact with a large number of objects that are perceptually associated exclusively with object-based transformations. Consider a pencil, a hammer, a flashlight or a telephone. We experience these

objects moving relative to the environment as they are manipulated by ourselves and others, but those manipulations are not systematically associated with changes in egocentric perspective. Thus, for stimuli depicting small, manipulable objects, imagined object-based transformations should be selected more often than perspective transformations—unlike the case for stimuli depicting bodies.[2]

Overview of Experiments

The current experiments were designed to provide converging tests of the dissociability of the two types of mental spatial transformations and to characterize the conditions under which each is selected. The multiple systems framework makes clear proposals for the effects of three factors on spatial reasoning:

1) *Effects of the spatial judgment required.* Perspective transformations should be more likely for tasks involving left-right judgments because such judgments are made relative to the spatial framework of the object. Object-based transformations should be favored for same-different judgments because those judgments require comparing the two objects as viewed from a third, external, reference frame.

2) *Effects of the stimulus presented.* Pictures of bodies should encourage both perspective and object-based transformations. They support perspective transformations because people have extensive experience of perspective transformations resulting from the movement of their own body. Bodies also support object-based transformations because people also experience the movements of others' bodies as objects. However, pictures of small objects should preferentially support object-based transformations, because as people move objects their personal perspective may not change with the object's motion.

3) *Effects of instructions.* To the extent that participants have control over the deployment of object-based and perspective transformation systems, they should be able to invoke one or the other when instructed to do so. However, the over-riding natural default settings described in proposals 1 and 2 should lead to reductions in performance.

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[2]Although small objects such as tools are not systematically associated with perspective changes, many may be associated with characteristic limb movements. In the multiple systems framework, body movements are identified as a distinct spatial transformation system, separate from both object-based transformations and egocentric perspective transformations. Recent research has demonstrated the importance of imagined body movements for spatial judgment tasks about manipulable objects (Kosslyn, Thompson, Wraga, & Alpert, 2001; Wexler et al., 1998; Wohlschläger & Wohlschläger, 1998).

Experiment 1 tested the first and third proposals using a within-participants design and measuring response latency. Experiment 2 tested the first and second proposals using a parallel design. As a converging measure, in this experiment we also obtained introspective reports from participants regarding the spatial transformations they thought they were using. The final experiment tested the first and second proposals using a between-participants design, with introspective report as the dependent measure.

Experiment 1: Manipulating the Instructions

Making left-right and same-different judgments about pictures of bodies leads to qualitatively different relationships between stimulus orientation and response time (Zacks, Mires et al., 2002; Zacks, Ollinger et al., 2002). We hypothesized that these different patterns of response time result from using different mental transformations to solve the two problems. Left-right judgments are made relative to a personal perspective, so they encourage perspective transformations in order to align the observer's perspective with that of the picture. Same-different judgments, however, involve comparison of two objects from an external perspective, which encourages participants to imagine one of the objects rotating. Thus, we predicted that participants would be more likely to perform perspective transformations in order to solve left-right problems, and more likely to perform object-based spatial transformations in order to solve same-different problems, other things being equal. The previous observation that response times in this task increased with orientation for the same-different task, but not for the left-right task, is consistent with that claim (Zacks, Mires et al., 2002).

Experiment 1 put this interpretation to a stronger test by pitting direct instruction against the judgment task manipulation. What might be expected if participants are explicitly instructed to perform a spatial judgment task using a mental transformation that violates these natural mappings? First, one would expect that participants' chronometric patterns would become more like the instructed transformation and less like the transformation corresponding to the natural mapping. Second, one would expect that overall performance would decline as a consequence of the lack of fit between the task and the instructions.

We tested these predictions by asking participants to perform the left-right and same-different tasks with pictures of bodies, first under neutral instructions (replicating Zacks, Mires et al., 2002), and then under instructions that explicitly described either a perspective transformation or an object-based spatial transformation. We predicted that for the left-right task, performance under perspective instructions would be relatively unchanged, whereas performance under object-based instructions would be more orientation-dependent, and slower overall. Conversely, we predicted that for the same-different task, performance under object-based transformation instructions would be relatively

unchanged, whereas performance under perspective instructions would be less orientation-dependent, and slower overall.[3]

Method

Participants. Participants were recruited from the Washington University community. Forty-two volunteers (mean age 26.8, range 18-55, 28 female) were paid $15 for their participation.

Spatial reasoning tasks. Each participant performed two spatial reasoning tasks. Both tasks employed line drawings of a human body (see Figure 1). Bodies were drawn with one arm outstretched, in one of two poses: the arm extended away from the body (uncrossed), or folded over the chest (crossed).

Same-different task. In this task, participants judged whether pairs of line drawings were identical or mirror images. The two pictures were arranged one above the other. The top picture was always upright (0 degrees). The direction of rotation (clockwise or counterclockwise) and orientation of bottom picture varied randomly from trial to trial. Orientation was varied in 30-degree increments from 0 to 180 degrees, with each of the seven possible orientations occurring equally often. Both pictures were always of the same pose (crossed or uncrossed arms), so that they were either identical or mirror images. Picture version was varied randomly from trial to trial. Participants were instructed, "For each pair, you should indicate whether the two figures are identical. The two figures will always be identical or mirror images of each other. They may appear in different orientations, but you should answer whether they would be identical if they were in the same orientation." Participants pressed the left button on a button box for "same" and the right button for "different." (These appeared as labels above the buttons, in case the participant forgot the mapping during the experiment.)

Left-right task. In this task, participants viewed single pictures, and reported whether the body's left or right arm was outstretched by pressing the left or right button, respectively. The stimuli were identical to those in the same-different task, except that the top picture was deleted and the remaining picture was centered on the screen. The same poses and orientations were used. Participants were instructed, "For each figure, you should indicate if the figure's right or left arm is outstretched." Participants pressed the left or right button on the button box to respond.

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[3] Strictly speaking, the hypotheses regarding overall difficulty were postdictions rather than predictions, as we did not consider overall difficulty when designing the experiment. Rather, the experiment was conducted primarily to test the hypotheses regarding orientation-dependence. However, the difficulty predictions derive from the spatial reasoning systems analysis by exactly the same logic as the orientation-dependence predictions. Nature was clearly more clever than us, as the overall difficulty effects were by far the biggest effects.

The trial structure was the same for both tasks. A prompt appeared on the screen: "Hit any button to go on."   When a button on the button box was pressed, a fixation cross appeared for 1500 ms, after which it was replaced by the stimulus (two pictures in the same-different task, one picture in the left-right task). The stimulus remained on the screen until the participant pressed one of two response buttons. If an incorrect response was made the computer sounded a buzzer, to encourage accurate performance. The protocol was implemented on Macintosh computers with the PsyScope experimental software package (J. D. Cohen, MacWhinney, Flatt, & Provost, 1993).

Procedure. Each participant completed six blocks of trials. During the first two blocks, they performed the left-right and same-different tasks without any special instructions (the *no instructions* condition). They then performed both tasks two more times. During one pair of blocks, they were directly instructed by the experimenter to perform each task by imagining a perspective transformation (the *perspective* condition). Specifically, before the left-right task participants were instructed to "answer the questions by imaging yourself in the position of the figure on the screen," and before the same-different task they were instructed to "answer the questions by imagining yourself in the position of each of the figures on the screen." During the other pair of blocks, they were directly instructed to perform each task by imagining an object-based transformation (the *object-based* condition).   Before the left-right task participants were told to "answer the questions by forming a mental image of the figure shown on the screen, and imagine the figure rotating until it is upright." Before the same-different task, they were instructed to "answer the questions by forming a mental picture of the figure shown on the bottom of the screen, and imagine the figure rotating until it is upright." To emphasize and clarify the instructions, participants acted out two sample trials with the experimenter before performing the task. In the perspective condition, they did this by physically rotating themselves into alignment with the stimulus; i.e. they performed a physical perspective transformation, demonstrating the imagined transformation to be performed. For the object-based condition, they were given a posable action figure (30 cm tall) and physically rotated the figure, thus performing a physical object-based spatial transformation that demonstrated the intended imagined transformation.   The demonstration stimuli used small rotations (up to 60 degrees) so as to be physically possible in the perspective transformation condition.

Each block consisted of 112 trials. For the same-different task this covered all combinations of pose, direction and amount of rotation, handedness, and match between the top and bottom picture. For the left-right task the last variable is not applicable, so all combinations of the other variables were tested twice.

Each participant performed the two no-instructions blocks first. This was followed by the two tasks either under perspective instructions or object-based instructions, followed by the same two tasks under the other instructions. The order of perspective and object-based instructions, and of task within each

instruction, was counterbalanced across participants. After each pair of blocks, and before receiving instructions for the next block, the participant was asked to describe how they performed the task. Participants who described a strategy that clearly violated the instructions during the instructed blocks (e.g., imagining the picture moving during a perspective block, or imagining one's self moving during a object-based block) were replaced.

Results

Participants who had an error rate of greater than 25% in any block of the experiment, or greater than 15% overall, were eliminated from the analysis. We also eliminated participants who reported during the debriefing that they had misunderstood or failed to comply with the instructions. Response time analyses were performed on correct trials only. In addition, response times were trimmed to eliminate outliers. For each participant, the mean and standard deviation of response times for each combination of instructions and task was calculated. Responses faster than 300 ms, or slower than three standard deviations from the mean for that condition were eliminated. In this experiment, one participant was eliminated due to a high error rate, and nine were eliminated because they reported during debriefing that they failed to comply with the instructions manipulation.[4] Of correct trials, 1.8% of the response times were identified as outliers.

For those participants included in the analysis, the overall error rate was low (2.15%). These errors came mostly from the same-different task: Mean error rates for the same-different task were 5.5% in the no instructions condition, 3.0% in the object-based instructions condition, and 4.1% in the perspective instructions condition. For the left-right task, the mean error rate was 0.1% in all three instructions conditions.

Effects of instruction on performance. Two aspects of performance were examined: variations in mean response time as a function of task and instruction, and variations in the relationship between orientation and response time as a function of task and instruction.

First, for each participant, mean response time was calculated for each combination of orientation, task, and instructions. These scores were submitted to a repeated measures analysis of variance (ANOVA). The overall effects of task and instructions on response time are shown in Figure 2, and match the predictions of the theory: Compared to the no instructions condition, providing perspective instructions had the effect of slowing performance on the same-

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[4] In these experiments, we adopted a conservative criterion of eliminating participants who reported using "tricks" to perform the tasks because such introspections, if accurate, invalidate the chronometric findings. However, in this experiment performance of those who reported using tricks was similar to that of the rest of the participants. In Experiment 2 this was also the case, except for those participants with error rates near or greater than 50%.
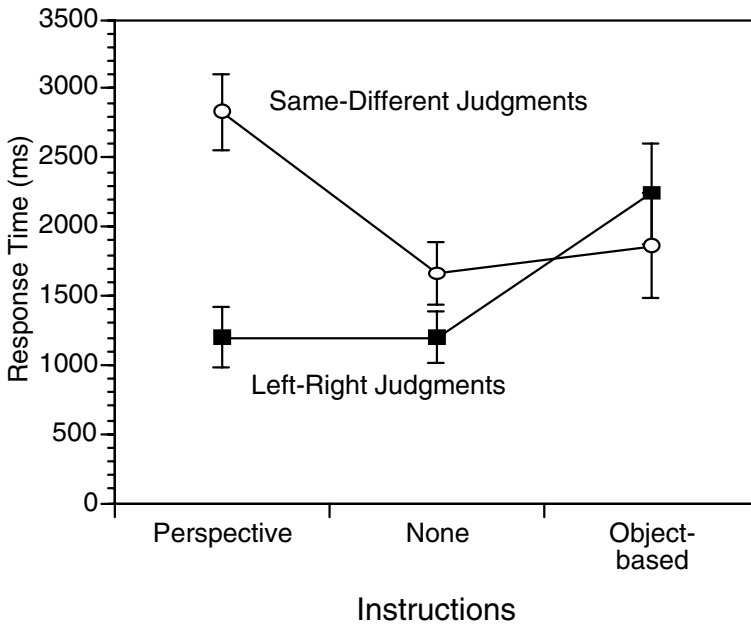
Figure 2. Mean response time as function of the judgment answered (left-right or same-different) and the instructions given for solving the problems (imagine yourself moving, none, or imagine the picture moving). Data are from Experiment 1. Error bars are 95% confidence intervals.

different task, $t(31) = 6.99$, $p < .001$, whereas providing object-based instructions had the effect of slowing performance on the left-right task, $t(31) = 7.28$, $p < .001$. There was no evidence that providing object-based instructions influenced performance on the same-different task, $t(31) = 1.09$, $p = .29$, or that providing perspective instructions influenced performance on the left-right task, $t(31) = 0.01$, $p = .99$. This pattern led to a significant interaction between task and instructions, $F(2,62) = 27.9$, $p < .001$. The main effects of task and instructions were also significant [task: $F(1,31) = 46.1$, $p < .001$; instructions: $F(2,62) = 16.9$, $p < .001$].

   The relationship between orientation and response time across individuals can be examined in two ways. First, one can take means over individuals, plotting the resulting average response profiles. These average data are plotted in Figure 3. As can be seen in the middle panel, performing the two tasks without special instructions led to two robustly different response time patterns, replicating previous findings (Zacks, Mires et al., 2002). For the same-different task response time increased strongly with orientation, whereas for the left-right
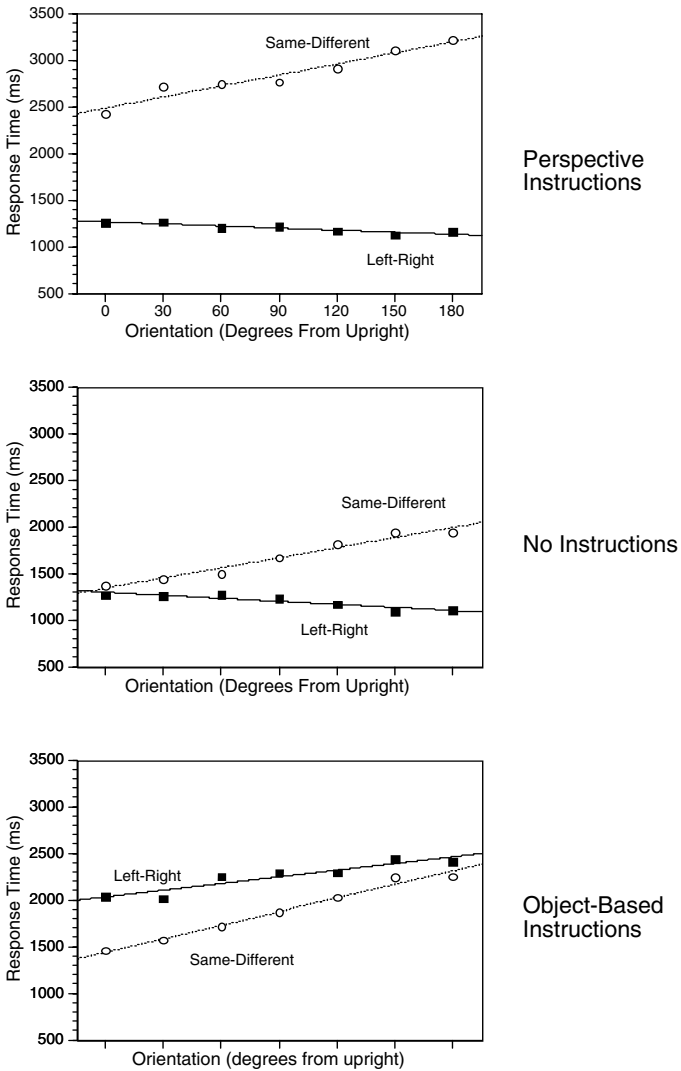
Figure 3. The relationship between stimulus orientation and response time as a function of the judgment answered (left-right or same-different) and the instructions given for solving the problems (imagine yourself moving, imagine the picture moving, or none). Data are from Experiment 1.

task increasing orientation had little effect on response time, if anything reducing it. As predicted, providing perspective instructions not only slowed performance of the same-different task, it also reduced the relationship between orientation and response time. Conversely, providing object-based instructions not only slowed performance in the left-right task, but also increased the relationship between orientation and response time.   In the response time ANOVA, these patterns led to a statistically significant main effect of orientation, $F(1,186) = 22.8$, $p < .001$, and significant two-way interactions between orientation and task, $F(12, 186) = 22.5$, $p < .001$, and between orientation and instructions, $F(12, 372) = 3.83$, $p < .001$.   The three-way interaction between orientation, task, and instructions was not statistically significant, $F(12, 372) = 1.20$, $p = .28$.

A second way of examining relationships between orientation and response time is to collapse across orientations, creating a summary statistic that describes the relationship between orientation and response time for each individual in each combination of stimulus set and task.   An appropriate summary statistic is the Pearson correlation r, which measures the degree of linear relationship between orientation and response time.   This has two attractive features for visualization: First, it separates the strength of the orientation-response time relationship in each condition from overall speed of responding.   (For example, consider a manipulation that simply slowed cognitive processing by a fixed multiple. This would affect the raw response times, but would not affect the correlation between orientation and response time.) Second, it shows the full distribution across individuals, allowing one to check that mean response time patterns such as those shown in Figure 3 are typical of the group, rather than resulting from averaging across participants. For Experiments 1 and 2 we have presented the data in both formats.

For each individual, the correlation between orientation and response time was calculated for each combination of instructions and task. This leads to a distribution of correlations for each combination of task and instructions. The resulting distributions are shown in Figure 4, and were submitted to a repeated measures ANOVA. As predicted, providing perspective instructions had the effect of shifting correlations for the same-different task down from a mean of .37 ($SD = .16$) to .21 ($SD = .19$), $t(31) = 4.21$, $p < .001$, but providing object-based instructions had little effect, shifting the correlations only to a mean of .38 ($SD = .18$), $t(31) = 0.14$, $p = .89$. Also as predicted, providing object-based instructions had the effect of shifting correlations for the left-right task up from a mean of -.15 ($SD = .21$) to a mean of .08 ($SD = .26$), $t(31) = 4.18$, $p < .001$, but perspective instructions moved correlations on the left-right task only to a mean of -.20 ($SD = .26$), $t(31) = 1.17$, $p = .25$. These effects resulted in a significant interaction between task and instructions, $F(2, 62) = 7.67$, $p = .001$. Both main effects were also significant [task: $F(1, 31) = 112.3$, $p < .001$; instructions: $F(2, 62) = 17.0$, $p < .001$].
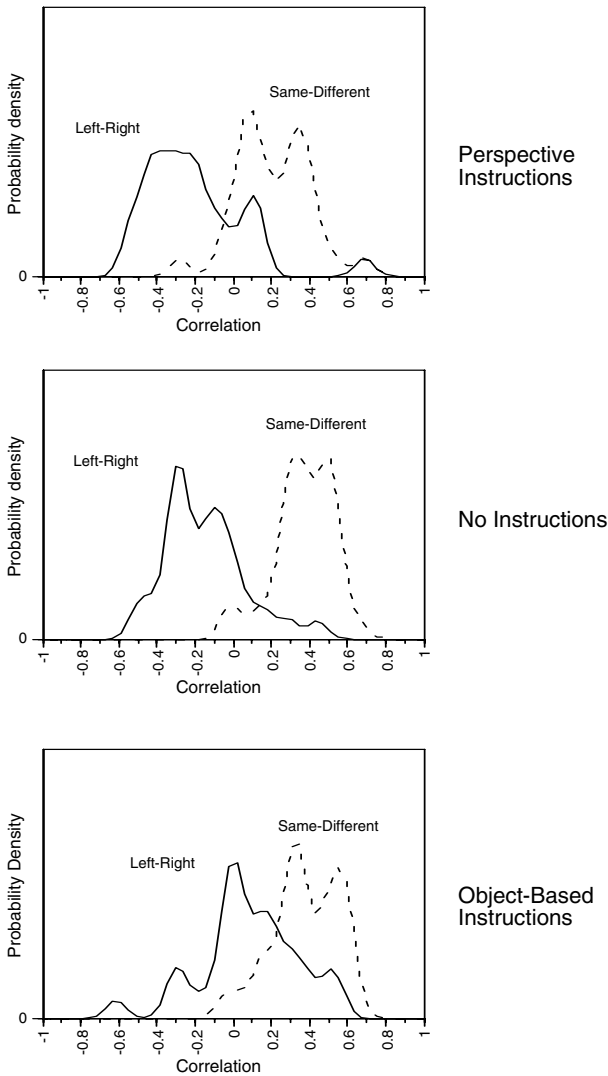
Figure 4. Distributions of correlations between stimulus orientation and response time, as a function of the judgment answered (left-right or same-different) and the instructions given for solving the problems (imagine yourself moving, imagine the picture moving, or none). Data are from Experiment 1. (For this figure and Figure 7, density functions were calculated by kernel estimation with a gaussian kernel of bandwidth .05.)

Discussion

As predicted by the multiple systems analysis, behavioral performance in the left-right and same-different tasks with bodies was affected systematically by explicit instructions regarding how to perform the task. When the instructions were inconsistent with the hypothesized natural transformation, performance was slowed and response time profiles were altered toward the instructed transformation. When the instructions were consistent with the hypothesized natural transformation, there was little effect on behavioral performance. That is, the framework predicted effects of both task and instructions on both overall difficulty and on the response time profiles, which were borne out by the data.

The data show that both direct instruction and judgment task manipulations can affect task performance. Further, they indicate that the two methods for studying mental spatial transformations can be fruitfully combined. In our framework, the task manipulation (same-different vs. left-right) was predicted to affect which spatial transformation system was brought to bear. Direct instruction was also predicted to affect which system was selected. Combining the two approaches allowed testing of detailed predictions of the multiple systems framework: a complex interaction in the response time profiles and a parallel interaction in the overall response times.

Experiment 2: Transformations of Bodies and Objects

The results of Experiment 1 provide support for the view that pictures of bodies afford both object-based and perspective transformations, depending on the judgment task performed. The multiple systems analysis implies not only that the transformation evoked should depend on the judgment required, but also that this dependence should be affected by the stimulus depicted. Experiment 2 tested this hypothesis. Participants performed left-right and same-different judgments about both bodies and small, manipulable objects. We predicted that for pictures of bodies the results would replicate those of the no-instructions condition of Experiment 1: increasing response time with increasing rotation for same-different judgments but not left-right judgments, reflecting object-based and perspective transformations, respectively. For pictures of objects, we predicted that participants would tend to perform object-based transformations for both tasks, leading to increases in response time with increasing orientation for both tasks. To test these hypotheses, we manipulated both the task performed (same-different or left-right judgments) and the stimulus materials (pictures of bodies and objects).

In this experiment, we also introduced a converging measure of spatial transformation use: introspective reports. We hypothesized that participants' introspections would correspond with the multiple systems interpretation of the chronometric performance of the participants in that experiment. That is, when making judgments about pictures of bodies participants would report using perspective transformations for the left-right task and object-based transformations for the same-different task, but when making judgments about

A.
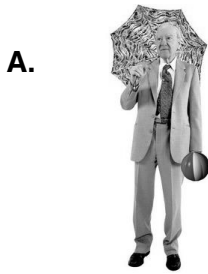
B.

Would the ball be in the same   Is the ball in the boy's left or
hand of each man?   right hand?s
(Correct: "no")   (Correct: "left")

C.

D.

Would the point of the iron   Would the bait on the
be near the same hand?   mouse trap be near
(Correct: "yes")   Leslie's left or right hand?
                                              (Correct: "right")

Figure 5. Tasks and example stimuli for Experiment 2.
A: Same-different judgments bout bodies; B: left-right
judgments about bodies; C: same-different judgments
about objects; D: left-right judgments about objects.

pictures of objects participants would report using object-based transformations for both the left-right and same-different tasks.

Method

Participants.   Participants were recruited from the Washington University community. Forty volunteers (29 female, mean age 20.1 years, range 18-25) participated in exchange for course credit or $10. One additional participant was replaced due to experimenter error, and four were replaced due to high error rates (see below).

Spatial reasoning tasks.   Each participant performed left-right and same-different tasks similar to those used in Experiment 1. However, rather than using line drawings of a single body, in this experiment we used color photographs of many bodies and many objects. The stimuli and tasks are illustrated in Figure 5. Photographs were taken from The Big Box of Art 800,000 (Hemera Inc., Gatineau, Quebec), and digitally edited. To create body stimuli, we selected bodies that were upright, photographed facing the camera, and had at least one arm extended. Both male and female pictures were selected, with a wide range of ages, ethnicities, poses, and costumes. For each body, an image of a rainbow-colored beach ball was edited in to mark the person's outstretched arm, and 12 versions were created by rotating the picture in 30-degree increments in the picture plane,. Another 12 versions were created by making a mirror image and then performing the same rotations. To create object stimuli, we selected objects that were photographed upright, and that had a clear left-right asymmetry in the plane of the photograph. A range of everyday objects was selected. For each object, 12 versions were created by rotating the object in 30-degree increments, and then superimposing it on a picture of a woman, photographed from the waist up, facing the camera with both arms outstretched toward the camera. This resulted in an image that looked as though the woman was reaching out to grab the object (see Figure 5). Another 12 versions were created by making a mirror image before rotating and superimposing. The objects and parts used are given in Table 1. The complete stimulus set is available from http://dcl.wustl.edu/research.html.

For all tasks, each trial began with a question, presented in the middle of the screen, which remained on screen until the participant pressed the middle button on a 3-button button box. The question was then replaced by one or two pictures, which remained on the screen until the participant responded by pressing the left or right button. Upon responding, the computer sounded a beep (for correct responses) or a buzz (for errors) and went on to the next trial.

For the same-different task with bodies, the question presented was "Would the ball be in the same hand of each X?" with "X" replaced by "man," "woman," "boy", or "girl," as appropriate. After the participant pressed the button, two of the body pictures were presented, one above the other. The top body was always upright. The bottom body was presented at a randomly chosen orientation, and could be either the same or the mirror image. For the left-right task with bodies, the question presented was "Is the ball in the X's left

Table 1
Objects and Object Parts Used in Experiment 2

Object	Part	Object	Part
coffee grinder	handle	mouse trap	bait
duck decoy	head	watering nozzle	spout
wooden shoe	toe	paring knife	blade
iron	point	pepper mill	handle
pot	handle	perfume bottle	bulb
teakettle	spout	walkie talkie	antenna
saucepan	handle	spray bottle	trigger
creamer	spout	teapot	spout
desk lamp	bulb	cooler	spout
mixer	beaters	toy car	grille
elephant figurine	trunk	toy dinosaur	head
blender	handle	gun	barrel
food processor	handle	toy rhino	head
skillet	handle	toy truck	cab
hand vacuum	handle	squirt gun	barrel
ice cream scoop	bowl	watering can	spout

or right hand?" with "X" replaced by "man," "woman," "boy", or "girl," as appropriate. After the participant pressed the button, one of the body pictures was presented, and the participant answered whether the ball was in the person's left or right hand.

For same-different judgments about objects, the question presented was "Would the X on each Y be near the same hand?" with X replaced by the name of a distinctive part of the object to be shown, and Y replaced by the name of the object. After the participant pressed the button, two of the object pictures were presented, one above the other. The top object was always upright. The bottom object was presented at a randomly chosen orientation, and could be either the same or the mirror image. For left-right judgments about objects, the question was "Would the X on the Y be near Leslie's left or right hand?" with X and Y replaced by the name of a distinctive part and the name of the object, respectively. After the participant pressed the button, one of the object pictures was presented, and the participant answered whether the named part would be near the woman's left or right hand if upright.

Introspective report questionnaire. Participants reported on how they solved the spatial judgment problems using a brief questionnaire. The questionnaire consisted of two sets of four questions each. The first set of questions asked participants to describe in their own words how they had solved the problems in each of the four blocks of trials. The second set of questions allowed them to indicate explicitly whether they had performed object-based transformations

and/or perspective transformations by endorsing one of four sentences. The first, "I imagined the picture moving," describes an object-based transformation. The second, "I imagined myself moving," described a perspective transformation. The third allowed them to indicate they had done both, and the fourth allowed them to indicate they had done neither. The four options were always presented in this order.

Procedure. Participants were tested individually. After providing informed consent, each completed a set of training trials with detailed on-screen instructions. The training program presented 16 trials for each combination of stimulus set and task. Participants were given the opportunity to repeat the training if they felt they still had questions. Before each block of trials, the computer displayed brief instructions to remind them of the task to be performed. For each combination of task and stimulus set, a block of 96 trials was presented. For all tasks, the identity of the body or object, rotation amount (0-180 degrees, in 30-degree increments), direction of rotation (clockwise or counter-clockwise), and handedness (left or right) were randomly selected on each trail. (Because the 0 and 180 degree rotations are identical for clockwise and counterclockwise rotations, these were tested only once. This differed from Experiment 1, hence the slightly smaller number of trials.) For both versions of the same-different task, whether the two pictures matched or mismatched was randomly varied from trial to trial. The identity of the object or body was counterbalanced within participants for each combination of task and stimulus set, as were rotation amount, direction of rotation, handedness, and matching; however, it was not possible to arrange that each body or object appear in all configurations (which would have required 12,288 trials per participant), so the relationship between identity and the other variables was randomized. For the same-different task, the assignment of the two buttons to "yes" and "no" was counterbalanced across participants. The order of stimulus sets (bodies vs. objects) and tasks (left-right vs. same-different) was counterbalanced across participants. For each stimulus set, the two tasks were performed one after the other, with the same task order for the two stimulus sets.

After completing the computer-based tasks, participants completed the introspective report questionnaire. They were then debriefed and excused.

Results

As in Experiment 1, participants with an error rate greater than 25% in any block, or greater than 15% overall, were eliminated from the analyses and replaced. This resulted in replacement of 4 participants. For the remainder, the error rate was low (5.52%) and consistent across conditions. For same-different judgments, the mean error rate was 5.08% for pictures of bodies and 5.57% for pictures of objects. For left-right judgments, the mean error rate was 3.31% for pictures of bodies and 8.57% for pictures of objects. (These error rates are slightly higher than those in Experiment 1, likely due to the more complex tasks and pictures.) Response time analyses were performed on correct trials only and outliers (1.8% of correct trials) were trimmed as described in Experiment 1.
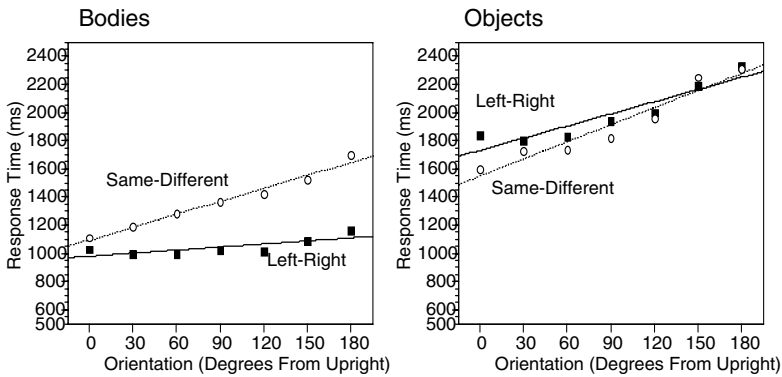
Figure 6. The relationship between stimulus orientation and response time as a function of the judgment answered (left-right or same-different) and the stimulus set (bodies or objects). Data are from Experiment 2.

Effects of task and stimulus manipulation on chronometric performance. Response time patterns were analyzed as for Experiment 1. Figure 6 shows mean response times as a function of orientation, task, and stimulus set. For judgments about bodies, response time increased more with increasing orientation for the left-right task than for the same-different task. However, for judgments about objects response time increased substantially with orientation for both tasks. This led to a statistically significant main effect of orientation, $F(6, 234) = 60.4$, $p < .001$, significant two-way interactions between orientation and task, $F(6, 234) = 10.8$, $p < .001$, and between orientation and stimulus set, $F(6, 234) = 7.75$, $p < .001$, and a marginally significant three-way interaction between orientation, task, and stimulus set, $F(6, 234) = 2.06$, $p = .06$.

As can be seen in Figure 7, the pattern of correlations was consistent with the pattern of mean response times: For judgments about bodies, correlations were robustly positive for the same-different task (mean $r = 0.38$, $SD = 0.20$), but close to zero for the left-right task (mean $r = 0.08$, $SD = 0.05$). For judgments about objects, however, correlations were positive for both the same-different task (mean $r = 0.32$, $SD = 0.03$) and the left-right task (mean $r = 0.21$, $SD = 0.03$). This led to a significant main effect of task, $F(1, 39) = 52.40$, $p < .001$, and a significant task by stimulus set interaction, $F(1, 39) = 10.1$, $p = .003$. Although correlations were higher for judgments about objects than judgments about phones, in this experiment the main effect failed to reach statistical significance, $F(1, 39) = 0.85$, $p = .36$.
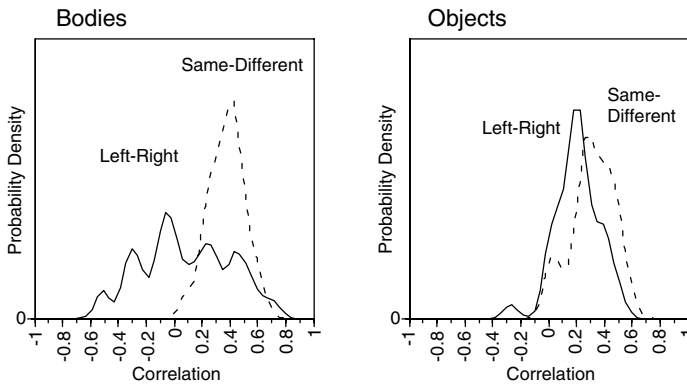
Figure 7. Distributions of correlations between stimulus orientation and response time, as a function of the judgment answered (left-right or same-different) and the stimulus set (bodies or objects). Data are from Experiment 2.

Introspective reports. Two coders, who had participated in collection of the data and were familiar with the general aims of the research, scored whether each of the free responses included mention of perspective transformations, object-based transformations, or "other" strategies. The wording of the questions made it impossible to blind the coders to the participant's condition, but the coders were blind to the participant's responses to the structured questions. Participants did not necessarily describe their problem-solving in terms of imagined spatial transformations: In some cases, participants described image visualization but no transformation, e.g., "looked at it, pictured it in 3-D, imagined it coming straight out of the page." In other cases they focused on the features they used to make the judgments, e.g., "same general shape, same elements on each phone." These were coded as "other." The coders agreed nearly perfectly: Of the 160 responses, the two coders disagreed on one instance of perspective transformations, one instance of object-based transformations, and four instances of "other" responses. Questions for which the coders disagreed were excluded from analysis.

The introspective report data are presented in Table 2. For judgments about bodies, introspective reports depended on the task: Participants were relatively more likely to report performing an object-based transformation, and less likely to report performing a perspective transformation, for same-different judgments than left-right judgments. For judgments about objects this task-dependence was reduced, and participants overwhelmingly reported performing object-based transformations for both types of judgment. This was true for both the free response data and the structured responses. Fisher's tests of goodness-of-fit

Table 2
Introspective Judgments in Experiment

	Free responses			*Structured responses*	
Condition	Perspective	Object-based	"Other"	Perspective	Object-based
Body					
Same-Different	3	36	9	5	36
Left-Right	19	18	16	19	23
Object					
Same-Different	1	35	10	2	40
Left-Right	7	34	18	9	36

Note. All counts are based on a total of 40 participants. Counts do not necessarily sum to 40, because multiple categories may be coded for one participant, and for a small number of free responses the two coders disagreed.

indicated that the frequency of perspective transformations and of object-based transformations varied across the four conditions, for both the free and structured responses (all p's < .001).

Discussion

This experiment tested the proposals of the multiple systems view that people's use of object-based or perspective transformations depends on both the judgment required and the stimulus about which the judgment is made. Patterns of response time provided robust support for both hypotheses. Response time was more strongly related to stimulus orientation for same-different judgments than left-right judgments, and more strongly related to stimulus orientation for judgments about objects than for judgments about bodies.

An important consideration in interpreting these results is that the geometry of the relationship between the viewer and the target of the spatial judgment was identical across all combinations of stimulus set and judgment task. Thus, differences in the patterns of response time cannot be attributed to differences in the geometry of the necessary realignment.[5]

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[5] This does not rule out the possibility that participants varied in the path of the transformation used to achieve that realignment, rather than in the type of transformation performed. But this explanation is highly unparsimonious in that it requires postulating multiple paths for the same geometry, only one of which can be the optimal path, and requires a *post hoc* explanation of why different paths would be chosen.

Because this experiment tested multiple bodies in different poses, and multiple objects, it provides evidence that these patterns generalize to bodies and small manipulable objects as classes. An interesting question for future research is how these patterns may change for stimuli that are somewhere in between a body and an object, such as stick figures, sculptures, dolls, or teddy bears.

Participants' introspective reports agreed well with the pattern of response times: Participants overwhelmingly reported performing object-based transformations for all conditions except for left-right judgments about bodies. This provides converging evidence that the transformation performed depended on both the stimulus shown and the judgment required. Overall, participants overwhelmingly tended to report performing object-based transformations. This could reflect either a reporting bias, or an overall tendency to favor object-based transformations in these sorts of tasks.

Although the introspective reports converge with the chronometric patterns in this experiment, some caveats are in order. One concern is that they may be sensitive to implicit task demands engendered by the contrast set of tasks and stimuli used. In other words, participants who perform a number of trials in different conditions may expect that they should report different transformations for the different conditions. Another concern is that participants may form their own theories of the task over the course of exposure to different task conditions. To minimize these effects on introspective judgments, we conducted a final study in which self-report data were collected after a single trial of one of the spatial reasoning task conditions.

Experiment 3: Spontaneous Descriptions of Mental Spatial Transformations

The primary goal of the final experiment was to replicate the introspective report paradigm of Experiment 2 while minimizing the influence of task demands or implicit theories on participants' introspections. To do so, we adopted a "one shot" methodology: All manipulations were performed between participants, and each participant performed only one spatial judgment trial, after which they reported how they solved the problem.

Method

Participants.   The experiment was presented as part of a packet of questionnaires administered in a large group.   The participants were 169 Washington University undergraduates who took part in partial fulfillment of a course requirement.

Materials. To keep the instructions simple and minimize extraneous item variability, we used the tasks from Experiment 1, and used one body picture (see Figure 1) and one object picture, which depicted a cellular telephone (see Figure 8). The telephone was chosen because it is a small manipulable object with an obvious asymmetry (the antenna). Each questionnaire consisted of four
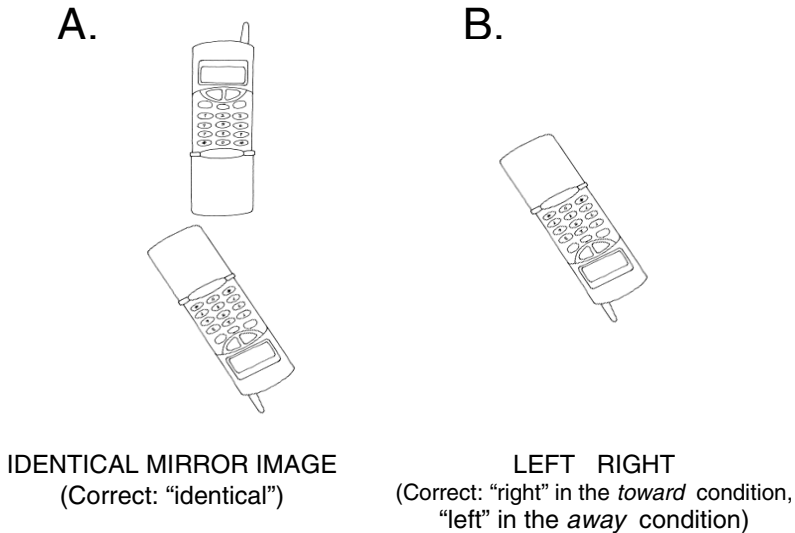
A.   B.

IDENTICAL MIRROR IMAGE   LEFT   RIGHT
(Correct: "identical")   (Correct: "right" in the *toward* condition,
                                       "left" in the *away* condition)

Figure 8.   Tasks and stimuli for judgments about cell phones in
Experiment 3. A: Same-different task; B: left-right task. The labels in
capital letters were printed in this format for the participants.

pages, which presented one trial of one of the spatial reasoning tasks, and asked
two self report questions about how the participant had performed the task. The
first page described the task to be performed. The second page showed the
stimuli and the response options. The third page asked the self report questions
and provided space for responses, and the final page provided a brief
explanation of the study for pedagogical purposes.

On the second page of the questionnaire, each participant was asked to make
either a same-different judgment or a left-right judgment about either a body or
a phone. For the phones, there is an ambiguity in the left-right judgments that is
not present for bodies: Should the participant describe the phone as if it were
facing with the keypad held *toward* themselves or *away* from themselves? We
disambiguated this by explicitly instructing the participants which interpretation
to adopt in the task instructions. Thus, there were five experimental conditions:
same-different judgments about bodies, left-right judgments about bodies, same-
different judgments about phones, left-right judgments about phones under
"away" instructions, and left-right judgments about phones under "toward"
instructions.

For the left-right task, one picture was shown. For both tasks, the single or
bottom picture was rotated 150 degrees clockwise from upright.   For all
versions of the questionnaire, the arm or antenna that was extended was
depicted such that it would be on the viewer's right if the picture were upright.
For the same-different stimuli, the pictures were identical. The left-right stimuli

Table 3
Errors and Introspective Judgments in Experiment 3

Condition	N	Errors	Free responses			Structured responses	
			Perspective	Object-based	"Other"	Perspective	Object-based
Body							
Same-Different	34	1	0	19	14	4	25
Left-Right	34	6	15	6	7	17	8
Phone							
Same-Different	34	2	0	12	20	2	25
Left-Right (away)	33	11	0	20	2	0	22
Left-Right (toward)	34	0	0	29	5	1	32

Note. For free responses, categories sum to the number of error-free responses.   For structured responses this is not necessarily so, because "both" and "neither" responses are included.

were the same as the bottom pictures in the same-different stimuli. Thus, the correct answer for both same-different conditions was "same," the correct answer for the left-right bodies condition and the same-different phones (away) condition was "left," and the correct answer for the left-right phones (toward) condition was "right."

After completing the mental transformation trial, the participants were queried about how they had solved the problem, using the same procedure as in Experiment 2. The first question asked them to "describe briefly your strategy for answering the question," and provided space to do so. The second question asked them to endorse one of four sentences to best characterize how they solved the problem. The first, "I imagined the picture moving," describes an object-based transformation.   The second, "I imagined myself moving," described a perspective transformation. The third allowed them to indicate they had done both, and the fourth allowed them to indicate they had done neither. The four options were always presented in this order.

Results and Discussion

Of the 169 questionnaires returned, there were 33 from the left-right phones (away) condition, and 34 from each of the other four conditions. Error rates were low except for the left-right phones (away) condition (11 of 33; see Table 3). Only questionnaires with correct responses were used in the analyses of the strategy questions reported here.   (Inspection showed the data for the participants who made errors were not substantially different from the rest.)

One coder scored each of the free responses as describing an object-based transformation, a perspective transformation, or "other." (An exclusive coding was used here, unlike in Experiment 2, because the responses were based on a single trial rather than many trials, over which the participant's strategy may

have changed.) The coder was familiar with the general line of research and with the definitions of each transformation type, and was blind to condition and to the participant's response to the structured question. Of the 149 forms with correct responses, 48 were scored as "other." These were distributed across the experimental conditions as shown in Table 3.

As Table 3 indicates, the pattern of the free response data is quite clear. When participants were shown pictures of bodies, their responses depended on the task: For the left-right task, 71% of those who described a spatial transformation reported performing a perspective transformation, but for the same-different task, all participants who described a transformation reported performing an object-based transformation. When participants were shown pictures of phones their responses were consistently object-based and independent of task: For both tasks, all participants who described transformations reported performing an object-based transformation. Fisher's exact test of goodness of fit showed the differences of proportions of perspective and object-based transformations across conditions to be statistically significant, $p < .001$.

The results of the structured responses were similar. In this case, participants had the option to endorse either both types of transformation or neither. For pictures of bodies, responses depended on the task: After making a left-right judgment, 63% of participants reported performing a perspective transformation and 30% reported performing an object-based spatial transformation, whereas after making a same-different judgment 12% reported performing a perspective transformation and 76% reported performing an object-based transformation. For pictures of phones, the proportion of participants reporting perspective transformations was negligible (6% or less) for both same-different and left-right judgments. Fisher's exact test of goodness of fit showed the differences of proportions across conditions to be statistically significant, $p < .001$. As in Experiment 2, there was an overall tendency to report performing an object-based transformation, evident in both the free and structured responses.

In short, participants' introspections about their mental spatial transformations following one trial of one spatial reasoning condition replicated those collected with many trials of several spatial reasoning conditions (Experiment 2). Introspective reports were influenced both by the spatial reasoning task required and by the stimuli presented. Participants who viewed pictures of bodies were influenced by the judgment task required, tending to report object-based transformations for the same-different task and perspective transformations for the left-right task. In contrast, participants who viewed pictures of phones overwhelmingly reported performing object-based transformations, independent of the judgment required.

General Discussion

Interacting with the world requires anticipating the consequences of one's own behavior as well as the behavior of other people and things. This, in turn,

requires using the present state to predict future outcomes, be they social ("What would he do if I…?") or spatial ("Will this glass fit in the dishwasher?"), by imagining a transformation of the environment. The research reported here investigated two mental transformations prominent in the spatial domain. People need to anticipate how objects will appear as those objects move, and people need to predict the consequences of their own movements. Each prediction relies on a different mental spatial transformation and is appropriate for a different set of circumstances. Mental life is fortunately flexible, so that mental transformations developed for one task can be co-opted for others.

The multiple systems framework provides an integrative theoretical basis for thinking about how spatial transformations relate to perceptual experience, how they are implemented by the brain, and when they will be performed. The experiments reported here provided tests of three central proposals of the framework. First, these data indicate that which transformation is evoked depends on the spatial judgment required. All three experiments indicated that, when the stimulus permits it, the two classes of transformation are preferred for different tasks: For pictures of bodies people appear to prefer to use object-based transformations to make same-different judgments and perspective transformations to make left-right judgments (see also Zacks, Mires et al., 2002). Object-based transformations afford efficient solution of same-different problems because they allow comparison in a common reference frame. Participants are asked to make a judgment that depends on the relationship between configurations in the two objects' reference frames, which are different from each other. By performing an object-based transformation, one can align the objects relative to the egocentric and environmental reference frames, such that features can be compared in a single reference frame. Perspective transformations afford efficient solution of left-right problems because the left-right axis is a prominent feature of one's own body's reference frame; aligning one's egocentric reference frame with that of a depicted object allows one to "read off" the correct response in the transformed reference frame.

Second, the data support the proposal that which transformation is evoked depends on the stimulus depicted. In Experiments 2 and 3, participants reported that for pictures of small objects, they used object-based transformations, but for judgments about bodies which transformation was used depended on the task. In Experiment 2, this led to response time patterns that were consistent with this proposal. This supports the claim of the multiple systems framework that imagined visuospatial transformations reflect our habitual experience of actual spatial transformations. People often have experiences in which people move around us, behaving as objects; but people also have experiences in which movements of their egocentric reference frame is associated with the movements of their own body. When coordinating behavior, it is often important to predict both what the world will be like if someone moves, and what the world looks like from their perspective. For small objects, however, the range of typical experiences is different. It is often important to predict

what the world would be like if an object were to move, but rarely important to predict what the world looks like to a telephone or a clothes iron. It would be very interesting to test how the patterns described here generalize to classes of object that are intermediate between people and small manipulable objects, such as statues, teddy bears, and four-legged animals.

Finally, the data from Experiment 1 indicate that participants can flexibly employ either object-based or perspective transformations when instructed to do so, and that this has predictable consequences for behavior. Most important, when people are asked to adopt a strategy that conflicts with the natural mappings predicted by the multiple systems framework, performance was less efficient.

Combining the Direct Instruction and Judgment Task Approaches

In Experiments 1 and 2, manipulating the judgment task (same-different vs. left-right) systematically influenced response time profiles, as predicted by the multiple systems framework. In Experiment 3, the same manipulation affected introspective reports of spatial transformation use. This finding illustrates the utility of the judgment task approach. In Experiment 1, the judgment task manipulation was combined with a manipulation of the direct instructions given to participants, leading to complex interactions between judgment task, instructions, and stimulus orientation, which were consistent with the multiple systems framework. These findings suggest it may be fruitful to consider jointly the effects of imagery instructions together with manipulations of task parameters to more tightly constrain theories of mental spatial transformations.

Spatial Judgments and the Focus on Mental Rotation

There is a long tradition in cognitive psychology of using spatial judgment tasks to study mental spatial transformations, and the current experiments fall squarely within this tradition. In studies such as these, participants are asked to make spatial judgments about physically presented stimuli, but it is hypothesized that a mental image must be formed and manipulated in order to make the judgment. Experimenters have used a range of judgment tasks, prominently including same-different judgments (e.g., M. S. Cohen et al., 1996; e.g., Shepard & Metzler, 1971) and left-right judgments (e.g., Cooper & Shepard, 1973; Parsons et al., 1995) such as those used here[6] as well as object identification judgments (e.g., Biederman, 1987; e.g., Tarr & Pinker, 1989). (It is currently a matter of some debate whether the recognition of objects at

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[6] Several experimenters have used alphanumeric characters for spatial judgment tasks. In these tasks the participant is asked whether the letter is normal or mirror-reversed. This is equivalent to a left-right judgment, because in both cases the stimulus has a left-right asymmetry and the participant is reporting which version is being shown. For simplicity, we refer to these as left-right judgments, but "judgments of chirality" is a more precise description.

unfamiliar orientations is accomplished by a spatial transformation, some other normalization procedure, or the use of orientation-invariant features.) Stimuli employed have included alphanumeric characters, hands, bodies, common objects, wire-frame objects and abstract 3-dimensional figures. However, these studies are striking in that virtually all have focused on one particular object-based spatial transformation: mental rotation.   Other object-based transformations such as object translation and scaling have received much less attention (but see Bennett & Warren, 2002; Bundesen & Larsen, 1975; Larsen & Bundesen, 1978, 1998; Larsen, Bundesen, Kyllingsbaek, Paulson, & Law, 2000), and perspective transformations have gone virtually uninvestigated in studies using these paradigms (but see Parsons, 1987; Zacks, Mires et al., 2002). The neglect of other mental spatial transformations in the context of judgment tasks is curious given that in richer tasks, such as learning environments and understanding narratives, other mental spatial transformations have received considerable attention.   In the spatial navigation literature, perspective transformations have been regarded as fundamental and have been studied intensively (Easton & Sholl, 1995; Farrell & Robertson, 1998; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Loomis, da Silva, Fujita, & Fukusima, 1992; Rieser, 1989).   When comprehending narratives, readers can imagine themselves in space and update their locations in scenes entirely by description (Franklin & Tversky, 1990). Readers can imagine either themselves turning within an scene or objects in the scene turning around them, depending on the point of view established by the narrative or the explicit instructions provided (Franklin, Tversky, & Coon, 1992; Tversky, Kim, & Cohen, 1999). In addition to self-movement, narrative comprehension requires imagining movements of story protagonists, which are also egocentric transformations because readers are hypothesized to place themselves in the position of the protagonist (Bower & Morrow, 1990; Bower & Rinck, 2001; Bryant, Tversky, & Franklin, 1992; Franklin & Tversky, 1990; Morrow, Bower, & Greenspan, 1989; Morrow, Greenspan, & Bower, 1987; Rinck & Bower, 2000; Rinck, Haehnel, Bower, & Glowalla, 1997; Rinck, Williams, Bower, & Becker, 1996). The present results suggest that issues raised by studies of navigation and narrative understanding can be fruitfully investigated using the judgment task approach (See also Franklin & Tversky, 1990; Tversky et al., 1999).

The Role of the Multiple Systems Framework

The multiple systems framework organizes proposals that are explicit or implicit in previous research on spatial cognition and its neural basis (Zacks & Michelon, in press). It is compatible with broader theories of mental imagery (e.g., Kosslyn, 1994, see esp. Ch. 10-11).   The power of this view is that consideration of the adaptive value of multiple spatial transformations and the facts of perception make specific predictions about behavior and neurophysiology. First, this reasoning allows prediction of the circumstances favoring particular spatial transformations (see "Converging Approaches," above).   Second, reasoning about the adaptive value of multiple spatial

transformations allows prediction of specific behavioral patterns that should result from particular mental spatial transformations. The fact that the complex behavioral pattern observed here can be (mostly) accounted for by this reasoning provides strong support for the multiple systems framework. Third, the multiple systems framework allows integration of behavioral, neuropsychological, and neurophysiological data. In particular, neuroimaging data (Creem et al., 2001; Zacks, Ollinger et al., 2002; Zacks, Rypma, Gabrieli, Tversky, & Glover, 1999; Zacks et al., 2003) and individual differences data (Hegarty & Kozhevnikov, 1999; Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001) support distinct processing components subserving aspects of object-based and perspective transformations. Finally, the multiple systems framework provides a means to integrate direct instruction and judgment task approaches to studying mental spatial transformations. The present research provides an example of the payoffs of this integrative approach; we hope it will also be of value in studying other classes of spatial transformation, such as imagined movements of parts of the body.

Acknowledgments

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