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Embodied Spatial Transformations: "Body Analogy" for the Mental Rotation of Objects

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The cognitive advantage of imagined spatial transformations of the human body over that of more unfamiliar objects (e.g., Shepard–Metzler [S-M] cubes) is an issue for validating motor theories of visual perception. In 6 experiments, the authors show that providing S-M cubes with body characteristics (e.g., by adding a head to S-M cubes to evoke a posture) facilitates the mapping of the cognitive coordinate system of one's body onto the abstract shape. In turn, this spatial embodiment improves object shape matching. Thanks to the increased cohesiveness of human posture in people's body schema, imagined transformations of the body operate in a less piecemeal fashion as compared with objects (S-M cubes or swing-arm desk lamps) under a similar spatial configuration, provided that the pose can be embodied. If the pose cannot be emulated (covert imitation) by the sensorimotor system, the facilitation due to motoric embodiment will also be disrupted.

Keywords: embodied cognition, body schema, shape matching, mental rotation, emulation

Humans often use metaphors to conceptualize abstract notions in concrete ways (e.g., spatial metaphors help describe temporal relationships; see Boroditsky, 2000). Embodied theories of conceptual representation propose that the human sensorimotor system may serve to embody abstract ideas (Gallese & Lakoff, 2005; Lakoff & Johnson, 1999). Precisely, if "ideas are objects" and "understanding is grasping" (Lakoff & Johnson, 1999, pp. 124–125), one would expect sensorimotor brain areas of the hand to be activated when reading either literal or metaphoric hand sentences (e.g., "She *grabbed* the fruit" vs. "The ideas slipped through his *fingers*," respectively) but not in response to nonhand control sentences. This prediction was indeed confirmed by Rohrer (2005) in a functional magnetic resonance imaging (fMRI) study that extended to the metaphorical domain similar findings of somatotopic brain correlates (i.e., the brain area corresponding to the limb) to literal hand–foot action words or sentences (Buccino et al., 2005; Hauk, Johnsrude, & Pulvermüller, 2004).

Given that people can use their bodies as a metaphor to comprehend abstract concepts such as time (e.g., "The hard times are *behind* us" or "I'm looking *forward* to a brighter tomorrow"), one might wonder whether "abstract" 3-D shapes such as Shepard and Metzler's (1971) arrangements of cubes (S-M cubes) can be embodied as well for facilitating object recognition. What features of a stimulus elicit body representations for mental spatial transformations? What are the computational consequences of performing a shape-matching task using an embodied transformation? These different issues are relevant to the fields of spatial cognition, object recognition, and imitation, as well as for validating motor theories of visual perception, according to which perception and action share a common representational domain (Hommel, Müsseler, Aschersleben, & Prinz, 2001; O'Regan & Noë, 2001). Although Wilson (2002) discussed six divergent kinds of views on embodied cognition within cognitive psychology and Rohrer (in press) identified 12 differing dimensions of the term *embodiment* at work in the cross-disciplinary literature on mental rotation and spatial language, we should note that our use of such terminology refers simply to the general idea that cognition is for action and can be well understood only by taking into account the body and its spatial and motoric representations.

Two kinds of embodiment can be invoked to explain how embodied spatial transformations are performed. First, body analogy can be implemented through *spatial embodiment*, or what Lakoff and Johnson (1999) have called the "bodily projection" of reference frames, whereby body axes (head–feet, front–back, and left–right) are mapped onto the embodied object, such as in "As the bus was approaching, he fell *in front*" or "He is hidden *behind* the tree." However, in the former example, the language is still ambiguous, because "in front" may indicate either that the character fell between the speaker–viewer and the bus or that he fell close to the bus front bumper, depending on whether the spatial reference is viewer centered (*egocentric* or *deictic*) or object centered (*exocentric* or *intrinsic*), respectively. Buses have intrinsic front and rear parts because the body axes of the driver are mapped–projected onto the bus. In contrast, because trees have no intrinsic front or back (contrary to vehicles), "front" refers to the

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part of the tree people see, whereas "behind" designates its occluded side. Of interest, when a narrative uses intrinsic rather than deictic spatial terms for describing a scene, readers prefer to embody the figure–object that provides the reference frame used to describe the scene (Bryant, Tversky, & Franklin, 1992). Thereby, although any perspective can be assumed, readers espouse the point of view of the embodied figure–object.

Second, motoric embodiment has received support from behavioral and neuroimaging data suggesting that observing, imagining, or executing actions exploits the same motor representations (see Decety, 2002, for a review). For example, when photographs of a human body, or mannequin, are sequentially presented at slow temporal rates, observers report paths of apparent motion that are consistent with the movement limitations of the human body (e.g., Chatterjee, Freyd, & Shiffrar, 1996; Kourtzi & Shiffrar, 1999). The fact that the perception of actions seems to be mediated by implicit knowledge of the anatomical and biomechanical constraints of the human body is consistent with motoric embodiment. Similarly, Daems and Verfaillie (1999) found long-term facilitatory priming when identifying anatomically possible postures but not for poses that are impossible for the human body to perform. Evidence for the role of biomechanical constraints on imagined action comes from psychophysical data in tasks where subjects must decide whether a randomly oriented body part belongs to the left or right side of the body (e.g., Cooper & Shepard, 1975; Parsons, 1987b, 1994). The time needed to perform this handedness judgment of a single visually presented human hand corresponds closely to the time needed to mentally simulate one's hand motion to the orientation of that hand, and the time needed for the corresponding real action (Parsons, 1987b, 1994). The mental chronometric reaction time (RT)-orientation patterns are not inevitably linear, as in the classic Metzler and Shepard (1974) studies of mental rotation, but strongly depend on the awkwardness of a movement of the depicted limb to the particular orientation (Parsons, 1987b, 1994). Neuroimaging studies aimed at dissociating visual and somatic processing have shown that brain regions activated by actual and imagined movement are strongly activated during these handedness judgments (Parsons & Fox, 1998).

Here, we theorized that bodylike stimuli afford embodied processing at both spatial and motoric levels. Both kinds of embodiment would in turn improve performance on the shape-matching task for both reference and comparison stimuli. Spatial embodiment would mediate encoding of the reference stimulus in terms of a body posture by mapping one's body axes onto the stimulus, on the basis of one's long-term knowledge of body structure. Simultaneously, motoric embodiment would occur, with the motor system covertly imitating the posture. Once the reference posture is embodied, then it would be rotated mentally in order to align it with the comparison posture. Motoric embodiment would help to maintain the postural spatial configuration during the mental rotation process. Because embodiment helps to encode and represent the spatial configuration of the rotated posture, embodiment and mental rotation processes can hardly be disentangled. Therefore, in order to study the computational consequences of embodied spatial transformations on shape matching we varied the body-likeness of the stimuli across experiments. Each of these issues is discussed in further detail in the next paragraphs.

Body knowledge, or the *body schema*, will be instantiated differently depending on whether embodied processing is being performed at the spatial or the motoric level. The body schema is a central concept in studies in which one's own body is the object to be spatially transformed (Reed, 2002). As a consequence of a lesion in a specific neural circuit, somatotopagnosia (Felician, Ceccaldi, Didic, Thinus-Blanc, & Poncet, 2003), a selective impairment in understanding body part names and particularly in locating them in space (whether on one's body—autotopagnosia—or on another person's or a doll's body—heterotopagnosia) may be observed (Denes, Cappelletti, Zilli, Dalla Porta, & Gallana, 2000; Felician et al., 2003; Shelton, Fouch, & Caramazza, 1998; Sirigu, Grafman, Bressler, & Sunderland, 1991). Neuropsychological evidence suggests that disorders of body knowledge could arise from the impairment of two distinct systems, the first containing semantic and lexical information (Coslett, Saffran, & Schwoebel, 2002; Le Clec'H et al., 2000) and the second storing a body-specific visuospatial representation (Guariglia, Piccardi, Puglisi Allegra, & Traballesi, 2002; Schwoebel & Coslett, 2005; Sirigu et al., 1991). The latter representation of the structure of the human body is reminiscent of Marr and Nishihara's (1978) theory of vision, in which the overall representation of the body and its parts would be a hierarchical set of interconnected elements, each defined by a volumetric primitive. The major axis of the human body would run from the head to the feet and be represented as a cylinder. The various parts of the body, such as the arms and legs, would have their own axes identified and be represented by cylinders as well. The fingers on the hand, the arms and legs on the body, and the whole body would make up such a descriptive hierarchy. We hypothesize that spatial embodiment relies on the instantiation of this structural level of description of body knowledge.

In contrast, motoric embodiment involves a sensorimotor instantiation of body knowledge via motor imagery. Consistent with this view is the fact that when individuals observe an action, neurons in premotor cortex "resonate" in a somatotopic manner, suggesting that the action is covertly reproduced (Buccino et al., 2001). This resonance would be part of an emulation process (Grush, 2004) that plays a role in representing and understanding the behavior of conspecifics (Wilson & Knoblich, 2005). The emulation hypothesis posits that motor centers generate an efferent copy of the motor commands that feeds an emulator of the musculoskeletal system. The function of this emulator is to predict the sensory consequences of the movement to "inform" the motor centers before the actual sensory feedback. Emulation stands in contrast to simulation accounts of motor imagery, whereby subliminal motor commands are supposedly "free spinning" (Jeannerod & Frak, 1999). Both the sensory and motor components of motoric embodiment are exemplified by the finding that phantom pain can be reduced in subjects with a lost or paralyzed limb if they are asked to match voluntary motor commands to a moving virtual replica of the impaired limb (Giraux & Sirigu, 2003). This suggests that emulation can restore the lost coherence in the sensorimotor inputs and outputs of the impaired limb. Likewise, the findings that observing the body of someone else being touched activates the same brain areas activated by the experience of being touched on one's body (Keysers et al., 2004) are consistent with an emulation account of motoric embodiment.

The Computational Consequences of Embodied Spatial Transformations

Typical mental rotation paradigms are shape-matching tasks requiring participants to decide whether objects pairs, presented in succession or simultaneously, are identical or different (i.e., mirror figures) across a variety of angular disparities in object orientation (Shepard & Cooper, 1982; Shepard & Metzler, 1971). The hypothesized cognitive processing stages for solving this 3-D shape-matching task are (a) perceptual encoding of both objects' shape and orientation, (b) mental rotation of the comparison object to align it to the reference object, (c) comparison between the mentally rotated comparison object and the perceptually available reference object, and (d) decision whether the objects' shapes match (P. A. Carpenter & Just, 1978). The behavioral signature of mental rotation for unfamiliar objects such as S-M arrangements of cubes is a monotonic increase of RTs with increasing angular difference between objects for correct responses when classifying objects as identical (Bauer & Jolicoeur, 1996; P. A. Carpenter & Just, 1978; Friedman & Hall, 1996; Metzler & Shepard, 1974; Parsons, 1987c). The intercept of the RT-orientation function (relating RT to angular disparity) is hypothesized to reflect encoding and decision processes; the slope reflects the time taken by the rotation process itself (Just & Carpenter, 1985).

Metzler and Shepard (1974) discussed mental rotation as an analogue top-down process that could be performed by mentally rotating the comparison object either as a unit or piece by piece (piecemeal rotation) to align it to the reference object. In both cases similar linear dependence of RT on angular disparity is predicted. In turn, error rates would be more sensitive than RTs to the effects of holistic versus piecemeal rotation. According to Hall and Friedman (1994), assuming that subjects compare a pair of S-M cubes by matching each corresponding bend (a three-dimensional L shape), each bend adds a potential source of error in the matching process. Actual mismatches will be detected if corresponding bends are from two different objects. Spurious mismatches will be detected if corresponding bends from a pair of identical objects are misaligned (e.g., at large angles of disparity) or if, owing to "noise," such bends are misrepresented. Following Kosslyn's (1981, 1991) theoretical approach on visuospatial cognition, this noise may have several origins. The visual buffer (visual working memory) would be inherently noisy: If object parts are rotated too far, they become too scrambled to be realigned by "cleanup routines." In addition, the visual buffer is a short-term memory storage system subject to decay; information is lost from the visual buffer via a passive process of fading. The visual buffer being the medium for both imaginal and perceptual visuospatial representations, there is also an interference between the rotated object (or its parts) and the visual input to be compared with. Finally, another source of error in the matching process is that each end of the comparison object is matched with its reference object counterpart, but the relationship between the rotated object ends is misrepresented. As a consequence of these different sources of error, response accuracy should degrade more rapidly as a function of angular disparity when adopting a piecemeal rather than a holistic mental rotation process.

Here, we theorized that performing a shape-matching task using an embodied transformation would produce different computational consequences. First, because of the increased cohesiveness of human posture by one's body schema (in terms of body structural description), we expected that mental rotation of human postures would operate in a less piecemeal fashion as compared with non-bodylike stimuli. Increased cohesiveness from spatial and motoric embodiment would in turn speed up the mental rotation and the shape-matching process, we believed, because the integrity of the rotated posture should better resist the distortions inherent to the visual buffer medium, with the amount of distortion increasing as the mental representation is rotated by greater angles at a step (Kosslyn, 1981). Our contention is that people are more likely to perform holistic rotation for matching human body shapes than for non-bodylike stimuli and that the holistic-versus-piecemeal distinction is most likely a matter of degree, not all or none. Moreover, as pointed out by Just and Carpenter (1985), if subjects have difficulty in representing the structure of an entire S-M figure at one time, then they will also have difficulty in rotating it at one time. Therefore, we theorized that although owing to decay and interference in the visual buffer a slight linear dependence of error rates on angular disparity might be observed for postures, greater orientation dependence would be observed for S-M cubes. Likewise, shape matching of body poses that are difficult to emulate would undergo equivalent damage.

The Present Study

Our main hypothesis is that if we embody (at both the spatial and motoric levels) an "abstract" 3-D shape (such as S-M cubes) by providing body characteristics to the shape, then the newly embodied shape stimuli will facilitate performance on the shape-matching task. However, if we cannot embody a pose (because the pose cannot be emulated on the basis of the musculoskeletal system properties), then, we predict, we should not get the full benefit of its "bodyness" for shape matching.

Sayeki (1981) added a human head to S-M cubes with spatial configurations suggesting a human posture, in a same–different mental rotation experiment, to trigger a "body analogy" process. He showed that these head-cubes figures not only increased mental rotation speed in the picture plane (RT-orientation slopes were almost flat) but also reduced error rates, as compared with similar S-M cubes without a head. These results can lead to two different interpretations: Either (a) the head acted as a spatial cue that polarized the S-M cubes and facilitated shape matching (in particular, the search for potentially matching ends or terminal arms of the figures; cf. Just & Carpenter, 1985), or (b) body analogy benefited from embodied processing whereas imagined transformation of abstract objects did not. Two other findings seem to favor the second interpretation. First, Parsons showed faster rates of picture-plane mental rotation for body (Parsons, 1987a) as compared with S-M cubes (Parsons, 1987c). Second, in an attempt to see whether it would facilitate performance on the shape-matching task, Metzler and Shepard (1974) investigated whether introducing color coding would minimize the need to search for the corresponding ends of their cube-object pairs and change the RT-orientation patterns of picture-plane mental rotation. It did neither, although research has shown that color coding might decrease overall RTs (Hall & Friedman, 1994). Therefore, although coloring the ends of the object pairs does not improve mental rotation speed, giving the shape a human posture and body characteristics does, in accordance with our embodiment hypothesis.

To understand the relative contribution of both the spatial and motoric levels of embodiment to successful body analogy, we manipulated the visual similarity between S-M cubes and human body during shape matching. Experiments 1 and 2 compared shape matching of S-M cubes with that of familiar (e.g., shaking hands) or unfamiliar (atypical postures defined by S-M-cubes configuration) human postures. We theorized that motoric embodiment would facilitate shape matching of familiar poses as compared with matching unfamiliar or atypical ones because the former would be easier to emulate. Experiments 3 and 4 examined which human body characteristics, when added to S-M cubes, facilitated the mapping of the body's cognitive coordinate system onto the S-M-cubes shape (spatial embodiment), and in turn the shape-matching process. To clarify whether the shape-matching performance differences for S-M cubes and posture can be attributed to spatial embodiment or differences in visual experience or familiarity, we studied shape matching of a familiar object in Experiment 5, namely, a desk lamp that provides characteristics similar to human bodies in terms of the multiple degrees of freedom of their joints and up–down orientation. Finally, Experiment 6 tested whether matching postures that are impossible (owing to a 180° rotation of the lower body around the trunk axis) would interfere with motoric embodiment and whether participants' subjective postural difficulty ratings of possible postures (if they were to actually perform the posture) would predict performance on shape matching of the latter, as expected under an emulation hypothesis.

Experiments 1–2: Comparing Object and Body Mental Rotation

Experiment 1

This first experiment compares mental rotation of S-M objects with that of familiar human postures, in the picture plane versus in depth around a vertical axis. In terms of rotation axis, it can be considered a partial replication of Parsons's (1987a, 1987c) studies, in which more rotation axes were investigated. However, it differs from these studies in several aspects. First, we used a same–different 3-D shape-matching task to compare performance at both stimulus pair types, whereas Parsons used different tasks in his two studies (left–right judgment of body poses vs. shape matching of S-M cubes). Second, we studied stimulus pair type among the same observers, rather than in different groups, as when comparing Parsons's (1987a, 1987c) studies. Finally, we examined both RTs and error rates as a function of orientation difference in stimuli, whereas Parsons (1987a, 1987c) was concerned mainly with RT functions. We theorized that human postures would enable embodied processing at both spatial and motoric levels, which in turn would improve shape-matching performance as compared with matching S-M cubes.

Method

Participants. A total of 18 individuals (19–49 years old) with normal or corrected-to-normal vision participated in this experiment.

Apparatus. The stimuli were displayed and the data collected by a PC using ERTS-VIPL, a PC-compatible software package that allows development and performance of psychological experiments (Beringer, 1994). Participants sat approximately 57 cm from a 21-in. monitor.

Stimuli. Six S-M objects and six body postures were created for the present experiment using Autodesk 3ds Max (http://www.autodesk.com/3dsmax). Three of each stimulus type (S-M cubes vs. postures) were used as original figures, and counterpart mirror figures were constructed from the latter. The original 3-D figures we used are displayed in Figure 1A. Each of the cube figures comprised 10 cubes and three right-angle bends. In contrast, the postures were similar to those used by Parsons (1987a) and Zacks, Mires, Tversky, and Hazeltine (2001; Zacks, Ollinger, Sheridan, & Tversky, 2002) and comprised one or two arm bends at elbow and shoulder.

For each trial, two figures of S-M cubes or body postures, either identical or mirror-image pairs, were presented simultaneously at orientations that differed by picture-plane (around the viewer's line of sight) or depth (around a vertical axis) rotations that ranged from 0° to 180° in 30° increments (see Figure 1B). The reference figures always appeared on the left side of the screen under a canonical upright orientation. Half of the

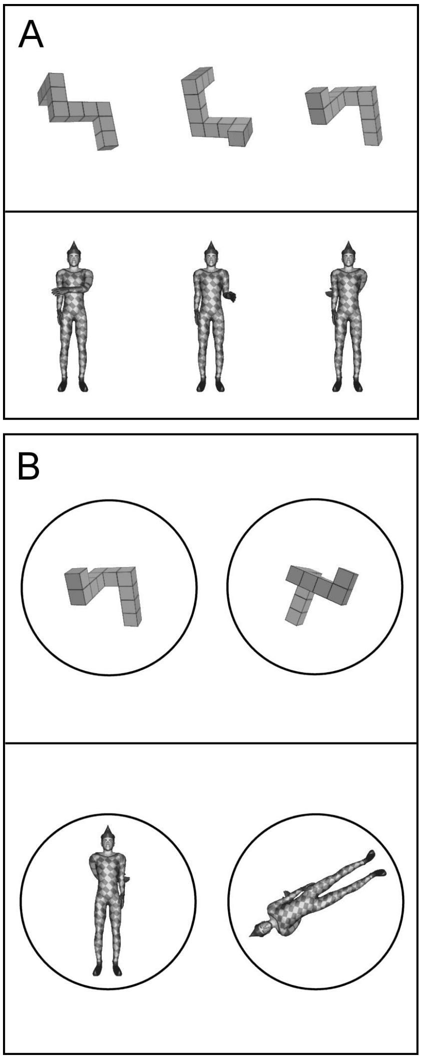

Figure 1. Experiment 1. A: Illustration of the original spatial configurations of Shepard–Metzler (S-M) cubes and posture stimuli. B: An example of "identical" trials of S-M-cubes pairs and posture pairs, for depth and picture-plane rotation, respectively.

Table 1
Mean Reaction Times for Correct Answers and Mean Error Rate at "Identical Pairs" for Experiment 1 as a Function of Stimulus Type and Rotation Type, Together With Rotation Slopes

Rotation and stimulus pair types	Reaction time (ms) *M*	Reaction time (ms) Slope (ms/degrees)	% error *M*	% error Slope (%/degrees)
Picture plane				
S-M cubes	3,853 (179)	19.29 [3.81]	18.5 (3.7)	0.19 [1.22]
Posture	2,120 (126)	6.98 [1.42]	5.2 (1.4)	*ns*
Depth				
S-M cubes	3,675 (176)	13.43 [2.21]	13.3 (2.9)	0.09 [0.77]
Posture	2,153 (95)	6.00 [1.98]	3.2 (0.9)	*ns*

Note. Values in parentheses are standard errors; values in brackets are Cohen's *d*s. S-M = Shepard–Metzler.

trials were identical-pair trials, whereas in the other half the figure pairs were different. Angular differences in stimulus pairs were obtained by a rotation of the comparison figure (whether identical or a mirror decoy) on the right side of the screen, either clockwise or counterclockwise relative to the reference figure. When the mirror figure was used as the reference figure (on the left side of the screen), the original figure was used as a decoy in the "different" trials (on the right side of the screen). In this experiment and the next ones, all of the stimuli (whether S-M cubes or postures) were pink colored and displayed against a gray background.

Procedure. A trial was initiated when participants pressed the space bar on the keyboard. A 1-s cleared screen was displayed, followed by a pair of figures, each of which was displayed inside a black circle whose diameter subtended 14° of visual angle (see Figure 1B). Participants were to determine as rapidly and accurately as possible whether the figures were the same (identical) or different (mirror figures), using the *Enter* or *Escape* key, respectively. The experimental session began with 12 practice trials not included for data analysis. Both practice and experimental trials were presented in a different random order for each participant without feedback. S-M-cubes-pair and posture-pair trials alternated randomly. If an RT exceeded the maximum 10-s display duration, a "Wake up!" message was presented on the screen.

Each participant performed 168 experimental trials: 2 rotation type (picture plane vs. depth) × 2 trial type (identical vs. mirror figure) × 2 stimulus pair type (S-M cubes vs. human postures) × 7 angular difference (0°, 30°, 60°, 90°, 120°, 150°, or 180°) × 3 reference stimuli. The order of stimulus presentation was randomized for each participant. All of these experimental factors were treated as within subject using an incomplete balanced design (Cochran & Cox, 1957).

Results and Discussion

Analyses of variance (ANOVAs) were conducted on RTs for correct responses to identical-pair trials as well as on the percentage of error for identical-pair trials, in keeping with previous research on mental rotation (Friedman & Hall, 1996; Friedman & Pilon, 1994; Metzler & Shepard, 1974; Parsons, 1987b). Moreover, across the six experiments, the significance level was fixed to $p < .05$. ANOVAs and post hoc tests (Tukey's honestly significant difference pairwise comparisons) were performed using the Statistica software package (www.statsoft.com).

For the sake of simplicity, we decided to report the ANOVA results separately for picture-plane and depth rotations, considering that our hypotheses concerned mainly the RT–accuracy differences in response-orientation pattern among different stimulus pair types. In addition, because testing for differences in means and rotation slopes across stimulus pair type conditions is a more direct way of testing our hypotheses, we report results for the angular difference factor only when the slopes are not significantly different from 0. Moreover, we provide summary tables of condition means and rotation slopes (collapsing across rotation angles). Finally, we report Cohen's (1988) *d* measure of effect size (the observed effect—whether a linear effect or a mean difference—divided by its standard deviation), because it allows for comparison of effect sizes[1]—when effects are significant—for rotation slopes[2] as well as differences in rotation slopes and in mean values.

RTs. Significantly greater RTs were observed for S-M-cubes pairs as compared with posture pairs, for both picture-plane, $F(1, 17) = 116.07$, $d = 2.54$, and depth rotations, $F(1, 17) = 107.37$, $d = 2.44$. RTs increased linearly with angular difference for each stimulus pair type whatever the rotation type (see Table 1 and Figure 2). Rotation slopes were steeper for S-M-cubes pairs as compared with posture pairs, for both picture-plane, $F(1, 17) = 47.86$, $d = 1.63$, and depth rotations, $F(1, 17) = 18.66$, $d = 1.02$.

Error rates. Percentage of error was computed to quantify response accuracy. Significantly greater error rates were observed for S-M-cubes pairs as compared with posture pairs, for both picture-plane, $F(1, 17) = 9.51$, $d = 0.73$, and depth rotations, $F(1, 17) = 9.58$, $d = 0.73$. Error rate increased linearly with angular difference for S-M-cubes pairs, for both picture-plane, $F(1, 17) = 26.86$, $d = 1.22$, and depth rotations, $F(1, 17) = 10.74$, $d = 0.77$. In contrast, there was no effect of angular difference on error rate for posture pairs, neither for picture-plane nor for depth rotations (Fs < 1; see Table 1 and Figure 2).

As mentioned in the introduction, error rates would be more sensitive than RTs to the effects of holistic versus piecemeal

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[1] According to the operational criteria proposed by Cohen (1988), the values 0.20, 0.50, and 0.80 delimit small, medium, and large effect sizes, respectively. Effect size computations were performed using LeBayesien software (Lecoutre & Poitevineau, 1996).

[2] The amount of variance explained by the linear trend is quantified by the r^2 value. However, r^2 provides the best fitting value of the *average* data points of the response-orientation pattern. It does not quantify the robustness of the linear trend, that is, its variability across subjects. Cohen's *d* is more appropriate for this purpose; the greater the effect size is, the more systematic (less variable) was the linear effect among individuals.

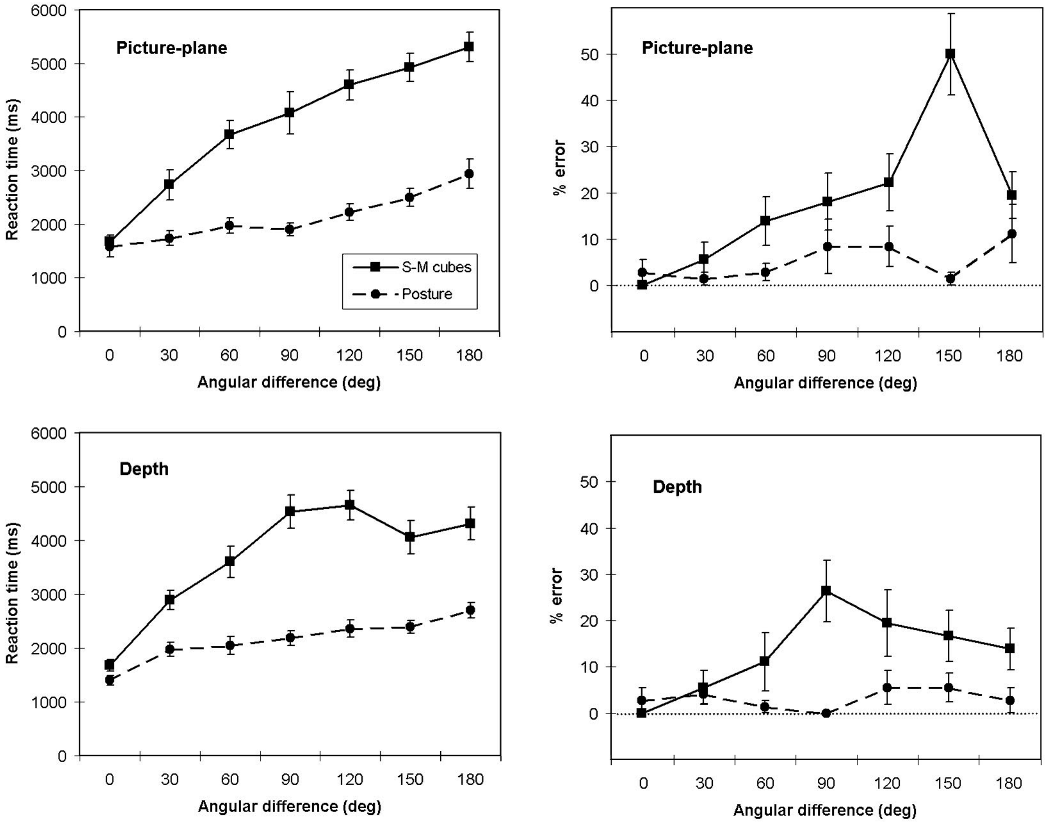

Figure 2. Experiment 1: Mean performance (with standard errors denoted by the error bars) as a function of angular difference in stimulus pairs and of stimulus pair type, for picture-plane and depth rotations. S-M = Shepard–Metzler; deg = degrees.

rotation, as well as those of noise in the visual buffer. The high level of error rates to S-M cubes as compared with familiar human postures, as well as the absence of orientation dependence in error rates, suggests that postures were matched using a holistic mental rotation (cf. the linear increase in RTs but not in error rate) whereby the rotated posture better resisted the noise of the visual buffer. In contrast, rotating S-M cubes was performed piecemeal because participants had difficulty in representing the structure of an entire S-M-cubes figure at one time, and therefore in rotating it at one time.

Our findings, although limited to the type of stimuli we studied, suggest that processing rotated familiar human postures is at a cognitive advantage in comparison to abstract 3-D objects. However, concluding from those results that human posture stimuli benefit from embodied processing would be a misleading shortcut. Before evoking embodied cognition as an explanation for faster and more holistic mental rotation of human posture stimuli, one must reject alternative hypotheses. The main alternative explanation would be that although a human body is more complex than S-M cubes, in terms of either geometric primitives or components (Biederman, 1987) or surface description (e.g., polygons number), the stimulus pair types were not equivalent in terms of spatial complexity. For example, the S-M cubes comprised three bends, whereas the human postures comprised only one or two bends. These stimuli were chosen to compare our findings with previous studies of spatial transformation of one's body (Parsons, 1987a; Zacks et al., 2001) or S-M cubes (Parsons, 1987c), using similar stimuli. However, it is well established that the complexity of the object, for example, the number of bends, cubes, and configurational dimensions, modulates the rate of mental rotation (Bauer & Jolicoeur, 1996; Hall & Friedman, 1994). Therefore, to fairly compare mental rotation of S-M cubes with that of human posture, both stimuli were equated in terms of spatial configuration in the next experiment, using atypical postures defined by S-M-cubes spatial arrangements. If similar behavioral results are obtained when matching S-M cubes or human postures equated for spatial configuration, then it would suggest that human postures are treated by the cognitive system as spatial arrangements not far from those of S-M cubes.

Experiment 2

In two different studies, Parsons examined the effect of rotation axis on imagined spatial transformation of one's body (Parsons, 1987a) or S-M cubes (Parsons, 1987c). He mentioned that "comparing the results of these two sets of studies is complicated by the fact that the two kinds of stimuli differ on more than a single dimension" (Parsons, 1987a, pp. 187–188). To reject stimulus complexity (e.g., the number of bends) as an explanation for the advantage of mental rotation of human posture over that of abstract objects such as S-M cubes that we found in Experiment 1, we applied the same procedure but after equating both stimulus types in terms of spatial configuration. We expected that in spite of using atypical postures defined by S-M-cubes spatial configurations, shape matching of the human body would remain at a cognitive advantage.

Method

Participants. A total of 25 new individuals (23–41 years old) with normal or corrected-to-normal vision took part in this experiment.

Stimuli. Six new S-M cubes and body postures were created for the present experiment using the same software as in Experiment 1. Three of each stimulus type (S-M cubes vs. postures) were original objects, and three were mirror figures. In contrast to Experiment 1, the new S-M cubes and body postures were created to be equivalent in terms of spatial configuration. The postures are biomechanically possible although unusual (see Figure 3).

Procedure. The same apparatus, procedure, and experimental design as in Experiment 1 were used.

Results and Discussion

RTs. Significantly greater RTs were observed for S-M-cubes pairs as compared with posture pairs, for both picture-plane, $F(1, 24) = 5.42$, $d = 0.47$, and depth rotations, $F(1, 24) = 8.67$, $d = 0.59$. RTs increased linearly with angular difference for each stimulus pair type whatever the rotation type (see Table 2 and Figure 4). Rotation slopes were steeper for S-M-cubes as compared with posture pairs, for both picture-plane, $F(1, 24) = 29.62$, $d = 1.09$, and depth rotations, $F(1, 24) = 7.38$, $d = 0.54$.

Error rates. Significantly greater error rates were observed for S-M-cubes as compared with posture pairs, for both picture-plane, $F(1, 24) = 19.82$, $d = 0.89$, and depth rotations, $F(1, 24) = 7.52$, $d = 0.55$. Rotation slopes of error rates for depth rotations were steeper for S-M-cubes as compared with posture pairs, $F(1, 24) = 16.61$, $d = 0.82$. In contrast, for picture-plane rotations, error rate increased linearly with angular difference for S-M-cubes pairs, $F(1, 24) = 49.94$, $d = 1.41$, but not for posture pairs, $F(1, 24) = 1.27$, although error rate varied significantly with angular difference, $F(6, 144) = 2.48$ (see Table 2 and Figure 4).

Although putting humans in atypical postures (defined by S-M-cubes spatial configurations) decreases human body familiarity, data of Experiment 2 are consistent with those of Experiment 1. The average RT advantage of body posture pairs over S-M-cubes pairs (initially observed in Experiment 1) dropped by a factor of about 4; however, the difference in error rate remained constant. Likewise, the mental rotation cost associated with S-M-cubes as compared with posture pairs (6.5 ms/degrees on average) decreased in comparison to Experiment 1 (10 ms/degrees), but it is still important and reliable in terms of effect size (see Tables 1 and 2). The smaller difference between stimulus pair types in Experiment 2 could in part reflect the activation of postural representations spreading to equivalent S-M-cubes configurations across trials.

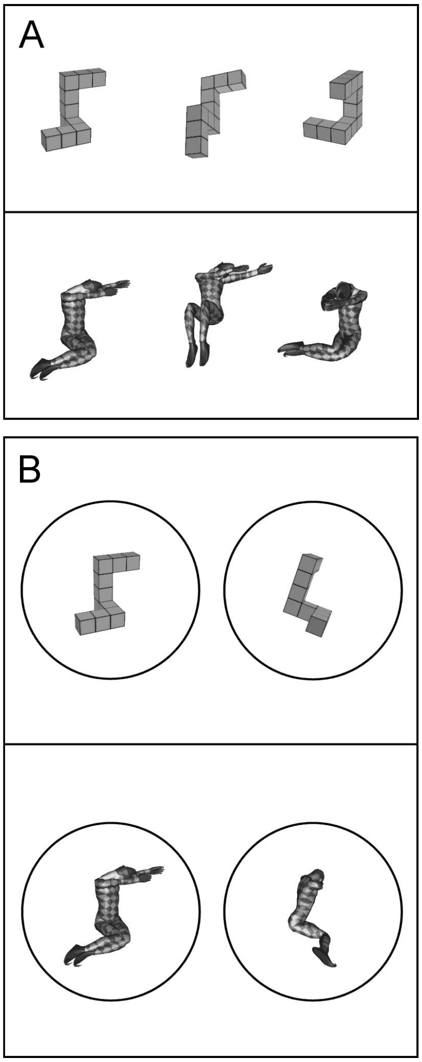

Figure 3. Experiment 2. A: Illustration of the original spatial configurations of Shepard–Metzler (S-M) cubes and counterpart posture stimuli. B: An example of depth rotation pairs, for "identical" trials of S-M cubes and posture stimuli, respectively. Here, although the angular difference in depth (60°) is the same, the spatial configuration of the comparison stimulus of posture pairs appears more ambiguous than that of S-M-cubes pairs.

As in Experiment 1, the increase in error rate with angular difference was negligible or absent for posture pairs and important for S-M-cubes pairs. This suggests that human postures were matched with a more holistic mental rotation than S-M-cubes pairs. However, human postures are not immune to error. The error rate for depth rotation of posture pairs (see Figure 4) indicates that, depending on the spatial configuration, there are orientations (e.g., 60° and 150°) at which stimulus shape turns out to be ambiguous to figure out the actual spatial configuration of the body (see Figure 3B)—that is, for solving the initial perceptual encoding of both objects' shape and orientation. However, for picture-plane rotations where the bidimensional shape is preserved across angular difference, postures are definitely at an advantage. The reference frames provided by the human body for spatial embodiment certainly account for this advantage. The role of visual discontinuities in the early stages of the object-comparison process was acknowledged by Metzler and Shepard (1974). They indeed carefully avoided "singular" orientations when constructing their depth pairs (Metzler & Shepard, 1974), so that an arm of the object

Table 2
Mean Reaction Times for Correct Answers and Mean Error Rate at "Identical Pairs" for Experiment 2 as a Function of Stimulus Type and Rotation Type, Together With Rotation Slopes

Rotation and stimulus pair types	Reaction time (ms)		% error	
	M	Slope (ms/degrees)	*M*	Slope (%/degrees)
Picture plane				
S-M cubes	3,715 (129)	17.59 [2.99]	21.6 (3.1)	0.23 [1.41]
Posture	3,290 (185)	9.71 [1.36]	10.1 (2.5)	*ns*
Depth				
S-M cubes	3,935 (169)	15.29 [1.79]	24.8 (3.2)	0.23 [1.39]
Posture	3,506 (147)	10.19 [1.45]	15.9 (3.5)	0.06 [0.48]

Note. Values in parentheses are standard errors; values in brackets are Cohen's *d*s. S-M = Shepard–Metzler.

would not be hidden behind the rest of the object or obscured by extreme foreshortening due to linear perspective. In some experiments, the stimuli we chose differed considerably in the angles at which visual discontinuities occurred, and hence, the local departures from linearity in the averaged patterns shown in our graphs may sometimes reflect the dips and peaks elicited by one or two of the stimuli's spatial configurations, instead of all of the configurations.[3] Alternatively, such a dip or peak at an angle may be due to a participant failing to notice that the angular difference is one in the picture plane or in depth and instead performing a more error-prone mental rotation around oblique axes to match both the reference and comparison stimuli.

Results indicate that matching familiar postures (e.g., shaking hands) is at an advantage (Experiment 1, with $M = 6.5$ ms/degrees) over matching atypical postures defined by S-M-cubes configuration (Experiment 2, with $M = 10$ ms/degrees). These findings are consistent with motoric embodiment of body pose, whereby familiar poses would be easier to emulate than unfamiliar or atypical ones. Building on the paradigm developed by Reed and Farah (1995), Denes and colleagues (2000) asked observers to compare pairs of either body poses or similar LEGO-block figures, from a 45° angular difference in depth. Patients suffering from autotopagnosia failed to a similar extent in both tasks, whereas age-matched control subjects responded more accurately in the body pose trials. These results speak for the involvement of body schema when comparing human postures, rather than block figures. Two questions then arise: Could body schema be used to disambiguate the spatial configuration of S-M cubes? Perhaps adding a human posture to the S-M cubes would evoke body schema for biomechanically reasonable spatial configurations? This hypothesis was tested in Sayeki's (1981) study of body analogy. However, he provided only descriptive results and did not investigate rotations other than in the picture plane. Therefore, we replicated his study in a third experiment, comparing mental rotation in the picture plane and in depth for S-M cubes with or without a head added to evoke a body posture.

Experiments 3–4: Body Analogy and Object Mental Rotation

Sayeki (1981) showed that adding a head to S-M-cubes drawings improved mental rotation speed and accuracy in the picture plane. To examine whether these results could be explained in terms of either spatial cuing or body analogy, we tested whether replacing the head with a cylinder would have equivalent behavioral consequences, in Experiment 3. Adding a cylinder instead of a head certainly provides the S-M cubes with an up–down axis, as the head does. However, it does not provide access to a multidimensional coding of the cubes' arrangement in terms of body structure, that is, spatial embodiment. Therefore, we expected that cylinder-cubes stimuli would induce performance intermediate between S-M-cubes and head-cubes stimuli. Furthermore, if embodied cognition taps long-term body knowledge (body schema), we theorized in Experiment 4, then comparing a body posture with a head-cubes figure should be faster and less error prone than matching S-M-cubes figures. This should occur in spite of the difference between the stimuli of posture-versus-head-cubes pairs being greater than the difference in S-M-cubes pairs.

Experiment 3

Method

Participants. A total of 24 new individuals (17–42 years old) took part in Experiment 3. All had normal or corrected-to-normal vision.

Stimuli. Experiment 3 used the same S-M cubes as in Experiment 2 as well as new figures. The head-cubes figures were similar to those used by Sayeki (1981)—that is, a head was added on the top of S-M cubes at a plausible position considering that the other part of the body was aligned with the cubes in a way similar to Experiment 2 postures but hidden to the observer (see Figure 5A). Three of each stimulus type were used as reference objects and three as decoys (mirror figure). In addition, cylinder-cubes figures were built in which the head of the head-cubes figures was replaced with a cylinder of similar volume (see Figure 5B). The axis of the cylinder coincided with the object's major limb axis (aligned with the invisible body trunk).

Procedure. The same apparatus, procedure, and experimental design as in the previous experiments were used, except that stimulus pair type involved three levels in Experiment 3 (S-M cubes, head cubes, and cylinder cubes).

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[3] Stimulus-specific analyses showed that in Experiment 1, the first S-M-cubes stimulus displayed in Figure 1A was particularly error prone at the 150° picture-plane angular difference. In Experiment 2, the third S-M-cubes stimulus, as well as both the first and third postures displayed in Figure 3A, were particularly error prone, but only at certain angular differences of depth rotations. None of the other experiments showed a specific effect of object spatial configuration.

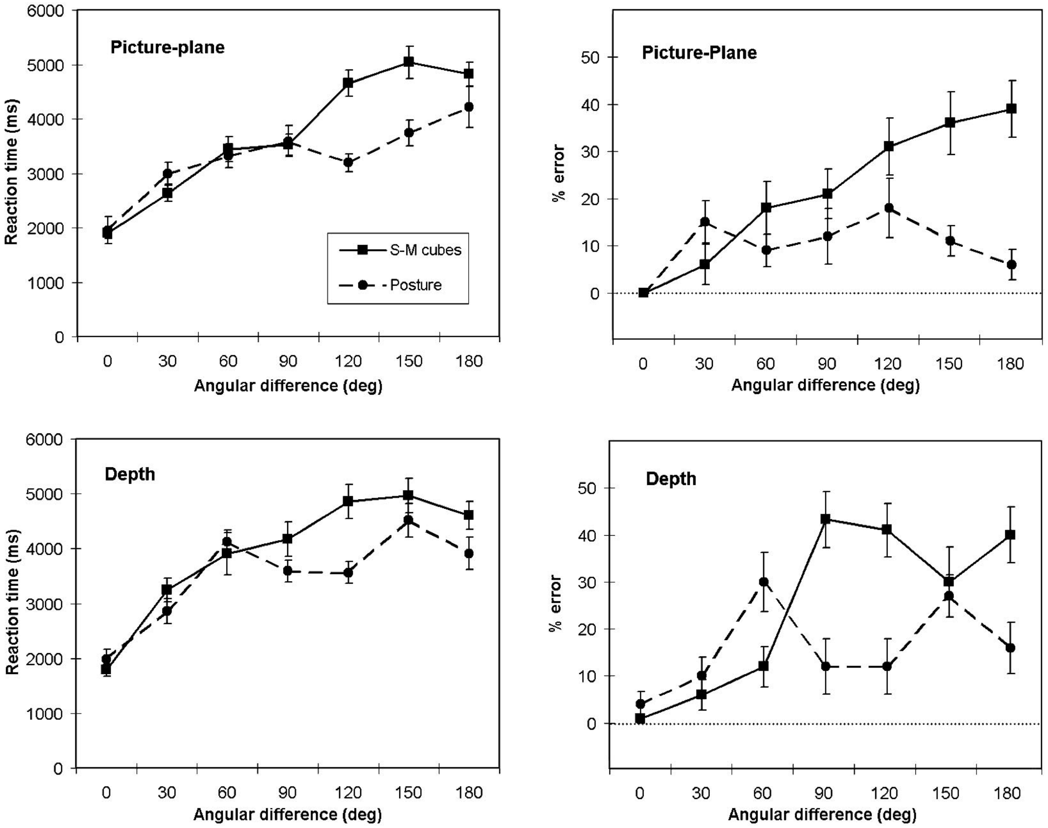

Figure 4. Experiment 2: Mean performance (with standard errors denoted by the error bars) as a function of angular difference in stimulus pairs and of stimulus pair type, for picture-plane and depth rotations. S-M = Shepard–Metzler; deg = degrees.

Results and Discussion

RTs. ANOVAs indicated a significant effect of stimulus pair type on RTs for both picture-plane, $F(2, 46) = 18.6$, and depth rotations, $F(2, 46) = 15.0$. Post hoc tests indicated that stimulus pair types were significantly different from each other for picture-plane rotations. Head-cubes pairs led to smaller RTs than cylinder-cubes pairs ($d = 0.74$) and S-M-cubes pairs ($d = 1.12$), whereas S-M-cubes pairs led to greater RTs than cylinder-cubes pairs ($d = 0.62$). In contrast, for depth rotations, S-M-cubes pairs led to significantly greater RTs as compared with head-cubes pairs ($d = 0.94$) and cylinder-cubes pairs ($d = 0.67$), but the latter two pairs did not differ.

RTs increased linearly with angular difference for each stimulus pair type whatever the rotation type (see Table 3 and Figure 6). For picture-plane rotations, rotation slopes of S-M-cubes pairs were significantly steeper than for head-cubes pairs, $F(1, 23) = 4.74$, $d = 0.44$, and cylinder-cubes pairs, $F(1, 23) = 5.30$, $d = 0.47$; however, rotation slopes for head-cubes pairs and cylinder-cubes pairs did not differ ($F < 1$). In contrast, for depth rotations, rotation slopes (with ds > 1.62) did not differ between stimulus pair types.

Error rates. Error rate varied with stimulus pair type for both picture-plane, $F(2, 46) = 14.26$, and depth rotations, $F(2, 46) = 6.25$. Post hoc tests indicated that for picture-plane rotations, S-M-cubes pairs led to significantly greater error rates as compared with head-cubes pairs ($d = 0.92$) and cylinder-cubes pairs ($d = 0.74$), but the last two pair types did not differ (see Table 3). In contrast, for depth rotations, the only significant paired comparison was S-M-cubes pairs leading to greater error rates than head-cubes pairs ($d = 0.60$).

Error rates increased linearly with angular difference for each stimulus pair type whatever the rotation type, except the error rate for head-cubes pairs, which did not vary with angular difference in depth rotation, $F(6, 138) = 1.20$ (see Table 3 and Figure 6). For picture-plane rotations, rotation slopes of S-M-cubes pairs were significantly steeper than for head-cubes pairs, $F(1, 23) = 11.80$, $d = 0.70$, and cylinder-cubes pairs, $F(1, 23) = 4.35$, $d = 0.43$; however, rotation slopes for head-cubes pairs and cylinder-cubes pairs did not differ, $F(1, 23) = 1.31$. In contrast, for depth rotations, rotation slopes for S-M-cubes pairs and cylinder-cubes pairs did not differ ($F < 1$).

These results suggest that although participants benefited from repetition of the spatial configuration of the S-M cubes across stimulus pair type conditions, there was an advantage for the mental rotation of head-cubes pairs and cylinder-cubes pairs, which was faster and less error prone. The latter two stimulus pair types differed in mean RT only for picture-plane rotations. This slight advantage of head-cubes pairs over cylinder-cubes pairs

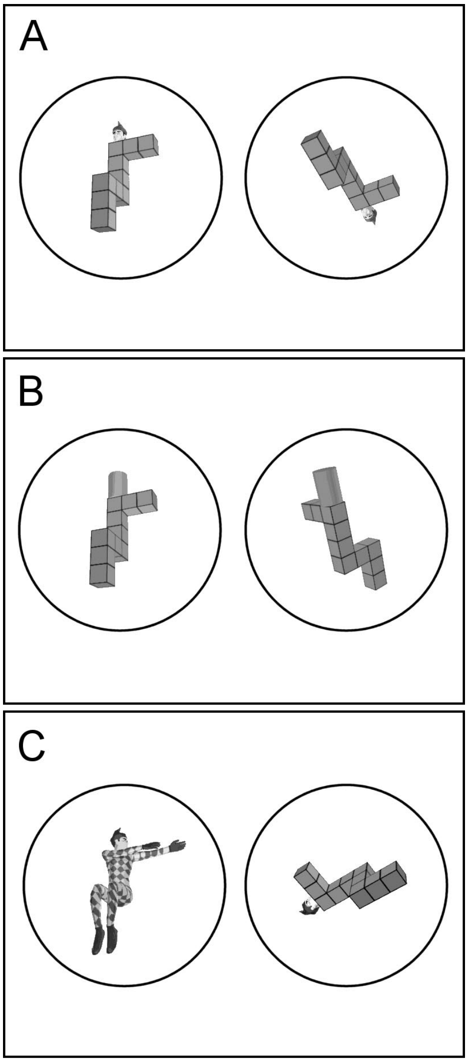

Figure 5. Illustration of the stimulus pair types used in Experiment 3 (A: A picture-plane rotation trial, for a "different" head-cubes pair; B: A depth rotation trial, for "identical" cylinder-cubes pair) and Experiment 4 (C: A picture-plane rotation trial, for an identical "posture vs. head-cubes" pair).

suggests that the head provided reference frames (left–right and front–behind dimensions) additional to the up–down axis also specified by the cylinder that facilitated the mapping of body axes onto the S-M cubes (spatial embodiment) and in turn the decision process for judging the handedness of the object.

The effect of stimulus pair type on performance was diminished in depth rotation trials for a computational reason. Parsons (1995) has shown that subjects are at an advantage for anticipating the appearance of an object rotating about an axis when there is full coincidence among a principal axis of the viewer's visual frame (whether vertical, horizontal, or along the line of sight), the object's major limb, and the rotation axis. Full coincidence of axes would simplify spatial computations regardless of embodiment. In all of our experiments, this full coincidence was achieved only in depth rotations and facilitated more holistic mental rotation similarly in the three stimulus pair type conditions. Indeed, the major limb of each reference object was always oriented upright. Therefore, picture-plane rotation trials were at a disadvantage because the object's major limb axis did not coincide with the rotation axis. In these trials, the head or cylinder on S-M cubes facilitated the matching of the S-M cubes' ends.

In summary, the results suggest not only that the head on S-M cubes acts as a spatial cue to facilitate matching an object's ends but also that it provides additional reference frames (up–down, left–right, and front–behind axes) stemming from spatial embodiment. Adding a head (rather than a cylinder of similar volume) on S-M cubes evoked a body posture that facilitated the mapping of one's body cognitive coordinate system onto the shape and in turn aided the shape-matching process. One may still wonder to what extent body analogy is tapping internal representations such as body schema. If adding a head to S-M cubes really evokes spatial embodiment, we theorized, then comparing a body posture to a head-cubes figure should be faster than matching S-M cubes, despite the greater difference in stimuli for posture-versus-head-cubes pairs. This prediction was tested in Experiment 4.

Experiment 4

Method

Participants. A total of 24 other individuals participated in Experiment 4 (16–26 years old). All had normal or corrected-to-normal vision.

Table 3
Mean Reaction Times for Correct Answers and Mean Error Rate at "Identical Pairs" for Experiment 3 as a Function of Stimulus Type and Rotation Type, Together With Rotation Slopes

Rotation and stimulus pair types	Reaction time (ms) *M*	Reaction time (ms) Slope (ms/degrees)	% error *M*	% error Slope (%/deg)
Picture plane				
S-M cubes	3,050 (192)	15.11 [1.61]	13.7 (2.4)	0.13 [1.05]
Head cubes	2,356 (151)	10.78 [1.74]	4.8 (1.0)	0.05 [0.66]
Cylinder cubes	2,675 (164)	10.49 [1.96]	6.0 (1.2)	0.08 [0.61]
Depth				
S-M cubes	3,123 (184)	11.70 [2.03]	13.3 (3.0)	0.11 [0.77]
Head cubes	2,643 (154)	9.96 [1.63]	6.5 (1.7)	*ns*
Cylinder cubes	2,809 (171)	10.72 [2.02]	8.7 (2.2)	0.09 [0.81]

Note. Values in parentheses are standard errors; values in brackets are Cohen's *d*s. S-M = Shepard–Metzler.

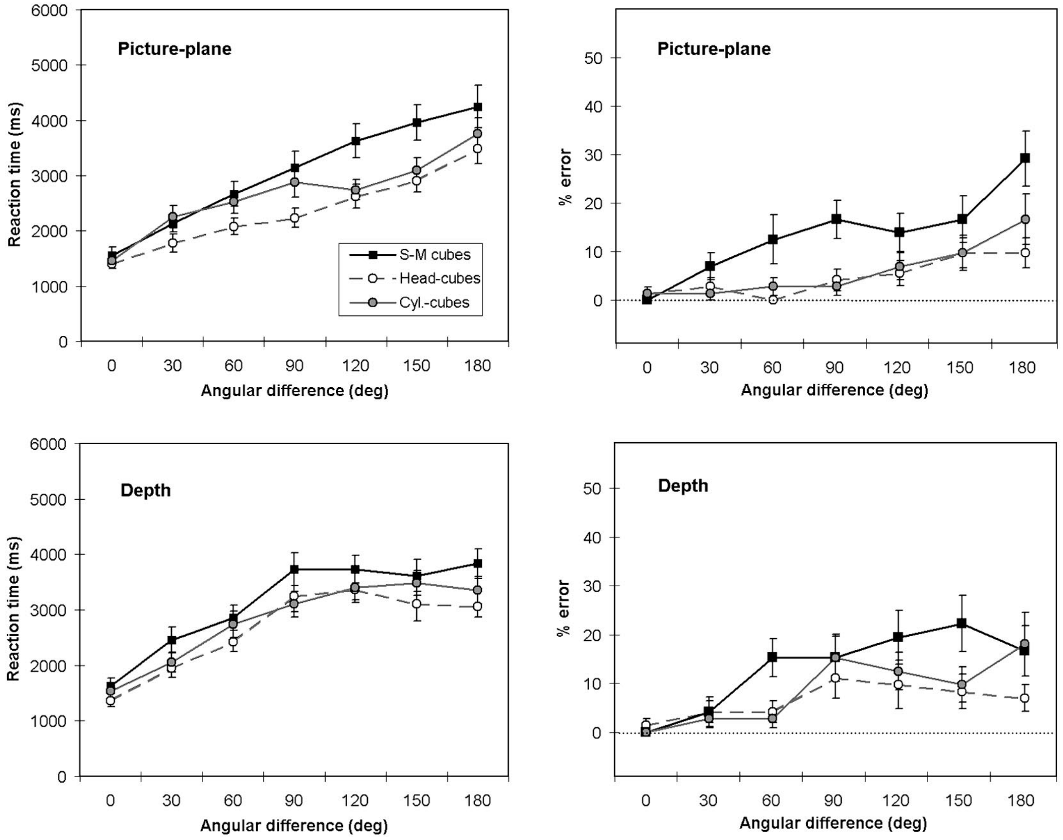

Figure 6. Experiment 3: Mean performance (with standard errors denoted by the error bars) as a function of angular difference in stimulus pairs and of stimulus pair type, for picture-plane and depth rotations. S-M = Shepard–Metzler; cyl. = cylinder; deg = degrees.

Stimuli. The same S-M cubes as in Experiment 3 were used. In addition, new body postures equivalent to those of Experiment 2 were used, except that the head was upright and the nose pointed toward the hands (in contrast, the nose pointed in a direction orthogonal to the arms' axis in Experiment 3). Likewise, new head-cubes figures were built with the head sagittal plane aligned with the arms. In addition, a new stimulus pair type was used, namely the posture-versus-head-cubes (P-H) pair, an example of which is illustrated in Figure 5C. In P-H pairs, the reference stimulus was always a human posture with the trunk upright, whereas the comparison stimulus was a rotated head-cubes stimulus.

Procedure. The same apparatus, procedure, and experimental design as in previous experiments were used, except that stimulus pair type involved four levels in Experiment 4 (S-M cubes, posture, head cubes, and P-H pairs).

Results and Discussion

RTs. RTs varied significantly with stimulus pair type both for picture-plane, $F(3, 69) = 21.85$, and depth rotations, $F(3, 69) = 9.07$. Post hoc tests for picture-plane rotations indicated significantly different RTs among stimulus pair types, except for posture and head-cubes pairs, which did not differ. S-M-cubes pairs led to greater RTs than P-H pairs ($d = 0.66$), posture pairs ($d = 1.33$), and head-cubes pairs ($d = 1.47$), whereas P-H pairs led to greater RTs than posture pairs ($d = 0.72$) and head-cubes pairs ($d = 0.75$; see Table 4). In contrast, for depth rotations, S-M-cubes pairs led to significantly greater RTs than posture pairs ($d = 0.75$) and head-cubes pairs ($d = 1.12$), whereas the other paired comparisons did not reach significance.

RTs increased linearly with angular difference for each stimulus pair type whatever the rotation type (see Table 4 and Figure 7). For picture-plane rotations, the rotation slope of S-M-cubes pairs was significantly steeper than for P-H pairs, $F(1, 23) = 17.61$, $d = 0.86$; posture pairs, $F(1, 23) = 10.51$, $d = 0.66$; and head-cubes pairs, $F(1, 23) = 9.10$, $d = 0.62$. However, rotation slopes for the latter three pairs did not differ (Fs < 1). In contrast, for depth rotations, rotation slopes did not differ between stimulus pair types.

Error rates. Error rate varied with stimulus pair type for both picture-plane, $F(3, 69) = 19.53$, and depth rotations, $F(3, 69) = 4.73$. Post hoc tests indicated that for picture-plane rotations, S-M-cubes pairs led to significantly greater error rates as compared with P-H pairs ($d = 0.73$), posture pairs ($d = 1.04$), and head-cubes pairs ($d = 1.14$). However, error rates of the last three pair types did not differ (see Table 4). In contrast, for depth rotations, the only significant paired comparisons were S-M-cubes pairs leading to greater error rates than posture pairs ($d = 0.71$) and head-cubes pairs ($d = 0.53$).

Error rate increased linearly with angular difference for each stimulus pair type whatever the rotation type (see Table 4 and Figure 7). For picture-plane rotations, the rotation slope of S-M-

Table 4
Mean Reaction Times for Correct Answers and Mean Error Rate at "Identical Pairs" for Experiment 4 as a Function of Stimulus Type and Rotation Type, Together With Rotation Slopes

	Reaction time (ms)		% error	
Rotation and stimulus pair types	*M*	Slope (ms/degrees)	*M*	Slope (%/degrees)
Picture plane				
S-M cubes	2,788 (121)	16.40 [2.40]	10.3 (1.5)	0.17 [1.50]
Head cubes	2,207 (118)	11.20 [1.99]	1.6 (0.5)	0.03 [0.49]
Posture	2,175 (98)	11.66 [2.47]	1.8 (0.5)	0.02 [0.45]
P-H pairs	2,487 (136)	10.77 [2.33]	4.6 (0.9)	0.04 [0.50]
Depth				
S-M cubes	3,068 (140)	14.25 [2.18]	10.7 (2.3)	0.11 [0.84]
Head cubes	2,615 (135)	11.77 [2.30]	5.0 (1.0)	0.05 [0.55]
Posture	2,738 (148)	12.15 [2.28]	4.6 (1.1)	0.06 [0.61]
P-H pairs	2,833 (147)	12.65 [2.54]	6.2 (1.1)	0.05 [0.67]

Note. Values in parentheses are standard errors; values in brackets are Cohen's *d*s. S-M = Shepard–Metzler; P-H = posture versus head cubes.

cubes pairs was significantly steeper than for P-H pairs, *F*(1, 23) = 38.49, *d* = 1.27, posture pairs, *F*(1, 23) = 36.25, *d* = 1.23, and head-cubes pairs, *F*(1, 23) = 32.24, *d* = 1.16, whereas rotation slopes of the last three pairs did not differ. In contrast, for depth rotations, the rotation slope of S-M-cubes pairs was significantly steeper than for head-cubes pairs, *F*(1, 23) = 4.80, *d* = 0.45, whereas each other paired comparison of slopes (see Table 4) did not reach significance.

We theorized that in P-H pairs, the head of the comparison head-cubes figure would induce a body analogy that would permit

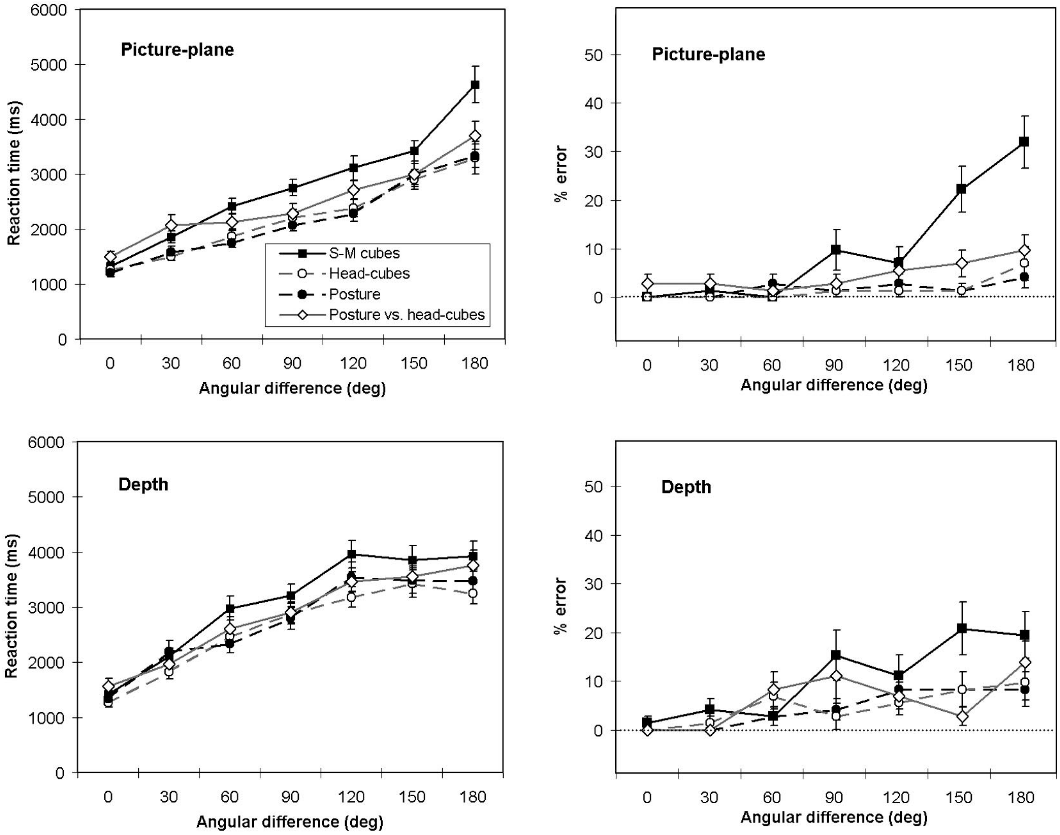

Figure 7. Experiment 4: Mean performance (with standard errors denoted by the error bars) as a function of angular difference in stimulus pairs and of stimulus pair type, for picture-plane and depth rotations. S-M = Shepard–Metzler; deg = degrees.

spatial embodiment and facilitate shape matching with the reference posture as compared with matching spatial arrangements of S-M cubes, in spite of the difference in stimuli for P-H pairs. Both RT and error data were consistent with this embodied processing hypothesis, especially when considering that P-H pairs, head-cubes pairs, and posture pairs had similar behavioral consequences. Moreover, the steeper increase in error rate for S-M-cubes pairs in comparison to the other stimulus pair types (by a factor of 3 on average) suggests that the latter types allowed for more holistic mental rotation thanks to the structural description and coordinate systems provided by the human body.

In summary, the results of Experiment 4 suggest that when participants matched a head-cubes figure to a posture, the head of the head-cubes figure acted as a retrieval cue for generating the corresponding body posture, possibly with the help of the observer's body schema. This body analogy process (via spatial embodiment) would make available to the observer all of the reference frames specific to one's body schema (i.e., the body-centered front–back, left–right, and up–down dimensions), which are, in contrast, not so directly available from S-M cubes. One's familiarity with the relationship of body parts (stored in one's body knowledge) and embodiment (whether spatial or motoric) are two possible accounts for the advantage of posture over S-M-cubes shape matching. To isolate the contribution of familiarity with one's body structure in posture shape matching, we examined performance to another (although less) familiar polyarticulated object in Experiment 5, namely the swing-arm desk lamp.

Experiments 5–6: Visual Familiarity Versus Embodied Processing

Experiment 5

An alternative account of the advantage for matching human postures over matching S-M cubes would be in terms of people's superior familiarity with human body structure. To clarify whether the previous performance differences could be attributed to familiarity with the body hierarchical structure rather than embodied processing, we examined 3-D matching of a familiar object, namely a swing-arm desk lamp, in comparison with matching S-M cubes or human postures. These desk lamps share at least two main characteristics with human bodies: (a) the multiple degrees of freedom of their joints and (b) an up–down orientation defined by the lamp bulb–stand axis. If the advantage of human posture over S-M cubes is due to knowledge (familiarity) of the relationship of an object's parts rather than embodiment, then the matching performance of desk lamp spatial configurations should be closer to that of human postures than to S-M cubes.

Furthermore, to avoid contaminating data patterns or reducing differences among the stimulus pair types by alternating the latter randomly, in Experiment 5 (as well as Experiment 6) we ran the stimulus pair type conditions in a separate block. Finally, to prevent learning of spatial configurations within blocks, due to the small amount of stimuli of each type presented repetitively across angular difference conditions, we presented two stimulus configurations per angle of rotation, randomized across subjects.

Method

Participants. A total of 21 new individuals (23–42 years old) with normal or corrected-to-normal vision took part in this experiment.

Stimuli. Fifteen new spatial configurations of body postures, and their S-M-cubes as well as desk lamp counterparts, were created for the present experiment using the same software as in Experiment 1. These postures consisted of five upper body configurations crossed with three lower body configurations, illustrated in Figure 8 (top panel). Examples of equivalent spatial configurations for each stimulus type are also illustrated in Figure 8 (intermediate panel). The B1 configuration is made of Upper Body B and Lower Body 1, whereas E3 combines Upper Body E with Lower Body 3. During the practice trials, participants were told that the lamp stand (cone and cylinder) was made of steel whereas the rest of the structure was aluminum. Moreover, they were told around which axes the desk lamp parts (i.e., the L-shaped lamp bulb and stand bends) could rotate. Although the desk lamp had an unusual modern design, none of the participants expressed difficulty in searching for the lamp bulb (a neon light colored yellow, whereas the rest of the object was pink) and stand while matching two desk lamp spatial configurations.

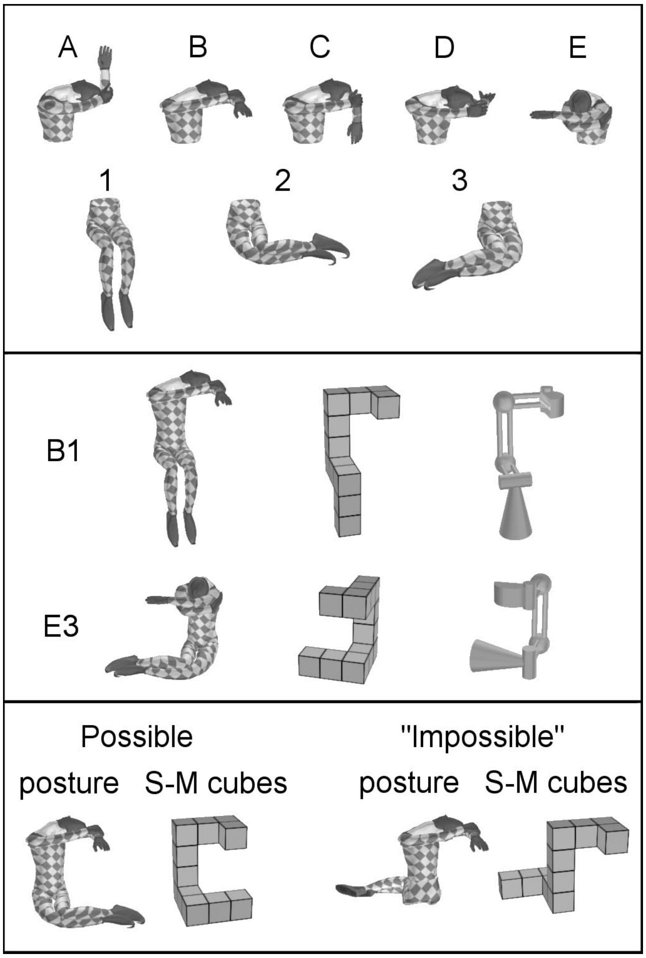

Figure 8. Top panel: Five upper body configurations were crossed with three lower body configurations to construct the 15 postures used in Experiments 5 and 6. Middle panel: Example of equivalent spatial configurations for each stimulus type of Experiment 5—posture, Shepard–Metzler (S-M) cubes, and a modern design swing-arm desk lamp. Bottom panel: Illustration of equivalent possible posture and S-M cubes (on the left) and their "impossible" counterparts (on the right) for Spatial Configuration B2, used in Experiment 6. Impossible postures were obtained by rotating the lower body parts (see top panel) 180° around the body trunk axis.

Procedure. The same apparatus as in the previous experiments was used. Each reference object and its mirror counterpart were used as reference stimuli, at the same angle of rotation condition. The stimulus pair type condition was run in a block, with block order counterbalanced across subjects. Within a block, the order of different stimuli was randomized for each subject. The C1 spatial configuration was always used for practice trials only. The experimental session began with 14 practice trials (2 per angular difference) before each block, not included for data analysis. Both practice and experimental trials were presented without feedback.

Each participant performed 336 experimental trials: 2 rotation type (picture plane vs. depth) × 2 trial type (identical vs. mirror figure) × 3 stimulus pair type (S-M cubes, posture, or desk lamp) × 7 angular difference (0°, 30°, 60°, 90°, 120°, 150°, or 180°) × 2 reference stimulus (each reference object and its mirror counterpart) × 2 spatial configuration (randomly chosen among the 14 other than C1). Two spatial configuration stimuli were used per angle of rotation, randomized and counterbalanced across subjects. All of these experimental factors were treated as within subject using an incomplete balanced design (Cochran & Cox, 1957).

Results and Discussion

RTs. RTs varied significantly with stimulus pair type, for both picture-plane, $F(2, 40) = 10.05$, and depth rotations, $F(2, 40) = 4.27$. Post hoc tests indicated that the only significant pairwise comparison among means of stimulus pair type was due to faster response to posture pairs than to lamp pairs, for both picture-plane ($d = 0.85$) and depth rotations ($d = 0.71$; see Table 5).

RTs increased linearly with angular difference for each stimulus pair type whatever the rotation type (see Table 5 and Figure 9). For picture-plane rotations, the rotation slope of posture pairs was significantly shallower (viz., faster mental rotation) than for S-M-cubes pairs, $F(1, 20) = 13.15$, $d = 0.79$, and lamp pairs, $F(1, 20) = 32.20$, $d = 1.24$, whereas the latter two pairs did not differ, $F(1, 20) = 3.09$. In contrast, for depth rotations, rotation slopes did not differ between stimulus pair type.

Error rates. Error rate varied with stimulus pair type for both picture-plane, $F(2, 40) = 14.80$, and depth rotations, $F(2, 40) = 10.40$. Post hoc tests indicated that for both picture-plane and depth rotations, posture pairs led to smaller error rates as compared with S-M-cubes pairs ($d = 0.99$ and $d = 0.63$, respectively) and with lamp pairs ($d = 1.01$ and $d = 0.99$, respectively). Error rates to S-M-cubes pairs and lamp pairs did not differ, whatever the rotation type (see Table 5).

Error rates increased linearly with angular difference for each stimulus pair type whatever the rotation type (see Table 5 and Figure 9). For both picture-plane and depth rotations, orientation dependence (as measured by rotation slope) was significantly smaller for posture pairs as compared with S-M-cubes pairs, $F(1, 20) = 19.35$, $d = 0.96$, and $F(1, 20) = 20.11$, $d = 0.98$, respectively, and with lamp pairs, $F(1, 20) = 26.61$, $d = 1.13$, and $F(1, 20) = 28.23$, $d = 1.16$, respectively. In contrast, rotation slopes for S-M-cubes and lamp pairs did not differ, whatever the rotation type.

Far from achieving the performance levels of the human posture stimuli, results suggest that matching desk lamps is as problematic as matching S-M cubes. Although desk lamps provide clear object ends (the lamp bulb vs. its stand) that should facilitate holistic mental rotation, error data patterns suggest that desk lamps' spatial configurations were matched using a more piecemeal process. Therefore, the advantage for postures over non-bodylike stimuli is not reducible to spatial cuing for simplifying the matching of stimulus ends. Also, Experiment 5 indicates that knowledge (familiarity) of the relationship of an object's parts is not the only important aspect in the superior body posture performance. However, strong claims about visual experience or familiarity cannot be made with this experiment. One way to do this would have been to train participants to the point of expertise on objects (as in the Greeble experiments; for a review, see Tarr & Cheng, 2003). Rather than examining further the role of perceptual expertise we continued to focus on the role of motoric embodiment in our final experiment.

Experiment 6

Experiment 5 provided evidence that the advantage of human posture over S-M cubes is not simply due to the availability of clear intrinsic axes that facilitate spatial embodiment or to one's familiarity of the relationship of body parts stored in one's body schema when matching spatial configurations. To demonstrate that motoric embodiment (emulation) takes part in posture matching, we devised a new experiment in which we compared shape matching for possible and impossible postures (obtained by rotating the lower body 180° around the body trunk axis), as well as for equivalent S-M-cubes arrangements.

Table 5
Mean Reaction Times for Correct Answers and Mean Error Rate at "Identical Pairs" for Experiment 5 as a Function of Stimulus Type and Rotation Type, Together With Rotation Slopes

Rotation and stimulus pair types	Reaction time (ms) *M*	Reaction time (ms) Slope (ms/degrees)	% error *M*	% error Slope (%/degrees)
Picture plane				
S-M cubes	3,056 (203)	16.66 [1.86]	11.2 (1.9)	0.17 [1.19]
Posture	2,632 (191)	10.92 [1.95]	3.9 (1.1)	0.03 [0.58]
Desk lamp	3,554 (212)	19.73 [2.67]	12.2 (1.7)	0.19 [1.39]
Depth				
S-M cubes	3,492 (221)	16.04 [2.10]	11.2 (1.9)	0.13 [1.04]
Posture	3,167 (214)	15.17 [2.26]	5.3 (1.4)	0.04 [0.58]
Desk lamp	3,659 (157)	17.15 [2.23]	13.8 (1.7)	0.16 [1.44]

Note. Values in parentheses are standard errors; values in brackets are Cohen's *d*s. S-M = Shepard–Metzler.

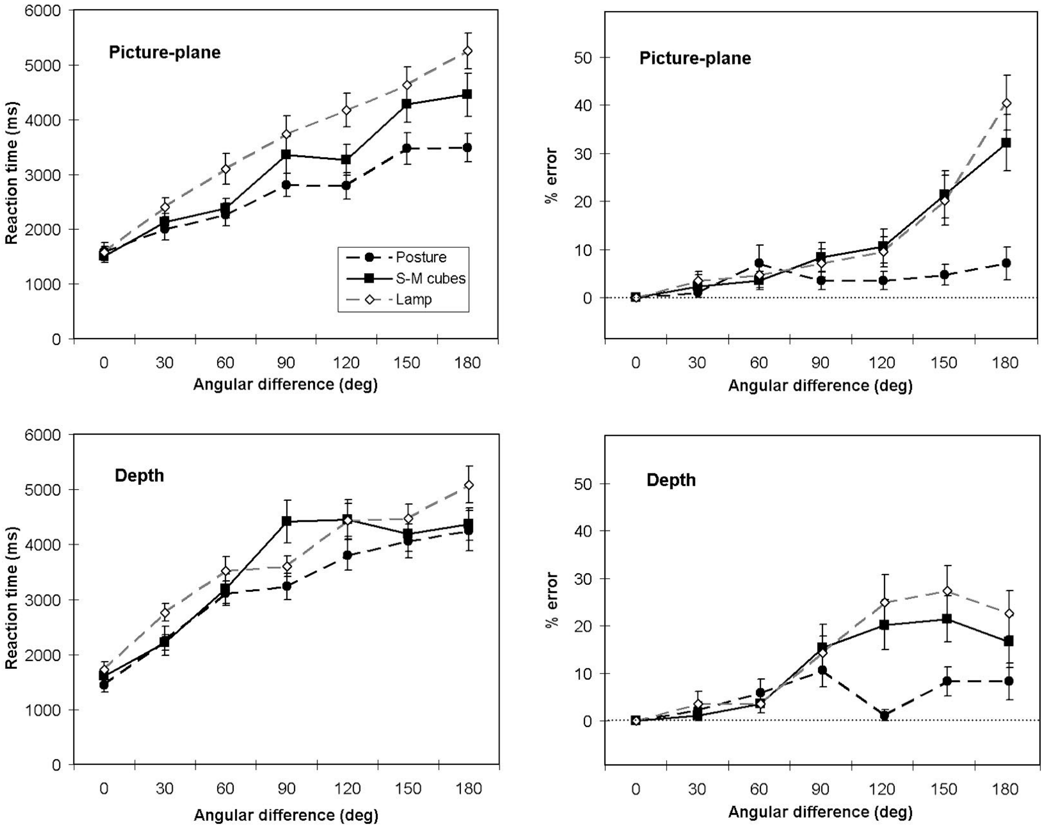

Figure 9. Experiment 5: Mean performance (with standard errors denoted by the error bars) as a function of angular difference in stimulus pairs and of stimulus pair type, for picture-plane and depth rotations. S-M = Shepard–Metzler; deg = degrees.

Given the evidence from the literature review that biomechanical constraints are stored in one's body knowledge, any reasonable interpretation of the embodied view would imply that if one cannot embody a pose (because the pose cannot be emulated on the basis of the musculoskeletal system properties), then one should not get the full benefit of its bodyness. Accordingly, the facilitation effects of bodylike stimuli should go away for impossible postures (when compared with equivalent S-M-cubes arrangements). In contrast, arrangements of S-M cubes should induce a similar matching performance, whether under possible or "impossible" (viz., equivalent to impossible postures) spatial configurations. The detrimental effect of impossible postures as compared with possible postures should manifest in steeper rotation slopes and/or greater mean values for both RT and error.

In addition, after the shape-matching experiment, we asked our participants to rate the relative postural difficulty of each previously viewed possible posture (in its reference orientation), if they were to actually replicate the posture. If motoric embodiment took part in the posture-matching task, we expected that subjective postural difficulty would predict RT to shape matching of possible postures.

Method

Participants. A total of 24 new individuals (18–31 years old) with normal or corrected-to-normal vision took part in this experiment.

Stimuli. Impossible body postures, as well as their S-M-cubes counterparts, were created from the 3-D computer graphics models used in Experiment 5. The impossible postures were obtained by rotating the lower body parts labeled 1, 2, and 3 (see Figure 8, bottom panel) 180° around the body trunk axis. The same operation was applied to S-M cubes to obtain "impossible" S-M cubes (although these are possible objects, the word *impossible* is used to specify that these configurations of cubes are the S-M-cubes counterparts of the impossible postures). Figure 8 (bottom panel) provides an example of equivalent possible posture and S-M cubes (on the left) and their impossible counterparts (on the right) for Spatial Configuration B2.

Procedure. The same apparatus and procedure as in Experiment 5 were used. Each participant performed 448 experimental trials: 2 rotation type (picture plane vs. depth) × 2 trial type (identical vs. mirror figure) × 2 shape type (possible vs. impossible) × 2 stimulus pair type (S-M cubes vs. posture) × 7 angular difference (0°, 30°, 60°, 90°, 120°, 150°, or 180°) × 2 reference stimulus (each reference object and its mirror counterpart) × 2 spatial configuration (randomly chosen among the 14 other than C1). Two spatial configuration stimuli were used per angle of rotation, randomized and counterbalanced across subjects. All of these experimental factors were treated as within subject using an incomplete balanced design (Cochran & Cox, 1957).

In addition, after the four blocks of shape-matching trials, participants performed a postural difficulty *rating task*. In each trial, a possible posture was presented in the center of the screen inside a black circle whose diameter subtended 14° of visual angle, under the same orientation as the reference stimuli of the shape-matching task. Below the posture was displayed a 9-point scale on which participants clicked with the mouse to indicate how difficult for them it would be to perform the displayed posture, without actually performing it. More precisely, participants were asked to indicate the relative difficulty of performing the to-be-judged posture in comparison to the others (from 1 = *the easiest posture* to 9 = *the most difficult one*). To facilitate this subjective, relative postural difficulty judgment, we displayed all of the 15 postures in a smaller size (45%) around the circle containing the posture, above as well as on the left and right sides of the screen, in a randomized position for each trial. Each participant performed 45 experimental trials—15 possible postures (from A1 to E3; see Figure 8) × 3 repetitions—in a different random order for each participant.

Results and Discussion

In contrast to previous experiments, we conducted 2 (shape type) × 2 (stimulus pair type) ANOVAs on RTs and error rates.

RTs. There were greater RTs to impossible than to possible stimulus pair types, for both picture-plane, $F(1, 23) = 16.24$, $d = 0.82$, and depth rotations, $F(1, 23) = 24.16$, $d = 1.00$. RTs to S-M cubes and postures did not differ on average, whatever the rotation type. Nevertheless, there was a significant Stimulus Pair Type × Shape Type interaction for depth rotations, $F(1, 23) = 12.51$, but not for picture-plane rotations, $F(1, 23) = 3.20$. Post hoc tests indicated that for depth rotations, impossible postures led to significantly greater RTs as compared with possible postures ($d = 0.96$), whereas RTs to possible and impossible S-M cubes did not differ (see Table 6). In addition, for depth rotations, impossible postures led to significantly greater RTs as compared with impossible S-M cubes ($d = 0.71$), whereas RTs to possible S-M cubes and postures did not differ (see Table 6). These results suggest that in spite of the richer coordinate system provided by the body than by S-M cubes, when the normal spatial relation between the upper body and lower body is counteraligned, it interferes with both spatial and motoric embodiment processes and consequently slows down shape matching. In contrast, RTs to S-M cubes did not suffer from this shape type (possible vs. impossible) effect.

RTs increased linearly with angular difference for each stimulus pair type whatever the shape type and rotation type (see Table 6 and Figure 10). For picture-plane rotations, the rotation slope of S-M-cubes pairs was steeper than for posture pairs, $F(1, 23) = 20.14$, $d = 0.92$, and that of impossible S-M-cubes pairs was steeper than for impossible posture pairs, $F(1, 23) = 14.06$, $d = 0.77$. In contrast, picture-plane rotation slopes for possible and impossible S-M-cubes pairs did not differ, $F(1, 23) = 1.95$, and those for possible and impossible postures did not either ($F < 1$). For depth rotations, none of the equivalent paired comparisons of rotation slopes reached significance. The greater orientation dependence for picture-plane rotations of cube arrangements suggests that human postures are at a cognitive advantage. This advantage owes to the body extremities that help to match the figure ends, which is crucial for picture-plane rotations. In contrast, matching ends for depth rotations is not mandatory, because both the reference and comparison objects are already upright as defined by the figure's major limb (consisting of four aligned cubes for S-M cubes and the body trunk for postures). As mentioned earlier, full coincidence of the viewer's vertical axis with the figure's major limb axis and the rotation axis simplifies the mental rotation process (Parsons, 1995), regardless of embodiment. Therefore, it may explain why RT rotation slopes for stimulus pair types did not differ in depth rotations, as in Experiment 5.

Finally, it is worth noting that whatever the rotation type, even at 0° angular difference, mean RT to impossible postures was significantly greater (as determined by post hoc tests) than to possible postures and both types of S-M cubes, whereas RTs for the latter three did not differ between each other. The cost for matching impossible postures presented under the same orientation, as compared with the other combinations of shape and stimulus pair types, $F(1, 23) = 14.77$, is suggestive of an interference effect, with participants' (normal) body knowledge disrupting emulation of impossible poses, rather than of a cognitive effort for encoding the 180° rotation of the lower body part in impossible postures.

Error rates. There were greater error rates to impossible than to possible stimulus pair types, both for picture-plane, $F(1, 23) = 23.88$, $d = 1.00$, and depth rotations, $F(1, 23) = 5.02$, $d = 0.46$.

Table 6
Mean Reaction Times for Correct Answers and Mean Error Rate at "Identical Pairs" for Experiment 6 as a Function of Shape Type, Stimulus Type, and Rotation Type, Together With Rotation Slopes

Rotation and shape types	Stimulus pair type	Reaction time (ms)		% error	
		M	Slope (ms/degrees)	*M*	Slope (%/degrees)
Picture plane					
Possible	S-M cubes	3,457 (190)	18.13 [2.32]	9.5 (1.6)	0.16 [1.26]
	Posture	3,054 (228)	12.71 [1.98]	2.4 (0.7)	*ns*
"Impossible"	S-M cubes	3,863 (182)	20.91 [1.97]	19.0 (2.7)	0.25 [1.54]
	Posture	3,899 (187)	13.16 [1.92]	5.5 (1.4)	0.08 [0.56]
Depth					
Possible	S-M cubes	3.765 (163)	17.42 [2.92]	11.3 (1.6)	0.15 [1.08]
	Posture	3,577 (199)	14.23 [1.73]	6.1 (1.2)	0.05 [0.62]
"Impossible"	S-M cubes	4,050 (170)	17.82 [2.52]	14.7 (3.2)	0.16 [0.81]
	Posture	4,694 (210)	14.20 [1.65]	12.4 (2.5)	0.11 [0.77]

Note. Values in parentheses are standard errors; values in brackets are Cohen's *d*s. S-M = Shepard–Metzler.

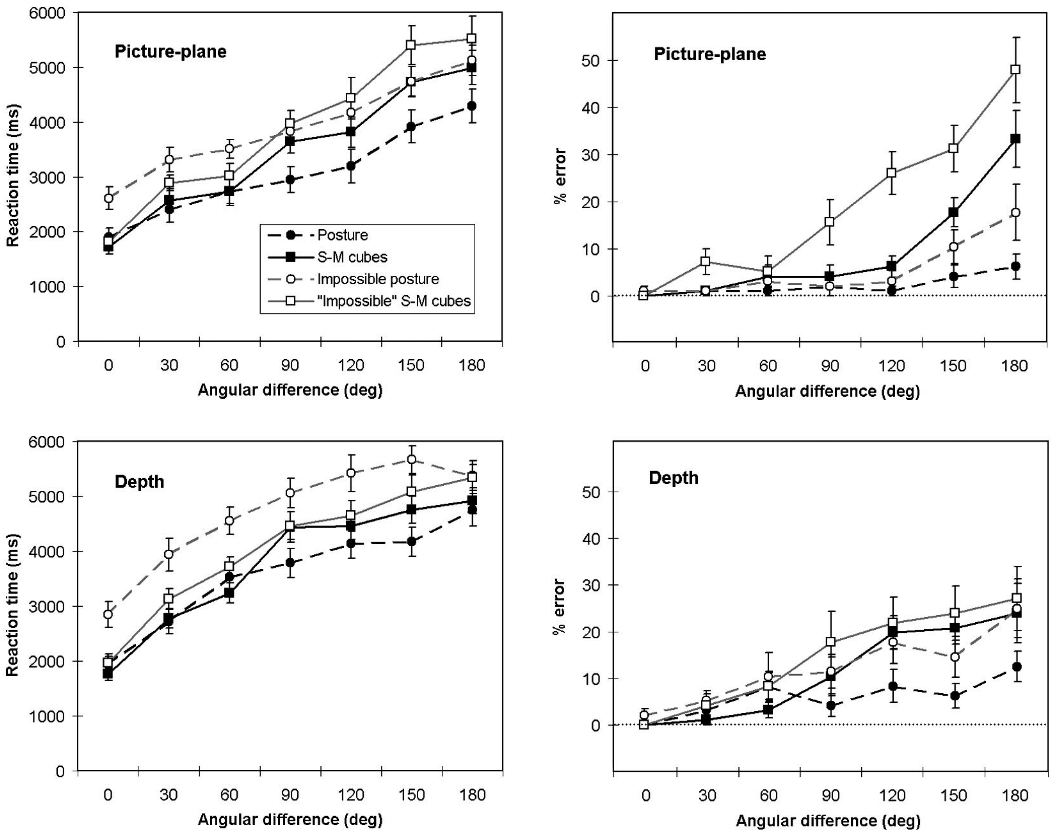

Figure 10. Experiment 6: Mean performance (with standard errors denoted by the error bars) as a function of angular difference in stimulus pairs and of stimulus pair type, for picture-plane and depth rotations. S-M = Shepard–Metzler; deg = degrees.

S-M-cubes pairs led to greater error rates than postures, for picture-plane, *F*(1, 23) = 32.26, *d* = 1.16, and depth rotations, *F*(1, 23) = 4.96, *d* = 0.45. Moreover, there was a significant Stimulus Pair Type × Shape Type interaction for picture-plane, *F*(1, 23) = 22.05, and depth rotations, *F*(1, 23) = 12.05. For picture-plane rotations, post hoc tests indicated smaller error rates for posture pairs as compared with S-M-cubes pairs, for both possible stimuli (*d* = 0.99) and their impossible counterparts (*d* = 1.04). Contrary to expectations,[4] greater error rates were observed for impossible S-M-cubes pairs as compared with their possible counterparts (*d* = 0.87), whereas error rates for possible and impossible postures did not differ (see Table 6). In contrast, for depth rotations, none of the equivalent paired comparisons reached significance. As with RTs, these findings suggest that body extremities helped to match the figure ends and facilitated shape matching across picture-plane rotations regardless of embodiment.

Error rate increased linearly with angular difference for each stimulus pair type whatever the rotation type, except it increased only marginally for picture-plane rotation of possible postures, *F*(1, 23) = 3.82 (see Table 6 and Figure 10). The latter result suggests that postures inconsistent with one's body schema induce more piecemeal mental rotation as compared with holistic rotation of possible postures, at least in the picture plane. For picture-plane rotations, orientation dependence for S-M-cubes pairs was greater than for posture pairs, for both possible, *F*(1, 23) = 29.05, *d* = 1.10, and impossible pairs, *F*(1, 23) = 27.06, *d* = 1.06. In addition, orientation dependence was greater for impossible than for possible pairs, for both S-M-cubes, *F*(1, 23) = 9.90, *d* = 0.64, and postures pairs, *F*(1, 23) = 7.07, *d* = 0.54. The latter finding suggests that although body extremities helped to match the figure ends, impossible postures disrupted spatial and motoric embodiment. In contrast, for depth rotations, we found only that possible S-M cubes led to steeper slopes than possible postures did, *F*(1, 23) = 13.98, *d* = 0.76.

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[4] This lower performance is due to the fact that the construction of impossible postures and their S-M-cubes counterparts had two different visual consequences: (a) The lower L-shape part (whether of the posture or the S-M cubes) of the reference stimuli was oriented backward instead of toward the observer, and consequently, (b) the relationship between the two ends of the 3-D shape was more symmetrical (see Figure 8, bottom panel). The degraded performance for object configurations with symmetrical ends was noticed by Metzler and Shepard (1974):

> This is consistent with the subjects' report that, owing to the approximately symmetric relationship between the two ends of this one object, it was sometimes more difficult to determine which end of one of the two views corresponded to which end of the other view in the presented pair—and that this was especially so when the rotation was in the picture-plane. (p. 165)

Subjective postural difficulty and motoric embodiment. An ANOVA on the postural difficulty ratings was conducted with a 5 (upper body configurations: A, B, C, D, or E in Figure 8, top panel) × 3 (lower body configurations: 1, 2, or 3 in Figure 8 top panel) within-subject design. Results indicated that subjective postural difficulty differed for both the upper body, $F(4, 96) = 95.89$, and lower body spatial configurations, $F(2, 48) = 37.14$. Post hoc tests indicated that the ranking in subjective postural difficulty, for the upper body, was E ($M = 2.62$) ≈ B ($M = 3.40$) < A ($M = 4.02$) ≈ C ($M = 4.78$) < D ($M = 7.86$); for the lower body, it was 1 ($M = 3.40$) < 3 ($M = 4.90$) ≈ 2 ($M = 5.31$). This ranking is consistent with the biomechanical constraints illustrated in Figure 8 (top panel) and readily reflects emulation of the observed postures. Finally, ratings were modulated by a significant Upper Body × Lower Body configuration interaction, $F(8, 192) = 3.63$, corresponding to the following ranking, in increasing difficulty: E1, B1, A1, E3, C1, E2, B3, A3, B2, A2, C3, C2, D1, D3, D2.

To test whether motoric embodiment took part in the previous posture-matching task, we performed a regression analysis on RTs and error rates to posture shape matching (for correct answers to "identical" trials) with subjective postural difficulty as a regressor, after statistically controlling for the effect of angular difference. Indeed, because we used two stimulus configurations per angle of rotation randomized across subjects, in order to prevent learning of spatial configurations within a block, we could not average data across subjects for performing regressions with both subjective postural difficulty (associated with a given postural spatial configuration) and angular difference as predictors. Therefore, we decided first to partial the mental rotation component out of RTs to shape matching (separately for each participant's data) and then to perform a simple regression on residual RTs with only subjective postural difficulty as a regressor and 14 data points (1 point per spatial configuration) averaged across all of the participants.[5] Posture C1 was excluded from this analysis, as it was used only in the practice trials of the shape-matching task.

Regression analysis on the data of the 24 participants showed that subjective postural difficulty contributed to shape matching of posture pairs, marginally for RTs ($R^2 = .18$, $\beta = .49$, $SE = .25$, $p = .074$) and significantly for error rates ($R^2 = .34$, $\beta = .63$, $SE = .23$, $p < .05$). The latter finding suggests that the more difficult it is to emulate the posture (according to the musculoskeletal system properties), the more piecemeal will be the spatial transformation process for matching shapes. As a control, to ensure that it was postural biomechanical difficulty rather than spatial configuration that predicted RT to shape matching, we performed the regression analysis on the data for S-M cubes, with performance to shape matching of S-M cubes as the dependent variable and subjective postural difficulty to their counterpart postures as the regressor. This last analysis showed no contribution of subjective postural difficulty to shape matching of S-M-cubes pairs, either for RTs ($p > .98$) or for error rates ($p > .11$).

In summary, our finding that subjective postural difficulty contributes to posture shape matching is evidence that both spatial and motoric embodiment are part of the posture shape-matching process. This is consistent with brain imaging studies showing that when individuals observe an action (in our case, a postural configuration), an internal replica of that action is automatically generated in their premotor cortex (Buccino et al., 2001). Moreover, it is consonant with the results of Experiments 1 and 2 indicating that familiar poses would be easier to emulate than unfamiliar or atypical ones. Finally, the fact that body advantage goes away for impossible postures (even when matching impossible postures presented under the same orientation) suggests that people's body knowledge contains information about the biomechanical constraints associated with their body joints that disrupts motoric embodiment (emulation) of impossible poses.

General Discussion

Understanding an action to reproduce it (imitation) or to recognize its intentional meaning (social communication) requires the extraction of invariant postural information across changes in visual perspective. According to motor theories of perception (e.g., Hommel et al., 2001; O'Regan & Noë, 2001; Wilson & Knoblich, 2005), perception and action share common representations. In the present study, we investigated to what extent (a) embodied processing accounts for the cognitive advantage of the imagined spatial transformations of the body over that of less familiar (desk lamp) or even unfamiliar (S-M cubes) objects and (b) one's body can be used as a metaphor to embody and match abstract shapes. In contrast to previous studies (e.g., Parsons, 1987a, 1987c; Zacks et al., 2001, 2002), we compared responses to these different types of stimulus pairs among the same participants (which was not the case when comparing data from Parsons, 1987a, 1987c) and always used a shape-matching paradigm.

Our study provides a new contribution to the field of embodied cognition by decomposing the processes mediating shape matching of postures rather than appealing to an interpretation of embodiment in terms of a direct relation with distal information (whether "real" or "represented") whereby the nervous system somehow "resonates" with the environment, namely via so-called mirror neurons when the distal stimulus is a conspecific (see Rizzolatti, Fadiga, Fogassi, & Gallese, 2002, for a review). We propose that shape matching of both the reference and comparison postures is performed in several steps. First, spatial embodiment or "bodily projection" (Lakoff & Johnson, 1999) is used to map one's body axes (head–feet, front–back, and left–right) onto the reference posture. Simultaneously, motoric embodiment occurs when brain motor centers emulate the displayed posture by mentally adopting the same pose (Grush, 2004). Once the reference posture is embodied, it is then spatially transformed (i.e., rotated mentally) in order to align it with the comparison posture.

Evidence of spatial embodiment comes from Experiments 3 and 4, showing that adding a head (rather than a cylinder of similar volume) on S-M cubes in order to evoke a body posture facilitates the mapping of the body's cognitive coordinate system (head–feet, left–right, and front–behind axes) onto the shape, in turn aiding the shape-matching process. Similarly, the fact that in spite of the difference in stimuli, matching a head-cubes figure to a posture leads to similar behavioral consequences as matching postures

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[5] For example, the linear function fitted to data of Participant 7, predicting RT to postures as a function of angular difference (Δangle) in picture plane, was $\text{RT} = 3{,}011.39 + (12.71 \times \Delta\text{angle})$. To partial the mental rotation component out of the 6,434-ms RT to posture A1, presented at the 180° angular difference for this participant, we computed $6{,}434 - (12.71 \times 180) = 4{,}146$ ms as the residual RT for the motoric embodiment of posture A1.

speaks for spatial embodiment. Altogether, these findings suggest that bodily projection is crucial for body analogy when matching abstract shapes. Moreover, the degraded performance for matching swing-arm desk lamps as compared with S-M-cubes pairs (Experiment 5) in spite of the lamp's up–down canonical orientation (as defined by the bulb–stand axis) implies that the advantage for matching postures over non-bodylike stimuli is not reducible to spatial cuing, for example, to facilitate the matching of stimulus ends.

The motoric embodiment of body posture is supported by several findings. First, Experiments 1 and 2 indicated that matching familiar postures (e.g., shaking hands, in Experiment 1) is at an advantage over matching atypical postures defined by S-M-cubes configuration (Experiment 2 and following). Familiar postures would be easier to emulate than unfamiliar or atypical ones. Consistent with this interpretation is the fact that subjective postural difficulty regarding the reference posture predicts performance at posture shape matching (see Experiment 6). In addition, the cost for matching impossible postures presented under the same orientation, as compared with the other pairs (possible postures or counterpart S-M-cubes configurations), is indicative of an interference effect with participants' (normal) body knowledge, rather than of a cognitive effort for encoding the 180° rotation of the lower body part in impossible postures. As discussed in the introduction, one's body knowledge contains information about the biomechanical constraints associated with one's body joints that would disrupt emulation of impossible poses.

The data gathered across our six experiments suggest that shape matching of spatial configurations of S-M cubes, desk lamps, or human postures is performed on the basis of mental rotation, as evidenced by the increase of RTs and error rates with angular disparity between 3-D shapes. However, depending on one's knowledge of the object structure, mental rotation would be performed along a piecemeal-to-holistic continuum. We theorized that if mental rotation is performed piecemeal (Hall & Friedman, 1994; Metzler & Shepard, 1974), then spurious mismatches at identical trials will produce a degradation of response accuracy with angular difference in picture-plane or depth orientation. Therefore, examining error-orientation patterns is crucial to detect spurious mismatches due to noise, decay, and interference in the visual buffer, as mentioned in the introduction. Contrary to S-M cubes or desk lamps, we showed that shape matching of human postures obtains a cognitive advantage owing to humans' body schema, which contains information regarding the hierarchy of interconnected body parts and in turn favors faster rotation rates. Thanks to this structural description, the integrity of the rotated posture can resist the distortions inherent to the visual buffer medium, increasing as the mental representation is rotated by greater angles at a step (Kosslyn, 1981). Therefore, people are more likely to perform holistic rotation for human posture than for non-bodylike stimuli (though not necessarily all of the time). Along those lines, our finding of more orientation-dependent error rates for impossible posture pairs as compared with possible posture pairs is consistent with evidence that shape inversion impairs sequential recognition of possible human body postures or faces (Reed, Stone, Bozova, & Tanaka, 2003) but not that of impossible body positions violating the biomechanical constraints of human bodies, because the latter would be processed less holistically.

The fact that shape matching of postures requires spatial embodiment was questioned by Zacks and colleagues (2001), who compared performance on same–different versus left–right tasks for rotations in the picture plane of body postures, as in Parsons (1987a). RTs increased monotonically with orientation from upright at the same–different task but not for laterality judgments (Zacks et al., 2001). On the basis of Parsons's (1987a) finding that the time for laterality judgments mimicked the RT-orientation patterns when viewers imagined adopting the displayed body orientation, as well as brain imaging studies, Zacks and colleagues (2001, 2002; Zacks, Gilliam, & Ojemann, 2003) proposed that in left–right tasks observers imagine an "egocentric perspective transformation" or viewer mental rotation. Instead of imagining themselves in the position of the pictured body, observers would solve same–different tasks by using an "object-based spatial transformation" or object mental rotation to align both the reference and comparison postures. However, although viewer mental rotation is generally at an advantage over object mental rotation (Wraga, Creem, & Proffitt, 1999), this is not the case when imagining physically impossible self-rotations such as a roll motion in the coronal plane (M. Carpenter & Proffitt, 2001; Creem, Wraga, & Proffitt, 2001; Van Lier, 2003), corresponding to the picture-plane rotations investigated by Zacks and colleagues (2001, 2002, 2003). The latter findings certainly run counter the hypotheses of Zacks and colleagues. An alternative explanation of the RT advantage for left–right over same–different tasks would be related to the number of stimuli to be processed. The visual buffer being the medium for both imaginal and perceptual visuospatial representations, interference between both the rotated comparison posture and the reference posture occurs in same–different tasks. In contrast, because in left–right tasks only one posture must be processed, there is no image interference. Finally, we note that in an fMRI study, Zacks and colleagues (2002) found that premotor cortex (a region involved in the multisensory representation of limb position in humans; see Lloyd, Shore, Spence, & Calvert, 2003) is activated bilaterally in both same–different and left–right tasks to human postures, a finding consistent with our motoric embodiment hypothesis (which they interpreted differently as the consequence of preparing conflicting motor responses).

In conclusion, we have shown how bodylike stimuli trigger constraints on mental rotation resulting from one's spatial and motoric embodiment. One's spatial embodiment contributes to the recognition of the body pose and orientation, whereas one's motoric embodiment contributes to the maintenance of the spatial configuration throughout the mental rotation process. Because embodiment assists both the encoding and the representation of bodylike stimuli during shape matching, the phrase *embodied spatial transformations* better designates this intimate relationship between embodiment and mental rotation processes. Embodied spatial transformations are relevant to the fields of spatial cognition, object recognition, and imitation, as well as when validating motor theories of visual perception. More generally, our contention is that both types of embodiment evolved for social communication (for a review of embodied cognition in social information processing, see Niedenthal, Barsalou, Winkielman, Krauth-Gruber, & Ric, 2005). When people prefer to adopt the perspective of their listener instead of their own for conveying spatial information to others (Schober, 1993), it is an instance of spatial embodiment. On the other hand, motoric embodiment would be crucial for motor learning based on imitation (Decety, 2002), language comprehension (Zwaan & Taylor, 2006), and metaphorical conceptualization (Gallese & Lakoff, 2005; Lakoff & Johnson, 1999).

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