Anatomical limitations in mental transformations of body parts

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Two experiments investigated whether possible and impossible body postures influence mental rotation processes differently considering that anatomical limitations constrain the way in which subjects perform mental transformations of body parts. In Experiment 1, mental rotation was performed on two stimuli presented simultaneously. Both possible and impossible body postures elicited mental rotation, although the mental rotation rate was slower for impossible postures. In Experiment 2, only one stimulus was presented at a time and subjects decided whether it represented a correct body-part configuration or not. A typical mental rotation function was only present for correct body-part configurations. The results are discussed in terms of the familiarity of the stimuli. Unfamiliar stimuli (physically impossible) are rotated via local representations of their parts, whilst global representations are used for rotating familiar (anatomically correct) stimuli.

INTRODUCTION

Most of our actions are driven indirectly by internally represented goals, rather than directly by the external environment. What are the nature and characteristics of those internal representations? Motor imagery can be defined as a dynamic state during which a person mentally simulates a given action. This specific type of mental imagery is quite different from other forms of imagery. As Jeannerod (1997) states: ‘‘motor images are experienced from within, as the result of a first person process where the self feels like an actor rather than a spectator. During motor imagery the subject feels himself executing the action,'
whether it involves the whole body (as in running for example) or it is limited to a body part (as in writing for example)” (p. 95).

A number of experiments have argued for a functional relationship between motor imagery and actual movement execution. For instance, it has been shown that muscular force is enhanced by an “imagined” training and that autonomic activation is increased, compared to rest, when subjects imagine motor actions with large physical effort (Decety, 1992). In addition, psychophysical experiments show that imagined movements preserve the same spatio-temporal characteristics and obey the same laws of movement control as those of actual movements (Decety & Michel, 1989; Viviani & McCollum, 1983). All this suggests that motor preparation and programming are almost identical whether subjects execute or imagine an action. Thus, executed and imagined actions seem to share the same properties. However, human bodies have anatomical limitations. They are a particular kind of stimuli, not necessarily comparable to other types of objects. There is evidence suggesting that visual processing of human bodies is performed by a separate body-specific representational system. Neuropsychological studies on autotopagnosia describe patients with the loss of a spatial representation of the body, distinct from the representation of external space. They are unable to localise body parts on themselves or others, which contrasts with their ability to locate parts of complex objects other than bodies (Ogden, 1985; Sirigu, Grafman, Bressler, & Sunderland, 1991). Moreover, Reed and Farah (1995) showed that when normal participants moved a part of their own body it facilitated their visual detection of changes in the same part of another person’s body, but not in spatially comparable parts of complex three-dimensional forms.

A variety of research has focused on mentally represented spatial transformations of body parts. Some studies have examined the representations in cognitive and perceptual tasks to determine how they reflect (a) the laws of physics, (b) approaches derived from kinematic geometry, or (c) principles of human biomechanics. On the whole, various phenomena support the idea that mental representations of actions take into account the biomechanical constraints of the represented movement. For instance, Shiffrar and Freyd (1990) examined apparent motion phenomena with stimuli consisting of parts of the human body. Usually, when subjects are presented with two successive stimuli, under appropriate conditions of frequency of presentation, they perceive a single moving stimulus. If the movement can follow two different paths, subjects always perceive the stimulus as moving along the shortest path. However, when the stimuli are human body parts, for example the forearm, Shiffrar and Freyd showed that subjects no longer perceive motion along the shortest path, but along a motion path that conforms to the biomechanical constraints imposed by the joints.

Furthermore, Parsons (1987) studied the mental transformation of body parts. He showed that the time to imagine spatial transformations of one’s hand from
one orientation to another is well correlated with how awkward that orientation is to adopt physically. Moreover, during this study, subjects seemed to mentally simulate the kinematic properties of their own bodies and avoided imagining physically awkward or impossible actions. The author concluded that imagined spatial transformations of one’s hand are apparently strongly affected by its normal range of motion.

Prior to this, Sekiyama (1982) used the mental rotation paradigm to examine motor imagery. Mental rotation, like the physical rotation of an object, requires more time to complete as the degree of rotation becomes greater. Shepard and Metzler (1971) were the first authors to describe a paradigm in which it is hypothesized that subjects have to master an internal rotation which consists of reorienting the rotated object in order to make a decision on it. Sekiyama presented her participants with line drawings of human left or right hands that varied in finger position and wrist rotation. Each hand could appear in any one of eight orientations in the picture plane. Participants had to decide as quickly and accurately as possible whether a right or a left hand was shown. Results showed that reaction times (RT) depended on the orientation of the presented hand, but not always in the way usually observed in mental rotation experiments. Sekiyama explained her results in terms of “manageable directions”: the shapes of the RT functions agreed with the anatomical constraints of the hand movements that would have been necessary to solve the task physically.

In a recent study, Petit, Pegna, Mayer, and Hauert (2003) compared the mental rotation of a hand attached to its forearm and arm in anatomically possible and impossible positions. A target (always in a vertical, i.e., 0° orientation) and a comparison stimulus (in many different orientations, both anatomically possible and impossible) were presented simultaneously on the screen. Although there was no overall difference in reaction time between the possible and impossible orientations, the speed of mental rotation was slower when the arm was in an impossible position, supporting the idea that biomechanical constraints are taken into account during motor imagery. Finally, Daems and Verfaillie (1999) found long-term facilitatory priming for anatomically possible human postures, but not for poses that are impossible to perform with a human body.

All these results suggest that the processing of body parts is “special” and different from other stimuli. In that case, to which of those two categories (bodies or external objects) would impossible body postures belong? Are the same cognitive representations and processes involved during mental rotation for possible and impossible body postures? Mental rotation seems to be different depending on the nature of the object.

According to Bethell-Fox and Shepard (1988), unfamiliar stimuli are rotated via local representations of their parts, whilst global representations are used for rotating familiar stimuli. This is because familiar stimuli have well
established internal representations that can be accessed and manipulated in a holistic fashion. At the same time, however, Dror, Ivey, and Rogus (1997) compared the mental rotation of possible versus impossible objects and found that the rates of rotation were comparable. They interpreted this lack of difference as evidence that local representations are preferred in visual mental rotation.

These results show that the nature of information processing during mental rotation may depend on the types of stimulus used. However, it may also change with variations in experimental procedure. Specifically, experiments in which individually presented, well-learned stimuli must be compared with a long-term memory representation may encourage analog processing of integrated internal representations, whereas experiments involving simultaneous comparison of unfamiliar visual objects may sometimes encourage more discrete, feature-based rotational processing (Shepard & Cooper, 1982).

In this study, we used the mental rotation paradigm with stimuli depicting the human body in both familiar (possible) and unfamiliar (impossible) postures presented either simultaneously for direct matching (Experiment 1) or individually for matching to long-term memory representations (Experiment 2). For each stimulus, the basic body context was constant at one orientation (vertical or 0°) and it was just the upper limb (thumb or forearm) that was presented in different orientations, in order to encourage a sense of body movement and evoke motor imagery. The aim of Experiment 1 was to determine whether possible and impossible body postures were processed in different ways during mental rotation. Reed, Stone, Bozova, and Tanaka (2003) compared the processing of possible body postures with biomechanically impossible body postures by using a forced-choice, same/different recognition paradigm for upright and inverted stimuli. They found that the inversion effect for body postures was diminished when the biomechanical constraints of body positions were violated. The authors concluded that body postures are processed configurally. Following this logic, we hypothesised that possible postures, being familiar stimuli, would be rotated in a configural, holistic process whereas unfamiliar body postures (physically impossible) would induce a piecemeal process. According to Cooper and Podgorny (1976), two factors contribute to response times during mental rotation. First, response times increase with greater angular distance through which the representation needs to be rotated. We suppose that this will be found in both holistic and part-by-part representations. Second, response times increase with greater number of segments that need to be processed. In a holistic representation, only one segment is rotated, whereas in a part-by-part representation, more segments are rotated, and the number of segments in the part-by-part representation increases with greater complexity of the object. We suppose that increased response times will be found for impossible postures compared to possible ones and also
that mental rotation rates would be slower for impossible postures (cf. Dror et al., 1997). Faster rotation rates should be found for possible postures because, in a holistic process, the stimulus is rotated as a single entity.

In this study, the relationship between the possible/impossible movement dimension and the size of the angular disparity between stimuli was directly manipulated. In addition, the mental rotation of hands and arms attached to the rest of the body was compared to the mental rotation of body parts presented in isolation. We hypothesized that, in the former case, mental rotation performance would be constrained by the biomechanical limitations implied by the presence of the rest of the body. On the other hand, there should be no such constraints linked to body parts presented in isolation. In other words, all orientations can be considered possible in the case of the isolated body parts. An impossible posture only arises because a body part (in a particular orientation) is attached to the rest of the body in an anatomically impossible manner.

**EXPERIMENT 1**

In this experiment, the relationship between the possible and impossible movements dimension and the size of the angular disparity between stimuli was directly manipulated by presenting a target picture either in an upright (0°) or upside-down orientation (180°), and a second picture in a number of different orientations. When the target is upright, small angular differences (up to 90°) in the to-be-matched probe stimulus correspond to limb orientations in the possible range of movement. When the target is upside down, these small angular differences correspond to limb orientations in an impossible range of movement. Any difference between these two situations is likely to reflect the fact that biomechanical constraints are taken into account during motor imagery and that possible and impossible body postures are processed in different ways. For larger angular differences (90° to 180°) between the target and probe stimuli the situation is mixed, because one stimulus (either the target or the probe) is in a possible orientation while the other one is in an impossible orientation. Thus, we might expect that these two conditions would not differ.

**Methods**

**Participants**

The research reported here was approved by the Ethics Committee of Macquarie University. Twenty undergraduate students (10 females, 10 males) took part in this experiment for course credit. All were right-handed and between 18 and 22 years of age (mean ± SD, 19 ± 1 years).
Apparatus

The experiment was run on a Dell PC computer with a 17” monitor with a 88Hz vertical refresh rate. Responses were recorded via a button box.

Stimulus presentation and the recording of the response times and errors were controlled by the DMDX software developed at Monash University and at the University of Arizona by K. I. Forster and J. C. Forster (Forster & Forster, 2003).

Materials

The stimuli were 4 pictures of arms and hands seen from different views, taken from the Premium Image Collection of Hemera Technologies Inc. (1997–2000) and transformed with a picture-editing software (Corel Photo-Paint). All pictures were asymmetric and were scaled to the same proportions. There were two pictures of isolated hands (see Figure 1, A1 and A2) and two pictures of arms attached to the rest of the body (see Figure 1, A3 and A4).

For each picture, only part of it was rotated clockwise in the picture plane. For instance, in the case of stimulus A1, the orientation of the thumb could vary, the rest of the hand staying in a vertical position (see Figure 1). For A2, the whole hand was rotated around the wrist, and in the two other cases the forearm changed orientation (see Figure 1). For each probe stimulus, the various angles were the same: from 0° (vertical, canonical orientation) to 180° (upside-down) in 30° steps. This implies that three angles (0°, 30°, 60°) corresponded to possible orientations of the body part, three of them (120°, 150°, 180°) corresponded to impossible orientations, while 90° orientation fell at the limit between the possible and impossible ranges of movement.

As a control, the relevant body parts were also presented alone, i.e., in the absence of the rest of the body, in the same 7 orientations as the body part in context (see Figure 1, columns C and D). In that case, no biomechanical constraints should be involved and hence there is no distinction between possible and impossible orientations. Moreover, these particular stimuli should follow a holistic rotational process if they are represented as single segments and all “possible”.

The stimuli were presented in pairs, one above the other, separated by 5 cm (with each stimulus measuring 10 × 10 cm; see Figure 2). The top picture (target) appeared in one of two orientations: 0° (Figure 2, a and b), or 180° (Figure 2, c and d), either facing left or right. The picture presented at the bottom of the screen (the probe) was in one of the seven different orientations ranging from 0° to 180° in 30° steps in the picture plane, facing either left or right. Thus, half of the pairs were identical pictures and the other half were mirror images. There were 56 presentations of each picture (2 target positions × 7 probe positions × 2 “same” and 2 “different” pairs), making a total of 448 trials. Figure 2 shows examples of the various stimulus conditions used.
Figure 1. Stimuli used in Experiment 1: columns A (target 0) and B (target 180) = Body part in context, columns C (target 0) and D (target 180) = Control.
Procedure

The experiment was divided into 4 blocks. Each block consisted of a particular body part attached to the rest of the body (Body condition) or presented in isolation (Control condition), randomly intermixed. For example, one block comprised pictures of the hand and thumb (Figure 1, A1 to D1); another comprised pictures of a woman and her isolated control arm (Figure 1, A3 to D3). Each participant completed all 4 blocks, with order of block counterbalanced across subjects.

Participants were seated approximately 50 cm from the computer monitor, in normal illumination conditions. Prior to the experiment, they were shown the drawings (the same ones they would see in the actual experiment) and the task was explained to them. At the beginning of each block they had 10 practice trials containing the Body and the Control presented in that particular block, e.g., A1 to D1, selected randomly and presented in a random order. They were asked to answer as quickly as possible whether the two pictures were of identical body parts, or mirror images, by pressing two different buttons on a button box with their thumbs (right thumb for identical pictures, left thumb for mirror images). Participants were instructed to avoid tilting their head. Reaction times were recorded from the time when the new target-stimulus set appeared on the screen until the participant pressed a button. If no response was given, the next set of stimuli appeared after 3 seconds.

Figure 2. Examples of the Body experimental conditions used in Experiment 1. a) and b) depict trials in which the target stimulus (top picture) was upright (0°); c) and d) depict trials in which the target stimulus was upside-down (180°). a) and d) are examples of trials with a small angular difference between the stimuli, within the possible and impossible ranges of movement, respectively. b) and c) are examples of trials with a large angular difference between the stimuli. The subjects judged whether the relevant body parts (the forearm, in this case) were identical or mirror-images.
Results

Responses and response times were recorded. Figure 3 shows the mean reaction times (RT) for the correct responses (Figure 3a) and error percentages (Figure 3b) of all 20 subjects.

Reaction times

The mean RTs for correct responses were analysed using a $2 \times 2 \times 7$ repeated measures ANOVA with Stimulus type (Body, Control), Target position ($0^\circ$, $180^\circ$) and Angle disparity ($0^\circ$, $30^\circ$, $60^\circ$, $90^\circ$, $120^\circ$, $150^\circ$, $180^\circ$) as within-subject factors.

There was a significant effect of Stimulus, $F(1, 19) = 6.69, p < .05$, with body parts presented in context eliciting slightly longer RTs than control stimuli. Also, a main effect of Target position, $F(1, 19) = 98.32, p < .001$ was shown, with slower RTs for upside-down targets compared to upright targets. A main effect of Angle, $F(6, 114) = 121.67, p < .001$ was revealed, with increasingly longer RTs for larger angular disparities. Finally, a significant Target position $\times$ Angle interaction, $F(6, 114) = 5.05, p < .001$ was found.

Given the difference we found between trials in which the target was at $0^\circ$ versus $180^\circ$, separate ANOVAs for target at $0^\circ$ and target at $180^\circ$ were performed. In the case of target at $0^\circ$, there was a main effect of Stimulus, $F(1, 19) = 5.74, p < .05$ with longer RTs for Body versus Control. Then, a main effect of Angle was revealed, $F(6, 114) = 83.92, p < .001$ with RTs gradually increasing with the angle disparity. There was also a significant Stimulus $\times$ Angle interaction, $F(6, 114) = 2.53, p < .05$, accounted for by a difference between Body and Control stimuli in the impossible range of motion ($120^\circ$ to $180^\circ$), but not in the possible one (see Figure 3a). For targets at $180^\circ$, we found a marginal effect of Stimulus, $F(1, 19) = 3.84, p < .06$ with RTs for the Body being slightly longer than for the Control, a main effect of Angle, $F(6, 114) = 80.64, p < .001$, but no interaction. Thus, in this case, there was no evidence for a difference between the possible and impossible ranges of motion.

Mental rotation rates

Mental rotation rates were calculated for the possible ($0^\circ$ to $90^\circ$) and impossible ($90^\circ$ to $180^\circ$) ranges of movement for each stimulus type, by fitting regression lines to the RT data in the respective ranges. The mean rates for the 20 subjects, expressed as ms/$^\circ$, are summarized in Table 1 and show substantially faster mental rotation rates for the possible range of movement when the target was upright compared to all other conditions.

The rates were analysed separately for target at $0^\circ$ and target at $180^\circ$, using a $2 \times 2$ repeated measures ANOVA with Stimulus type (Body, Control) and Possibility (possible, impossible range of movement) as within-subject factors.
Figure 3. Mean RT (a) and percent error (b) as a function of the angle disparity for body part presented in context and in isolation; Body 0 = body part attached to the rest of the body, with the target stimulus at 0°; Body 180 = body part attached to the rest of the body, with the target stimulus at 180°; Control 0 = isolated body part, with the target stimulus at 0°; Control 180 = isolated body part, with the target stimulus at 180°; Lighter symbols represent the impossible range of movement. Note that when the target was at 180°, the small angular disparities correspond to probe orientations of 180°, 150° and 120°, i.e. the impossible range of movement.
For targets at 0°, there was a significant main effect of Possibility, \( F(1,19) = 7.57, p = .013 \), and a marginal Stimulus × Possibility interaction, \( F(1,19) = 3.77, p = .067 \), but no overall difference between Body and Control stimuli. As can be seen from Table 1, there was a large difference in mental rotation slopes between possible and impossible ranges of movement for Body stimuli, \( F(1,19) = 13.92, p < .01 \), but a much smaller, and non-significant, difference for Control stimuli, \( F(1,19) = 0.97, p = .34 \). In contrast, when the target was at 180°, there were no differences at all between the possible and impossible ranges of movement, nor between types of stimuli (all \( F \)s < .13). These results are reminiscent of the body inversion effect described by Reed et al. (2003).

**Errors**

Contrary to reaction times, the \( 2 \times 2 \times 7 \) repeated measures ANOVA with Stimulus type (Body, Control), Target position (0°, 180°) and Angle disparity (0°, 30°, 60°, 90°, 120°, 150°, 180°) as within-subject factors showed no effect of Stimulus type, \( F(1,19) = 0.29, p < .60 \), therefore no difference between the body part presented in context and the control stimuli. Only the main effects of Target position, \( F(1,19) = 42.13, p < .001 \), and Angle, \( F(6,114) = 22.50, p < .001 \) were significant, revealing more errors for the target at 180° than for the target at 0° and increasingly higher error rates with bigger angle disparities. However, a significant Stimulus × Target position × Angle interaction, \( F(6,114) = 2.30, p < .05 \), was revealed. This was due to the fact that, for the larger angular disparities, there were more errors when the target was upside down in the Body condition compared to the Control condition. The opposite was true for upright targets (see Figure 3b).

Separate ANOVAs for target at 0° and target at 180° were performed. In both cases there was a main effect of Angle, \( F(6, 114) = 9.88, p < .001 \) for target at 0°, and \( F(6, 114) = 18.33, p < .001 \) for target at 180°, but no differences between Body and Control stimuli, and no 2-way or 3-way interactions. Therefore, there was no systematic effect of the possible/impossible manipulation on errors.

**TABLE 1**

Mean mental rotation slopes (±SD), expressed as ms°, as a function of possible and impossible ranges of movement and stimulus type

<table>
<thead>
<tr>
<th>Target at 0°</th>
<th>Target at 180°</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Possible range</strong></td>
<td><strong>Impossible range</strong></td>
</tr>
<tr>
<td>Body part in context</td>
<td>1.95 (1.48)</td>
</tr>
<tr>
<td>Control</td>
<td>2.16 (1.26)</td>
</tr>
</tbody>
</table>
Discussion

The results of Experiment 1 indicate, first of all, that mental rotation was performed in a qualitatively similar manner for both types of stimuli (Body and Control), as RTs and errors increased linearly with the angle disparity between the two pictures on the screen. This occurred regardless of whether the target was upright or upside down. As mentioned in the Introduction, this result does not discriminate between a holistic or piecemeal process.

Despite this, RTs and error rates were significantly higher when the target was presented upside down (180°) compared to when the target was upright (0°). This difference was present across all angular disparities, even when both the target and the probe stimulus were in the same orientation (angle disparity = 0, a case that should not require mental rotation since they are completely identical pictures). This very consistent difference between upright and upside-down targets suggests an additional processing stage in the trials containing upside-down targets, which is not present when the target is upright. It is possible that, on trials containing an upside-down target, subjects rotated both pictures to the upright before making a comparison (cf. Harris, Harris, & Caine, 2002, Experiment 3). Alternatively, the difference could be due to the fact that the target at 180° is more difficult to process because it represents an impossible orientation of a body part (in the case of the Body condition only) and it is thus processed part-by-part instead of holistically (i.e., a body-inversion effect).

The results also indicate slower RTs for Body than for Control stimuli in the impossible range when the target was upright. This difference is not likely to be due to the fact that larger rotations are harder for Body compared to Control stimuli, because the same effect was not apparent when the target was upside down. Thus, this difference is more likely due to the biomechanical constraints implied in the Body pictures leading to a piecemeal (slower) rotational process. This conclusion is supported by the fact that we also found a large difference in the mental rotation rates between the possible and impossible ranges of movement. In particular, for stimuli depicting body parts attached to the rest of the body, mental rotation rates were much faster across the anatomically possible orientations, compared to the impossible orientations, when the target stimulus was upright. No such difference was found for body parts presented in isolation, consistent with the idea that biomechanical constraints have no effect on performance for these stimuli and that they are all processed in a similar fashion. In contrast, mental rotation rates were generally much slower when the target was upside down, with no differences between types of stimuli or ranges of movement. As mentioned before, these trials always contain an impossible body posture (the target) and it is interesting to note that the mental rotation rates were similar to those found for the impossible range of movement when the target was upright. Hence, our results indicate that mental rotation rates were always slower
when at least one of the pictures (target or probe) was in an impossible orientation. However, when both pictures were in possible orientations, mental rotation rates were significantly faster, with a slight advantage for the body parts presented in context, probably because those pictures are more familiar and thus easier to mentally rotate. This last result proves that the faster rates cannot be a function of the complexity of the picture, as Body pictures are more complex than the Control pictures (and in general lead to longer RTs), yet they resulted in faster rotation rates.

These findings confirm and extend those of Bethell-Fox and Shepard (1988) and Reed et al. (2003) by showing that possible and impossible body postures are processed differently in mental rotation. Impossible, unfamiliar postures lead to increased RTs and slower mental rotation rates compared to possible body orientations. As mentioned in the Introduction, these results are consistent with possible body postures being processed holistically and anatomically impossible postures being processed in a piecemeal fashion.

**EXPERIMENT 2**

In Experiment 1 we found evidence consistent with the idea that biomechanical constraints are taken into account when performing mental rotation of body parts and that mental rotation is different depending on the nature of body parts. Different strategies appeared to be used to rotate possible and impossible body postures. Taking the question of the nature of processes during mental rotation one step further, one could wonder whether different strategies would be used depending on the experimental procedures. In the Sekiyama (1982) and Parsons (1987) studies, subjects saw a single picture of a hand and had to decide whether it was a left or a right hand. There is good evidence that, in such cases, people tend to solve the task by relating the picture to their own body (e.g., Bonda, Frey & Petrides, 1996; Parsons, Fox, Downs, Glass, Hirsch, Martin, et al., 1995), and this may enhance the effect of biomechanical constraints on task performance and involve analog processing of integrated internal representations. On the other hand, in Experiment 1, subjects may have been able to do the task with only minimal reference to their own body and any internalised knowledge of biomechanical constraints, simply by comparing the two stimuli presented simultaneously on the screen. This is supported by Shepard and Cooper (1982) who note that the rate of rotation can be dramatically affected by the experimental procedure. In particular, simultaneous presentation and matching may induce a strategy of part-by-part rotation and comparison (Carpenter & Just, 1978), whereas a task requiring only matching to long-term memory may encourage the rotation of a single, well-integrated internal representation.

To assess this, in Experiment 2 we presented only one picture which the participants had to compare to a memory representation, to decide whether
it was an anatomically correct depiction of a body-limb configuration. In this situation, subjects may rely on motor imagery, leading them to adopt different strategies when dealing with possible and impossible body orientations.

Methods

Participants

This study was approved by the Ethics Committee of Macquarie University. Twenty-seven undergraduate students (22 females, 5 males) took part in this experiment for course credit. All were right-handed and between 17 and 32 years of age (mean ± SD, 21 ± 5 years). The participants were not aware of the purposes or predictions of the experiment until after test completion.

Apparatus

This was the same as Experiment 1.

Materials

Three of the 4 pictures of Experiment 1 were used: (1) the palm of a right hand with the thumb in different orientations (Figure 1, A1), (2) a woman seen from the back with her right forearm in different orientations (Figure 1, A3), (3) a man’s profile with his right forearm in different orientations (Figure 1, A4).

Two versions of each picture were created: one in which the rotated body part matched the side of the body (e.g., the right forearm attached to the right upper arm) and one in which the opposite limb was used (i.e., the left forearm attached to the right upper arm). Note that the Matching stimuli also match the representations stored in long-term memory, as they are anatomically accurate configurations. In contrast, the Opposite stimuli are unfamiliar and incorrect depictions of body configurations.

The body part was rotated clockwise in the picture plane from 0° to 180° in 30° increments. The first 3 orientations (0° to 60°) represent possible orientations and the last 3 (120° to 180°) are anatomically impossible to adopt. The 90°-orientation is at the limit between the possible and impossible range of movements. Figure 4 shows examples of the stimuli in different experimental conditions.

Procedure

Given the difficulty of the decision required, we presented each of the 3 body pictures in a separate block in order to avoid confusion caused by switching the stimuli. Each participant completed all 3 blocks, in different orders. Each block consisted of 56 trials (4 Matching and 4 Opposite trials for each of the 7
orientations) in random order. For example, for stimulus A3, the 4 Matching trials are 4 repetitions of a right forearm on a right upper arm and the 4 Opposite trials are 4 repetitions of a left forearm attached to the right upper arm (see Figure 4).

Participants sat in front of a computer screen at a distance of approximately 50 cm and were instructed to avoid tilting their head. At the beginning of each block they had 10 practice trials containing Matching and Opposite trials related to that particular block presented randomly. They were asked to answer as quickly as possible whether or not the rotated body part was the matching (i.e., anatomically accurate body-part configuration) or the opposite limb. They responded by pressing two different buttons on a button box with their thumbs (right thumb for Matching body part, left thumb for Opposite body part). We did this, rather than the more usual ‘‘left’’/‘‘right’’ decision, because that decision would have been ambiguous in our stimuli which contained left and right body

Figure 4. Examples of stimuli used in Experiment 2. a) and c) depict Match trials (e.g., the forearm matches the side of the body it is attached to and also matches the body configuration stored in memory); b) and d) depict Opposite trials (e.g., a left forearm and hand attached to the right upper arm). a) and b) are biomechanically possible postures, while c) and d) are impossible postures. The subjects’ task was to decide whether the body part was the matching or opposite one.
parts as well as left and right sides of the body. We also wanted to avoid the use of ‘‘possible’’ and ‘‘impossible’’ labels, because our stimuli (whether Matching or Opposite) were depicted in both possible and impossible orientations. Reaction times were recorded from the time when the stimulus appeared on the screen until the participant pressed a button. If no response was given in 3 seconds, the stimulus was replaced by the next one.

Results

Responses and response times were recorded. As there were no differences between the individual stimuli, the corresponding RTs and error rates were collapsed. Figure 5 shows the mean RT for correct responses (a) and error rates (b) for all 27 subjects.

Reaction times

The RTs for the correct responses were analysed using a repeated measures 2 × 7 ANOVA with Match (Matching body part versus Opposite body part) and Orientation (0°, 30°, 60°, 90°, 120°, 150°, 180°) as within-subject factors. It revealed a main effect of Match, $F(1,26) = 70.52, p < .001$, with shorter RTs for the Matching body parts than for the Opposite ones. Also, a main effect of Orientation, $F(6,156) = 23.68, p < .001$, was found, with RTs increasing gradually as the body part was rotated further from the upright. Finally, there was a significant Match × Orientation interaction, $F(6,156) = 8.62, p < .001$, indicating that RTs for the Matching and Opposite arms were different in the possible range of motion (i.e., up to 90°) but very similar in the impossible range (see Figure 5a). This was confirmed by simple comparisons which showed significant differences between the Matching and Opposite arms for the possible angles (0°, 30°, 60°, 90°); $F_6 > 9.6, ps < .005$. However, these differences were not significant for the impossible angles (120°, 150°, 180°); $F_6 < 2.56, ps > .11$. This implies that an anatomically realistic, familiar picture is more easily processed in the possible range of motion than a non-realistic, unfamiliar one, but this difference disappears in the impossible range of movement.

A final analysis consisted of calculating the rate of mental rotation for the Matching and Opposite body parts. In the case of the Matching limb, we observed a typical mental rotation function (see Figure 5a), with a speed of mental rotation of 3.04 ms/°, or 327.9°/sec. This corresponds to what is believed to be the average mental rotation rate (Corballis, Zbrodoff, & Roldan, 1976). In the case of the Opposite limbs however, the RTs did not conform to the typical function, yielding a rate of 0.83 ms/° or 1209.5°/sec, which is well outside the usual range obtained in mental rotation experiments. This indicates that participants used different strategies for the Matching and Opposite body parts.
Figure 5. Mean RT (a) and mean percent errors (b) as a function of orientation in Experiment 2, plotted separately for Matching and Opposite body-part configurations. Angles greater than 90° represent impossible orientations.
Errors

The repeated measures 2 × 7 ANOVA on error rates with Match (Matching versus Opposite body part) and Orientation (0°, 30°, 60°, 90°, 120°, 150°, 180°) as within-subject factors revealed a main effect of Match, $F(1, 26) = 5.29, p < .05$, a main effect of Orientation, $F(6, 156) = 18.84, p < .001$, as well as a significant Match × Orientation interaction, $F(6, 156) = 8.30, p < .001$. This interaction is clearly illustrated in Figure 5 (bottom panel). The percentage of errors for the Matching limbs is very low in the possible range and progressively increases across orientations, whereas the errors for the Opposite limbs are substantially higher and stay more or less constant through the possible and impossible ranges.

Discussion

We found longer RTs and higher error rates overall for the Opposite (i.e., anatomically inaccurate) body part compared to the Matching one. This suggests that it was more difficult to perform the task when the stimulus depicted an unfamiliar body configuration, which did not match a representation stored in long-term memory. Additionally, we found a significant difference between Matching and Opposite body parts in the possible range of motion, with RTs being consistently shorter for Matching stimuli. This difference can be attributed to the fact that this was the only case which conformed to the anatomical and biomechanical constraints of real bodies—that is, an anatomically correct body configuration depicted in an orientation that is physically possible to adopt. In contrast, no such difference was obtained in the impossible range of movement, presumably because in this case both types of stimuli depicted an impossible or unfamiliar posture. These first results support the idea that, in the case of anatomically correct body configurations, the stimuli were processed as a single entity, whereas biologically impossible postures were processed part-by-part.

Furthermore, in this experiment, the typical mental rotation function, with an average mental rotation speed, was only present in the case of the Matching body parts, whereas the Opposite trials gave rise to a flat RT function and a putative mental rotation speed that was well outside the range normally seen in mental rotation experiments (Tarr & Pinker, 1989). This confirms that these two types of stimuli were processed in qualitatively different ways.

Overall, the results suggest that our subjects found it much easier to carry out the task when the picture was anatomically realistic, both in terms of familiarity of configuration and normal range of movement.

GENERAL DISCUSSION

This study investigated whether the nature of body part stimuli influence mental rotation processes, with the expectation that anatomical limitations
would constrain the way in which subjects perform mental transformations of body parts. Several results from Experiments 1 and 2 are consistent with this notion. First, in Experiment 1, we found that it seems to be more difficult to carry out the task when the target stimulus is upside down. Indeed, for the same angle discrepancies longer RTs and higher error rates were found when the target was at 180° (i.e., in an impossible orientation), than when it was upright. Second, when the target was upright (i.e., in a possible orientation), we found that mental rotation rates were significantly faster for probe stimuli depicted in the possible range of motion than in the impossible range of motion. According to Cohen and Kubovy (1993), the speed of rotation is a more direct estimation of mental rotation itself than RT. These findings replicate the ones reported by Bethell-Fox and Shepard (1988) for non-body stimuli, and provide strong evidence of a difference between possible and impossible ranges of motion. Specifically, possible familiar body postures are processed holistically as a single entity and thus more easily and faster than impossible, unfamiliar, postures.

In Experiment 2, there was a difference between anatomically correct (Matching) and anatomically incorrect (Opposite) body configurations in the possible range of movement, with RTs being consistently shorter for anatomically correct stimuli. This difference was not present in the impossible range, where the RTs and errors were equally high. This supports the idea that whenever there is an anatomically incorrect body configuration or an impossible orientation, the stimuli are processed in a slower, piecemeal fashion. Moreover, the RTs for the anatomically correct configurations conformed to the classical mental rotation function, increasing linearly across orientations. However, no such effect was present for the anatomically incorrect configurations, with RTs being uniformly slow at all orientations. It is as if participants were not able to mentally rotate the incorrect configurations, presumably because they have no experience with and, thus, no mental representation of such objects.

Although we did find evidence for differences in mental rotation processes for body parts linked to anatomical constraints in both experiments, there were some differences between experiments. In Experiment 1, the difference between possible and impossible movement ranges was quite subtle and was only apparent in some performance parameters (e.g., the speed of mental rotation). This relatively weak effect can be attributed to the fact that subjects could directly compare the two stimuli, in much the same way as they would treat other external objects and so, they were less influenced by the motor limitations implied in the pictures. As Shepard and Cooper (1982) state, simultaneous comparison of stimuli is more likely to lead to discrete, feature-based rotational processing. In contrast, in Experiment 2, which was designed to avoid direct comparison of two pictures, a clear qualitative difference between possible and
impossible postures was apparent. As for Experiment 1, we could say that possible, familiar postures were processed holistically and that impossible, unfamiliar postures were rotated in a piecemeal fashion. However, many studies have shown that mental rotation of unfamiliar objects is possible (e.g., Cooper, 1975; Shepard & Metzler, 1971), hence, this does not explain why a flat function was obtained for our anatomically incorrect stimuli. Indeed, the results of Experiment 1 show that body parts depicted in impossible orientations can be mentally rotated in situations that allow direct comparison with another stimulus. Therefore, the most likely explanation for the difference seen in Experiment 2 is that, in this case, subjects need to compare the stimulus to a stored representation, and such a representation was not available for anatomically incorrect body configurations. In other words, in Experiment 1, two stimuli were shown simultaneously which enables the subjects to compare them directly, whereas in Experiment 2, only one stimulus was presented at a time so that it can only be compared to a stored representation. Presumably, if this representation does not exist, the results will not show a typical mental rotation function because the subjects are not rotating the stimulus to a representation that is in a particular orientation. This is in accordance with Shepard and Cooper (1982) who state that individually presented, well-learned stimuli must be compared with a long-term memory representation. Stimuli lacking full mental integration may have to be processed differently.

As described in the Introduction, evidence for a specific system that deals with mental transformations of body parts comes from a number of neuropsychological and psychological studies that show dissociations between mental transformations of body parts versus other objects (Daems & Verfaillie, 1999; Ogden, 1985; Reed & Farah, 1995; Sirigu, Grafman, Bressler, & Sunderland, 1991). It is likely that in Experiment 2, subjects utilised this motor imagery system, which would incorporate knowledge of the anatomical and biomechanical constraints of real bodies. These results are compatible with those reported by Sekiyama (1982) and Parsons (1987) who found facilitation for orientations of hands in accordance with the biological constraints of the hand movement.

In conclusion, we have found evidence that possible and impossible body postures are processed differently in a mental rotation paradigm, linked to the fact that anatomical and biomechanical constraints are taken into consideration during mental transformations of body parts. This implies that the transformation of these stimuli is carried out by a system that incorporates knowledge of the kinaesthetic properties of normal human movements. Familiarity and expertise with particular configurations of body parts influence mental transformation by developing an increased ability to use configural information. When presented with an unfamiliar (physically impossible) configuration of body parts, participants appear to rely less on configural processing.
REFERENCES


